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SEISMIC QUALIFICATION TESTS OF SPRINKLER SYSTEMS

A STUDY FOR FLEXHEAD INDUSTRIES

PART 1

Summary Report to Sponsor:

FlexHead Industries

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1. INTRODUCTION

1.1 General

This report describes the seismic performance of two FlexHead Industries sprinkler systems tested together with Armstrong World Industry Inc. suspended ceiling systems at the University at Buffalo between August 18 and August 24, 2005. The testing protocol adopted for the full-scale tests described in this summary report is that prepared by the International Code Council, which is entitled *ICC AC156, Seismic Qualification Testing of Nonstructural Components* (ICC, 2004), which is denoted hereafter as AC156.

A number of studies related to the seismic performance of Armstrong World Industry Inc. suspended ceiling systems have been completed in recent years (incl. Repp et al., 2003a, 2003b; Badillo et al., 2002, 2003a, 2003b; Kusumastuti et al., 2002; Cyr et al., 2004; Gulec et al. 2005). However, the studies reported herein are the first conducted on a large-scale ceiling assembly including lay-in tiles and sprinkler lines and heads.

Chapter 2 of the report describes the earthquake simulator, the test frame and the FlexHead systems. Chapter 3 introduces the topic of seismic qualification and describes the earthquake histories used in the testing program. Summary results are presented in Chapter 4. References are provided following Chapter 4.

Additional information on the tests reported herein will be presented in SEESL technical reports that are being prepared at the time of this writing.

2. EXPERIMENTAL FIXTURE AND TEST SPECIMENS

2.1 Earthquake Simulator

One of the two six degrees-of-freedom earthquake simulators in the Structural Engineering and Earthquake Simulation Laboratory (SEESL) of the State University of New York at Buffalo was used to evaluate the FlexHead sprinkler systems. These two simulators can be rapidly repositioned from directly adjacent to one another to positions up to 100 ft (30.48 m) apart. Together, these tables can host specimens of up to 220.5 kips (981 kN) and as long as 120 ft (36.6 m), and subject them fully in-phase or totally uncorrelated dynamic excitations. Each earthquake simulator has plan dimensions of 11.8 ft x 11.8 ft (3.6 m x 3.6 m) and is made of a welded steel construction with a weight of approximately 17.6 kips (78 kN). A steel testing platform of plan dimensions 23 ft. (7.01 m) by 23 ft. (7.01 m) extends the useful testing area of the simulator. The Hydraulic Power Supply (HPS) subsystem for both simulators consists of four MTS Model 506.92 pumps rated at 185 gpm (700 lpm) at 3,000 psi (207 bar) each. Additional information can be found at www.nees.buffalo.edu.

The two six degrees-of-freedom earthquake simulators are designed for the nominal performance shown in Table 2.1. These performance data are based on uniaxial sinusoidal motion of the simulator with a rigid 44.1 kip (196 kN) payload. System performance levels are reduced with payloads larger than a nominal payload. Acceptance testing of the simulators has verified a frequency response of 0-100 Hz with the bare platform and 0-50 Hz with a 44.1 kip (196 kN) payload. Input or command signals to the table can be of the following types: harmonic motions (sinusoidal, square, and triangular), random motions, and any recorded earthquake history.

2.2 Test Frame

A 16 ft. (4.88 m) by 16 ft. (4.88 m) square frame of ASTM Grade 50 steel was used to test all eight FlexHead systems. Figures 2.1 through 2.3 present detailed information on the frame. Figure 2.1 is a plan view of the base of the frame. The frame was attached to the simulator platform using 1 in. (25 mm) diameter bolts in the beams that were oriented in the east-west direction. Figure 2.2 shows the details of the top of the frame. The ceiling and sprinkler systems were installed then constructed inside of the test frame. Some ceiling systems were attached to the inside face of the 2 in. x 6 in. (51 mm x 152 mm) timber ledger shown in Figure 2.3. Figure 2.4 is a photograph of the test frame mounted on the earthquake simulator.

Table 2.1 Performance data for the six degree-of-freedom earthquake simulators

Table size	11.8 ft x 11.8 ft (3.6 m x 3.6 m)
Maximum specimen mass	110.2 kips (490 kN) max.; 44.1 kips (196 kN) nominal
Maximum overturning moment	332 kip-ft (451 kN-m)
Maximum off center loading moment	108 kip-ft (147 kN-m)
Frequency range	0.1~50 Hz nominal; 100 Hz max.
Stroke (X axis, Y axis, Z axis)	±5.91 in, ±5.91 in, ±2.95 in (±150 mm, ±150 mm, ±75 mm)
Velocity (X axis, Y axis, Z axis)	49.2 in/sec (1250 mm/sec), 49.2 in/sec (1250 mm/sec), 19.7 in/sec (500 mm/sec)
Acceleration (X axis, Y axis, Z axis)	±1.15 g, ±1.15 g, ±1.15 g

2.3 Instrumentation

Accelerometers and displacement transducers were used to monitor the response of the simulator platform, the test frame, the ceiling support grid in each ceiling system and the sprinkler system. Accelerometers were located at different points on the simulator platform, on the test frame, on the ceiling support grid, and on the sprinkler system. Figures 2.5 and 2.6 are photographs of accelerometers installed on components of the sprinkler system. Horizontal displacements of the frame were measured with linear variable displacement transducers (LVDT) located on the north and west sides of the frame.

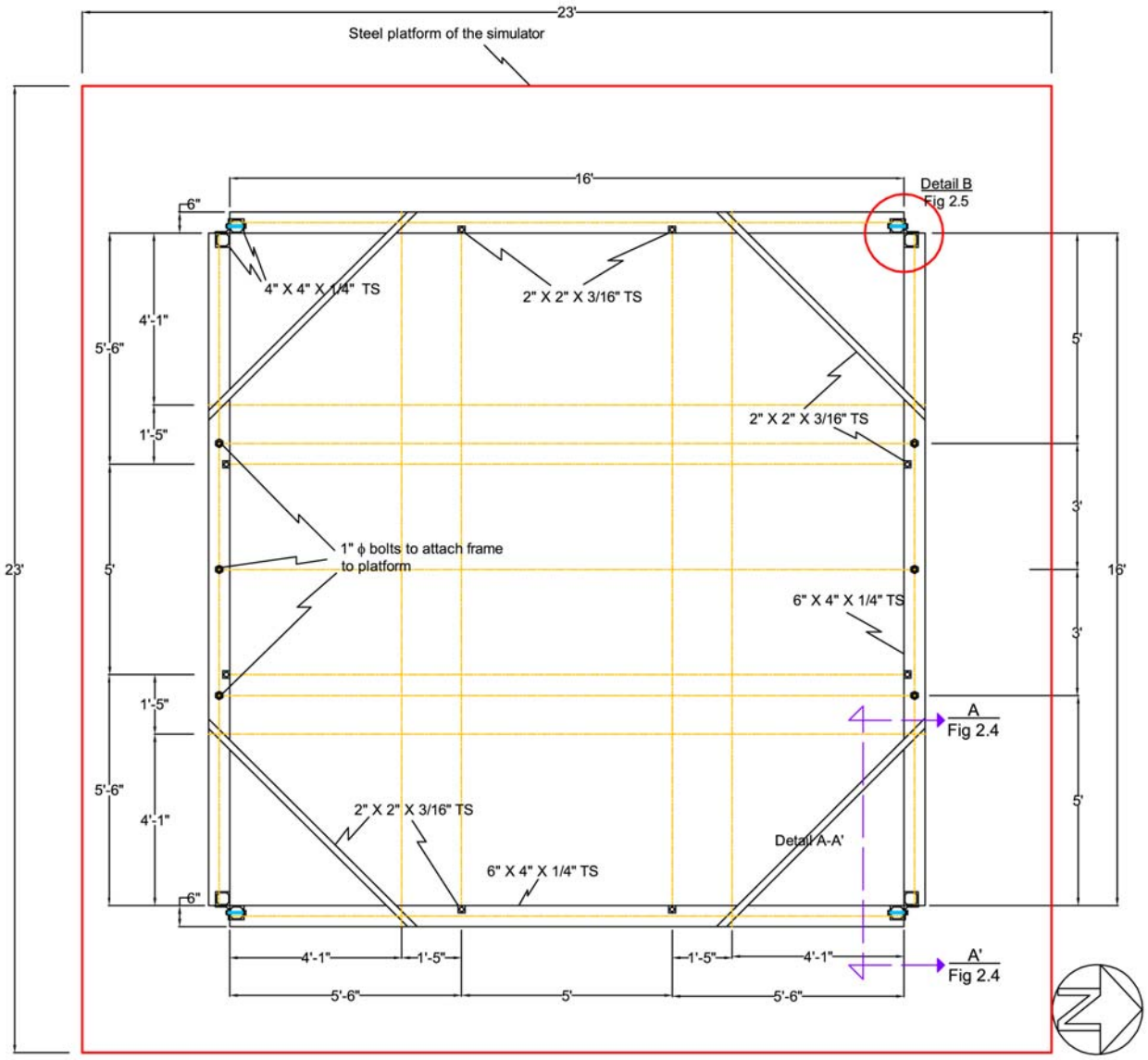


Figure 2.1 Plan view of the base of the frame

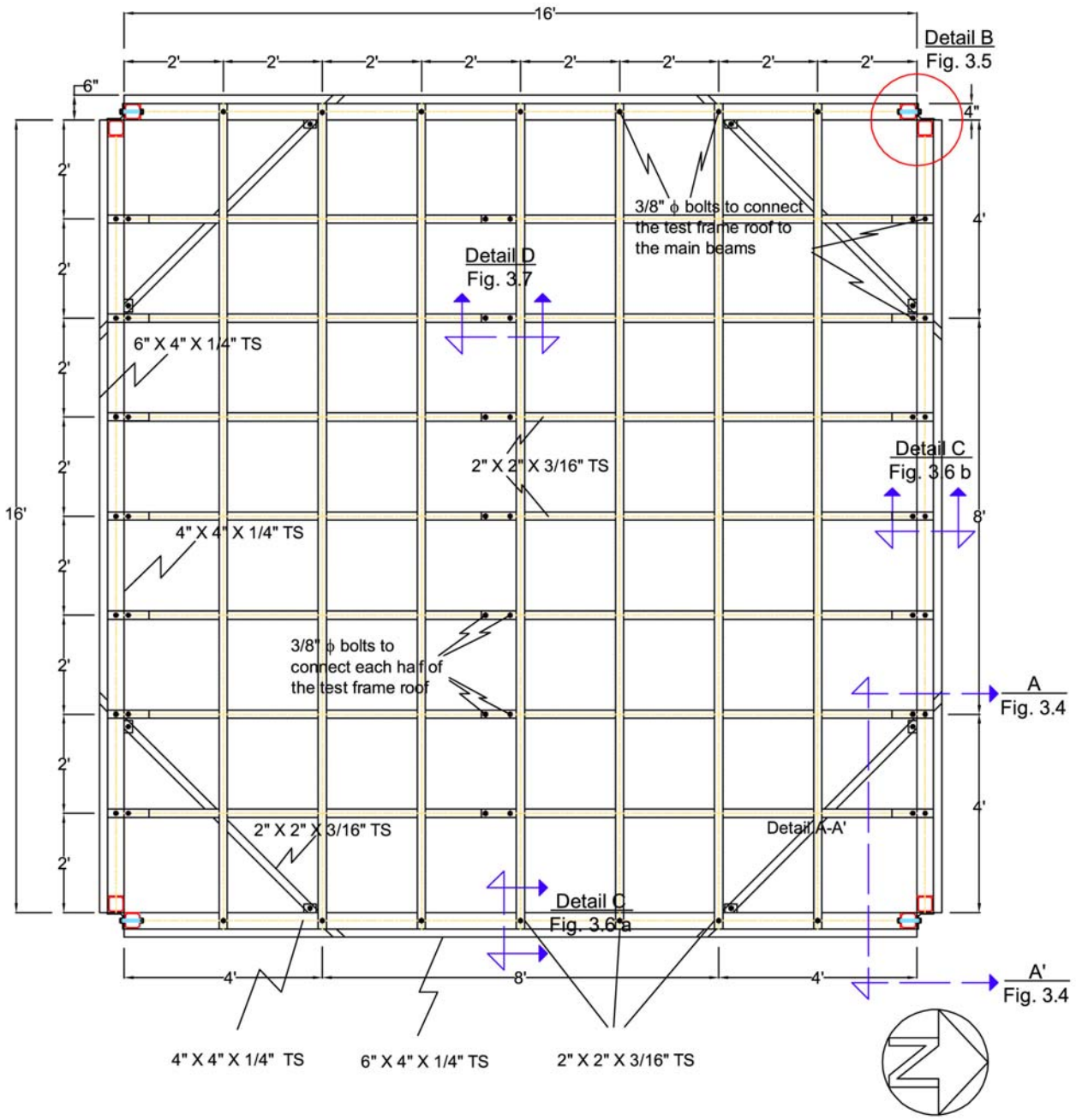


Figure 2.2 Plan view of the top of the frame

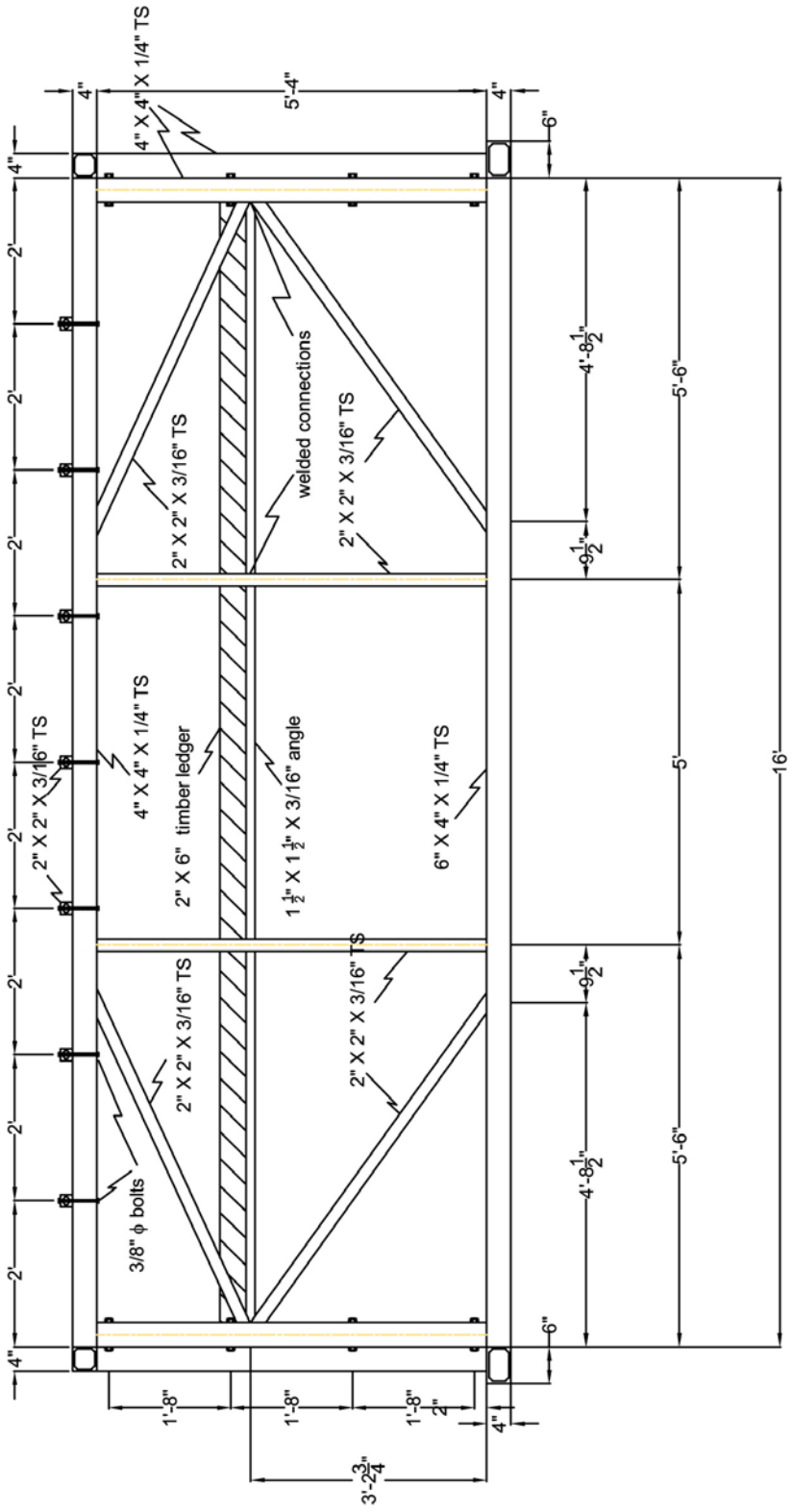


Figure 2.3 Elevation of the east side of the frame

Figure 2.4 Test frame mounted on the shaking table at the University at Buffalo

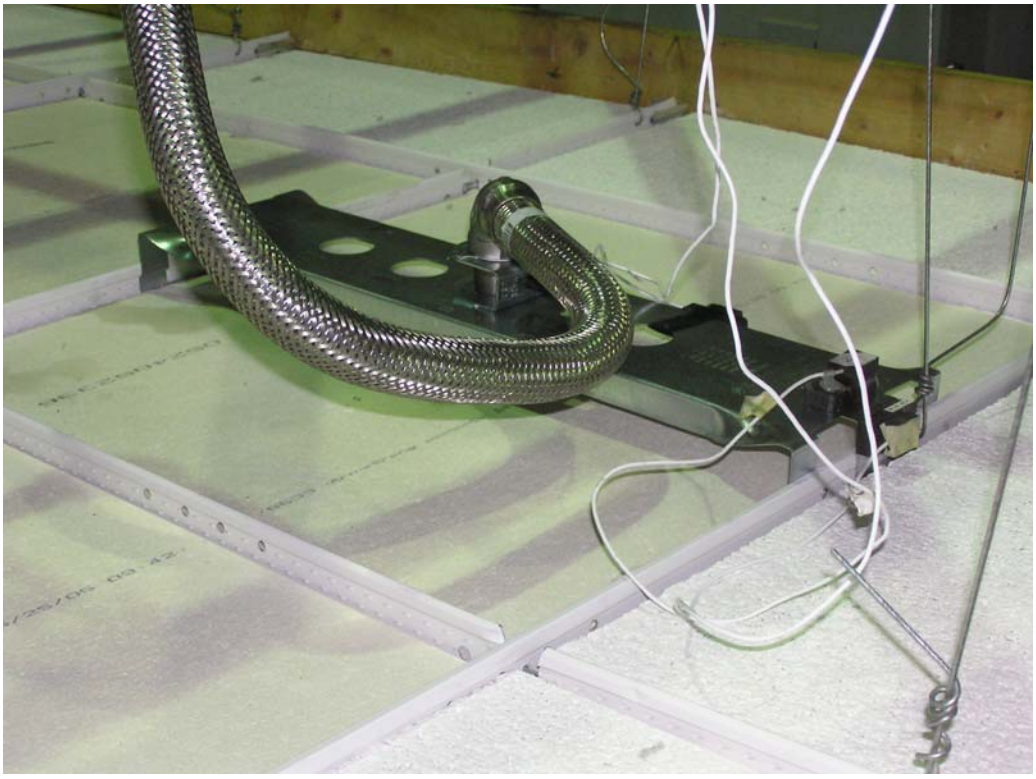


Figure 2.5 Accelerometers on the FlexHead bracket

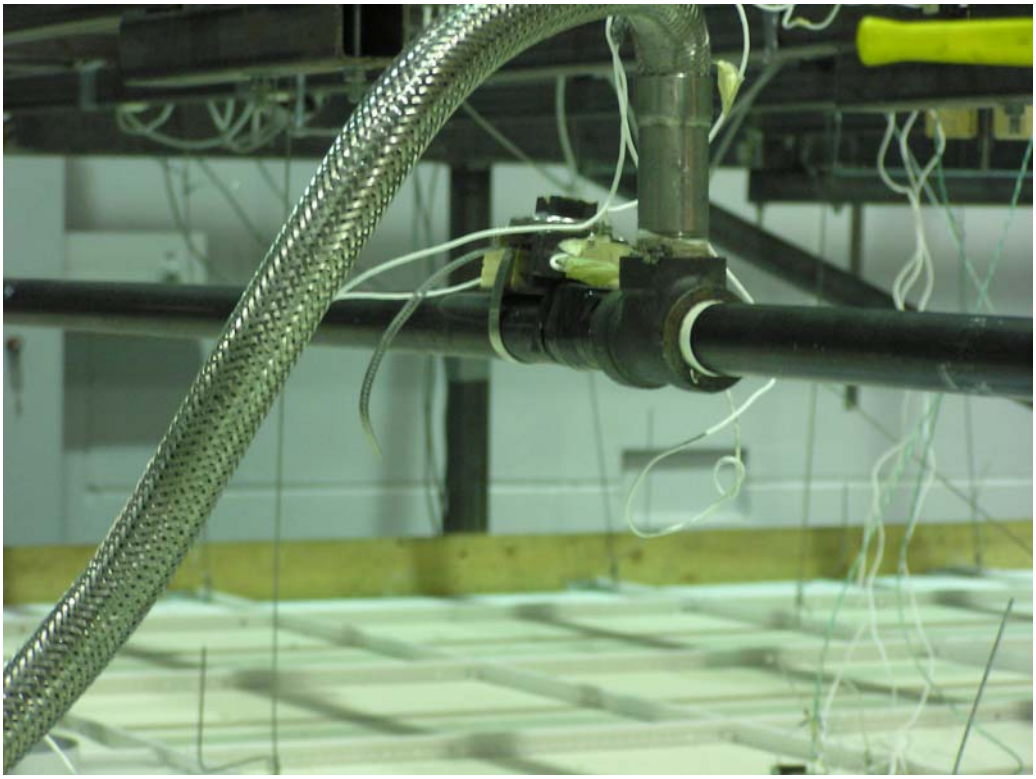


Figure 2.6 Accelerometers installed on the piping system

2.4 Specimen Description

2.4.1 Introduction

This section presents information on each of the FlexHead/ceiling systems tested as part of this study.

A standard schedule 40 piping system was attached to the test frame per NFPA 13. Figure 2.7 is a plan view of the piping system that included one main line and two (east and west) branch lines. The piping system was supported by vertical rod braces at 4 locations, denoted V in the figure: 2 on the main line and one at the northern end of each branch line. Inclined rods provided lateral bracing to the branch lines (in most of the tested systems) at the two locations, one per line, denoted H in the figure. Unidirectional seismic (lateral) braces were provided on the main line; these braces are also shown in Figure 2.7. The FlexHead flexible hoses, which joined the hard piping to the sprinkler heads, were connected to the branch lines as shown in Figure 2.7. Figure 2.8 is a photograph of part of the sprinkler-ceiling system. The orange and white arrows identify the main and branch lines, respectively. The red arrows identify the vertical rod supports to the main line. The yellow arrows identify the unidirectional seismic (lateral) braces.

Four FlexHead flexible sprinkler hoses were installed between the branch lines of the piping system (2 on the eastern side and 2 on the western side) and the plane of the Armstrong ceiling system. Top *takeoff* connections (see Figure 2.9a) were used on the western branch line and side *takeoffs* (see Figure 2.9b) were used on the eastern branch line. The sprinkler system was pressurized to between 60 *psi* and 65 *psi* for each of the FlexHead tests. Figure 2.10 is a photograph of the machine used to pressurize the piping.

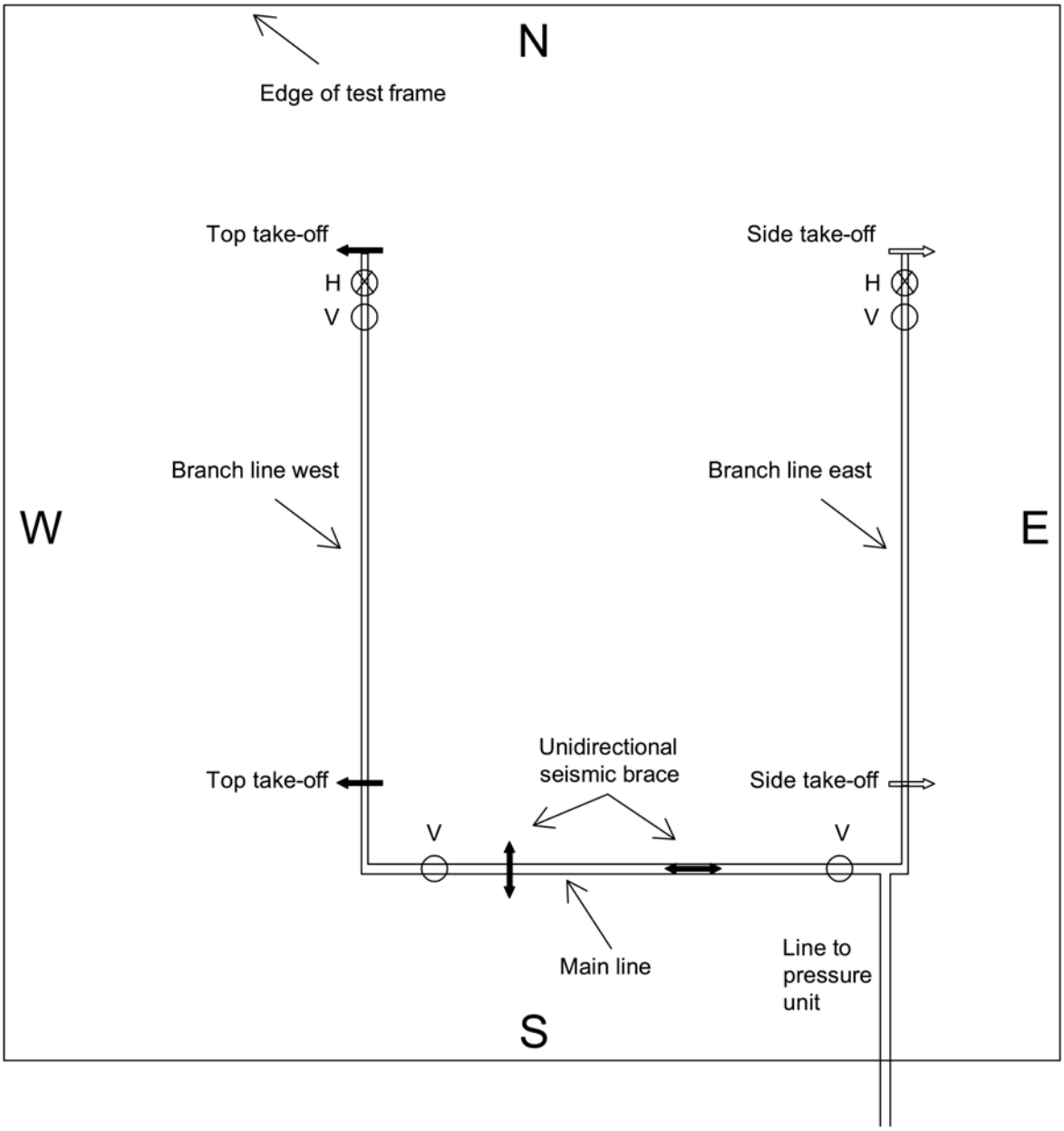


Figure 2.7 Plan view of key components of the sprinkler piping system

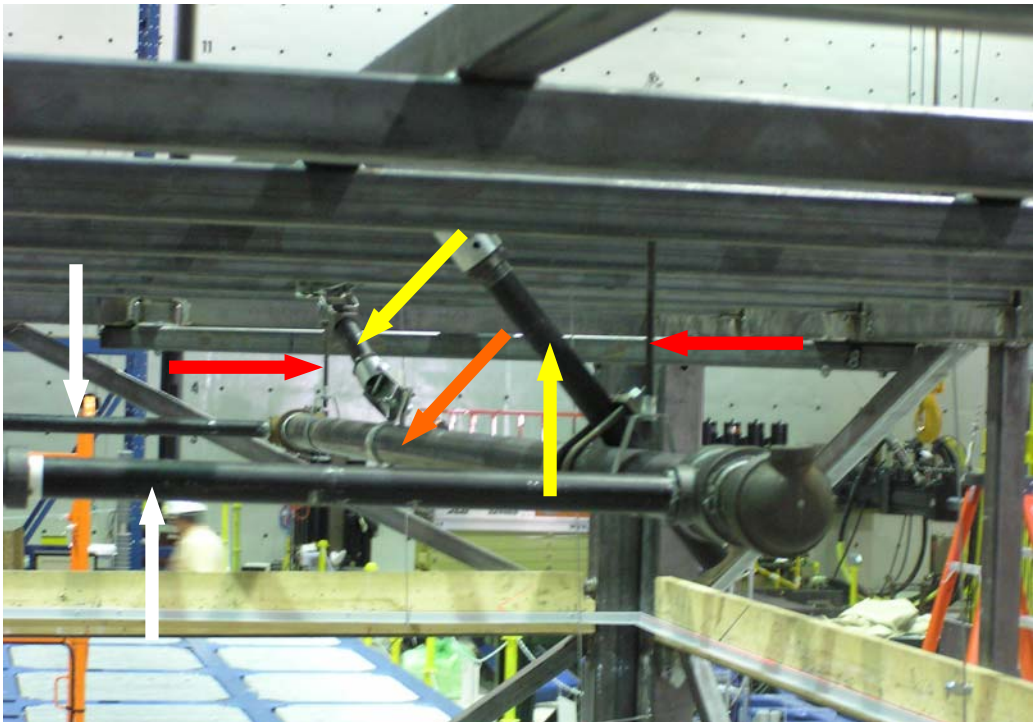
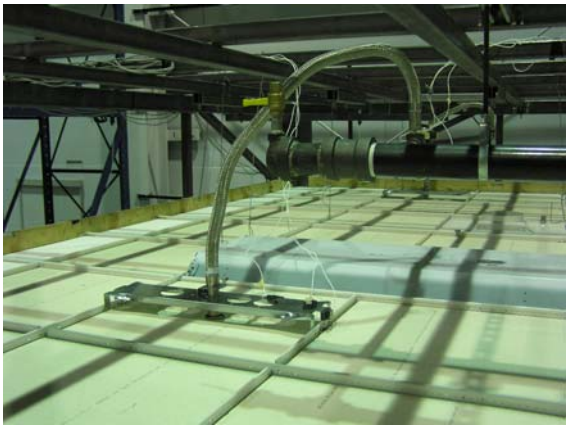
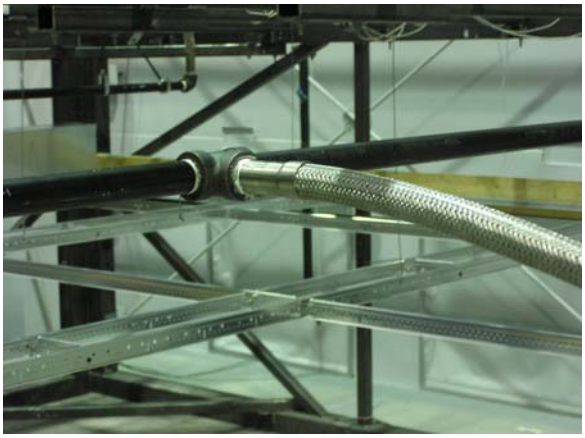


Figure 2.8 Lateral bracing and vertical support to the main pipe line



a. top takeoff



b. side takeoff

Figure 2.9 Connection points for the FlexHead flexible hoses

Figure 2.10 Unit used to pressurize the piping system

Two types of ceiling systems were used for qualification testing per AC156 (ICC, 2004). The following two subsections identify the ceiling system used with each FlexHead test assembly. Table 2.2 provides summary information on each ceiling system. For tests of each assembly, FlexHead Industries and Armstrong World Industries installed the sprinkler systems and ceiling systems, respectively.

Table 2.2 Summary information for the ceiling systems

FlexHead System ID	Test series	S_S test level[1]	Comments
1	I10	0.25-2.50	Standard schedule 40 piping system with seismic bracing, FlexHead bracket MP24BKT, two FlexHead Model #2036 units on the east side and two Model #2048 units on the west side of the test frame, with Armstrong Standard Seismic Design Category D, E and F ceiling system
2	J10	0.25-1.75	Standard schedule 40 piping system with one horizontal sway brace, FlexHead bracket MP24BKT, two FlexHead Model #2036 units on the east side and two Model #2048 units on the west side of the test frame, with an Armstrong Standard Seismic Design Category C ceiling system

1. The test level indicates the range of short period spectral acceleration S_s to which the system was subjected.

2.4.2 FlexHead System 1

FlexHead system 1 (see column 1 of Table 2.2) was composed of an Armstrong *Standard Seismic Design Category D, E and F Heavy-Duty T-bar Grid Ceiling System*, equipped with lights, diffusers, and the piping system of Section 2.4.1.[1] The sprinkler piping system was pressurized to 60 *psi*. Four FlexHead MP24BKT brackets were installed on the ceiling grid as the lower attachment points for the flexible hoses. One bracket is identified by the white arrow in Figure 2.11. On the eastern side of the test frame, two FlexHead Model #2036 ($36''$ OAL) flexible hoses were joined to side takeoff sprinkler fittings on the eastern branch line. On the western side of the test frame, two Model #2048 ($48''$ OAL) flexible hoses were joined to top takeoff sprinkler fittings on the western branch lines. Figure 2.12 is a view of the top of FlexHead system 1. A 2" wide wall molding was screwed to the ledger and installed around the perimeter of the ceiling system. The ceiling tiles were installed with a $3/4''$ gap between the edge of the tiles and the molding as seen in Figure 2.13.

[1] Armstrong World Industries advised the authors that this ceiling system was constructed to comply with ASTM Standard C635, *Standard Specification for the Manufacture, Performance and Testing of Metal Suspension Systems for Acoustical Lay-in Panel Ceilings* (ASTM, 2000) and that the ceiling construction details comply with the *Recommendations for Seismic Restraint for Direct Hung Acoustical Tiles and Lay-in Panel Ceilings, Seismic Zones 3-4* (CISCA, 1991b).

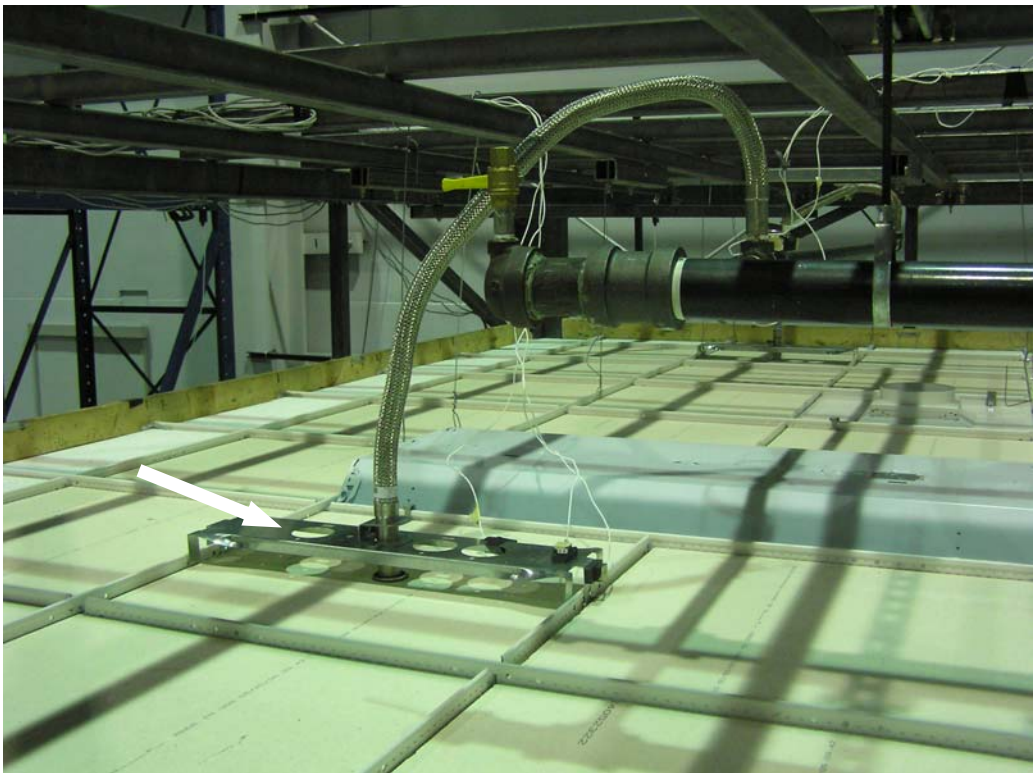


Figure 2.11 Sprinkler connection detail on the western side of FlexHead system 1

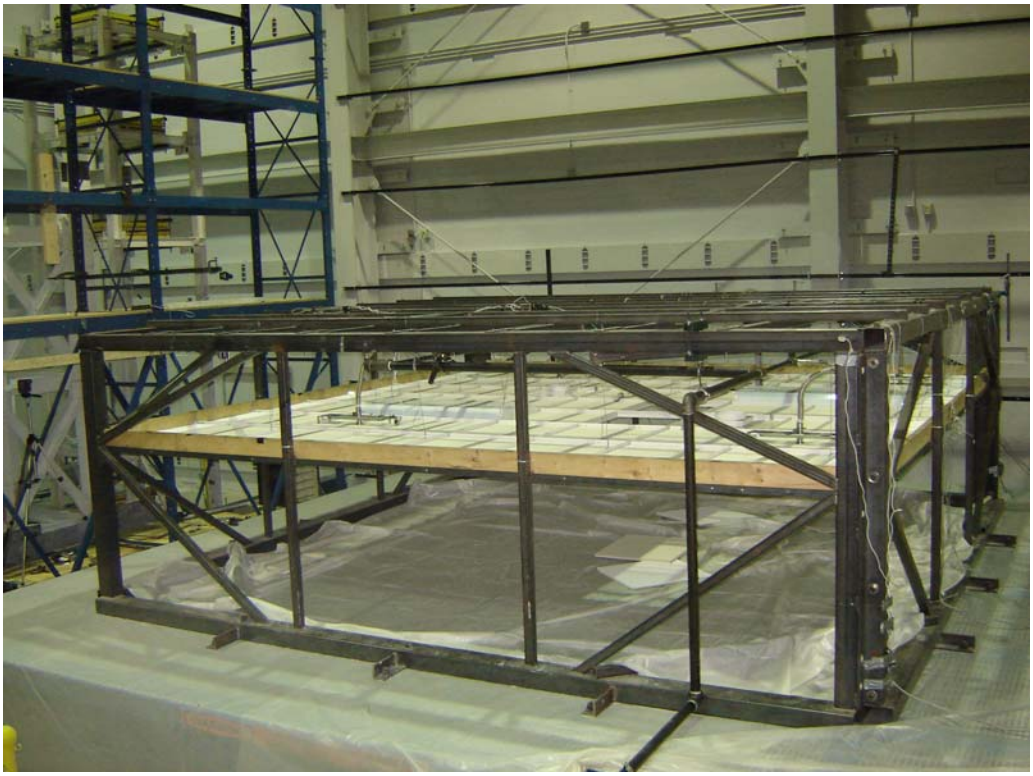


Figure 2.12 Top view of the FlexHead system 1

Figure 2.13 Edge connection detail in FlexHead system 1

2.4.3 FlexHead System 2

FlexHead system 2 (see column 1 of Table 2.2) was composed of a standard Armstrong *Seismic Design Category C Intermediate Duty Ceiling System*.[2] The ceiling system was constructed with a $7/8''$ wall molding attached to each ledger. A $3/8''$ clearance was maintained between the tiles and the molding. The ceiling grid was not provided with either lateral bracing or a compression strut. The piping system was installed per Section 2.4.1 but the lateral bracing to the branch lines and a uni-directional lateral brace on main line were removed. One lateral brace was retained for the main line. The sprinkler piping system

[2] Armstrong World Industries advised the authors that this ceiling system was constructed to comply with ASTM Standard C635, *Standard Specification for the Manufacture, Performance and Testing of Metal Suspension Systems for Acoustical Lay-in Panel Ceilings* (ASTM, 2000) and that the ceiling construction details comply with the *Recommendations for Seismic Restraint for Direct Hung Acoustical Tiles and Lay-in Panel Ceilings, Seismic Zones 0-2* (CISCA, 1991a).

was pressurized to 65 *psi*. Four FlexHead MP24BKT brackets were installed on the ceiling grid as the lower attachment points for the flexible hoses. On the eastern side of the test frame, two FlexHead Model #2036 (36″ OAL) flexible hoses were joined to side takeoff sprinkler fittings on the eastern branch line. On the western side of the test frame, two Model #2048 (48″ OAL) flexible hoses were joined to top takeoff sprinkler fittings on the western branch lines.

3. SEISMIC QUALIFICATION AND EARTHQUAKE HISTORIES

3.1 Introduction

Each of the FlexHead sprinkler systems described in Chapter 2 was subjected to a set of combined horizontal and vertical earthquake excitations for the purpose of qualification. The qualification procedures were those of the *ICC AC156 Seismic Qualification Testing of Nonstructural Components* (ICC, 2004), which is denoted hereafter by AC156. The following section in this report presents summary information on seismic qualification and the earthquake histories used for the qualification of the sprinkler and ceiling systems.

3.2 Seismic Qualification of the Sprinkler and Ceiling Systems

3.2.1 ICC Requirements for Seismic Qualification of Nonstructural Components

Several requirements must be fulfilled for testing nonstructural components per AC156. As part of these requirements, a general description of the system to be tested must be provided (see Chapter 2). This description must include the primary equipment product function, overall dimensions, weight and restrictions or limitations on equipment use. Seismic parameters must also be provided, such as equipment attachment elevation, structure roof elevation, seismic coefficient and equipment importance factor. The test specimen must also adequately represent the entire equipment product line (to be provided by the manufacturer, FlexHead Industries, see Chapter 2).

To qualify a test system, ICC writes that the system must be subjected to a testing program that includes a pre-test inspection and functional compliance check, resonance search tests, random multi-frequency seismic simulation tests, and a post-test inspection and a functional compliance check.

3.2.2 Limit States of Response

Limits states of response must be defined for qualification testing; where a limit state is a boundary between acceptable and unacceptable performance. For this testing program, three limit states were identified: 1) water leakage from any component of the piping system, 2) movement of the sprinkler head from its intended location, and 3) ceiling system integrity, herein defined as failure of the suspension grid.

3.2.3 Horizontal and Vertical Target Spectra for Qualification

The earthquake excitations used for the qualification of the ceiling system were obtained using the spectrum matching procedure recommended by ICC. The first step in the process is to define a target

spectrum or required response spectrum (RRS). Per ICC, the RRS is obtained as a function of the mapped spectral acceleration at short period, S_S. Spectra are generated for horizontal and vertical design basis earthquake shaking.[3]

The required response spectrum for horizontal shaking was developed using the normalized ICC response spectrum shown in Figure 3.1. (The ordinates in the range of frequency from 0.1 Hz to 1.3 Hz are recommendations only.) The values of the parameters A_{RIG} and A_{FLX} that define the ordinates of the horizontal spectrum are calculated with equations presented below.

For horizontal design basis earthquake shaking, the International Building Code (IBC, 2003) defines the short period design basis earthquake acceleration response as:

$$S_{DS} = \frac{2}{3} F_a S_S \tag{3.1}$$

where S_{DS} is the design spectral response acceleration at short periods, F_a is the site coefficient, and S_S is the mapped maximum earthquake spectral acceleration at short periods. Based on AC156, the spectral acceleration A_{RIG} of a rigid component (assumed to have a frequency $f \geq 33$ Hz) is given by (3.2) and that of a flexible component A_{FLX} is given by (3.3).

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[3] The 2003 NEHRP *Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* (FEMA, 2003) use Seismic Design Categories (A through F) as a means of classifying a structure based on its Seismic Use Group and the severity of the design earthquake ground motion at the building site. As general guidance (Bachman, 2005) and based on short period response accelerations, site classes B through D (see Table 4.1.2.4a of FEMA, 2003) and Seismic Use Groups I through III, buildings assigned to Seismic Design Category (SDC) C have values of $0.16 \leq S_S \leq 0.75\,g$, buildings assigned to SDC D have values of $0.33 \leq S_S \leq 1.70\,g$, and buildings assigned to SDC E or F have values of $1.50 \leq S_S \leq 2.40\,g$. Nonstructural components such as ceilings and sprinkler systems that qualify at a level of $S_s \geq 0.75\,g$ should satisfy the requirements for SDC C regardless of the site of the building. Similarly, nonstructural components that qualify at a level of $S_S \geq 1.70\,g$ and $S_S \geq 2.40\,g$, should meet the requirements for SDC D and E/F, respectively, regardless of the site of the building. For a project-specific design, values of spectral demand for nonstructural components should be checked on the basis of the location of the site of the building, site class, Seismic Use Group and location of the component within the building, all as presented in FEMA (2003).

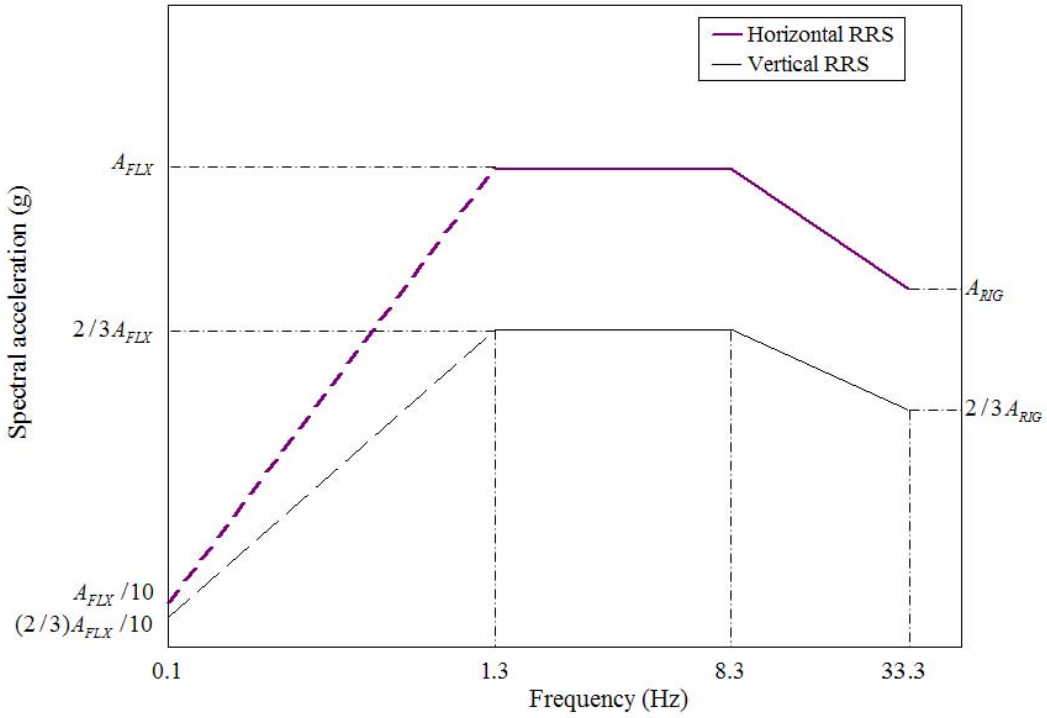


Figure 3.1 Required response spectra for horizontal and vertical shaking

$$A_{RIG} = 0.4 \cdot S_{DS}(1 + 2\frac{z}{h}) \leq 1.2 \cdot S_{DS} \tag{3.2}$$

$$A_{FLX} = S_{DS}(1 + 2\frac{z}{h}) \leq 1.6 \cdot S_{DS} \tag{3.3}$$

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 the 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 the buildings structure, it is conservative, but appropriate, to set $z = h$.

Table 3.1 shows the parameters used in this study to obtain the RRS for horizontal shaking for 5 percent damping for a mapped spectral acceleration at short period S_S between 0.25 and 2.50, with $S_S = 1.0\,g$ shown highlighted in yellow.

Table 3.1 Parameters to calculate the horizontal RRS (*z*/*h*=1.0)

S_S	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**	**2.25**	**2.50**
F_a	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
S_{DS}	0.17	0.33	0.50	0.67	0.83	1.00	1.17	1.33	1.50	1.67
A_{FLX}	0.27	0.53	0.80	1.07	1.33	1.60	1.87	2.13	2.40	2.67
A_{FLX} /15	0.02	0.04	0.05	0.07	0.09	0.11	0.12	0.14	0.16	0.18
A_{RIG}	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00

Figure 3.2 shows the RRS in the horizontal and vertical directions for 5-percent damping for a mapped spectral acceleration at short period of $S_S = 1.0\,g$. The ordinates of the vertical required response spectrum (RRS) are given by ICC as two-thirds (2/3) of the horizontal RRS. Namely, A_{FLX} = 1.07 and A_{RIG} = 0.80 for $S_S = 1.0\,g$.

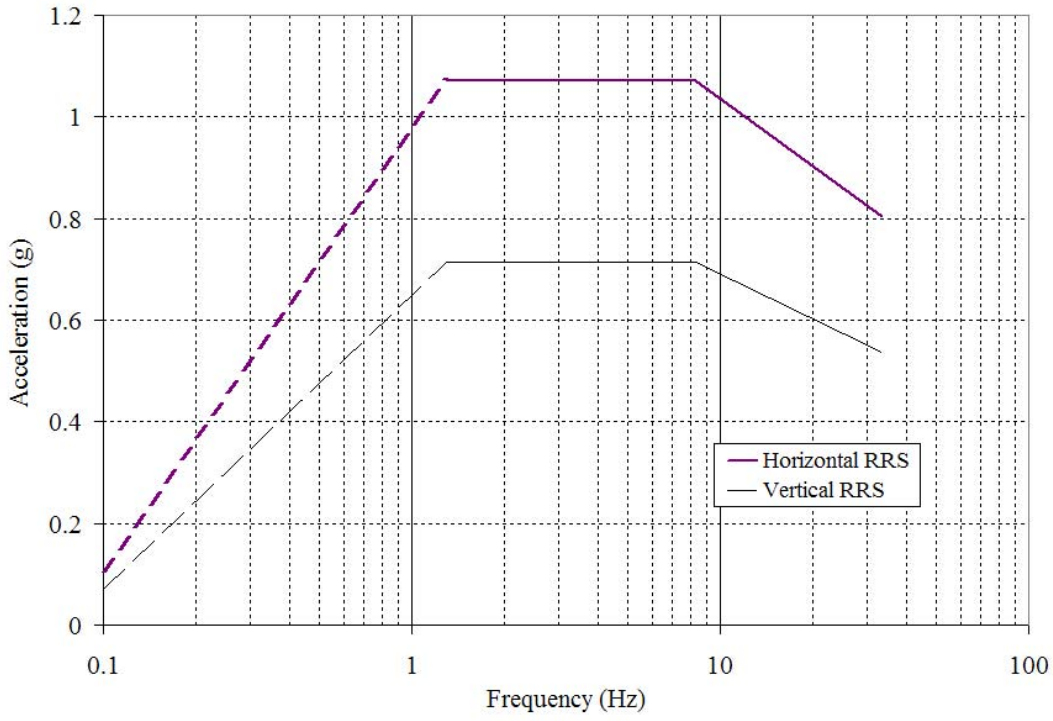


Figure 3.2 RRS for horizontal and vertical shaking for $S_s = 1.0\,g$

3.2.4 Description of Simulation Tests

For the purpose of the qualification, each of the FlexHead/ceiling test assemblies was subjected to a set of horizontal and vertical earthquake excitations. Each set include single-axis resonance search tests using white noise excitation along each (programmable) orthogonal axis of the simulation platform. The resonance search tests were undertaken to establish the natural frequency of the ceiling frame system. Each set of excitations included a series of triaxial earthquake motions that were established for different multiples of the target or required response spectrum (RRS) as recommended by the 2003 International Building Code (ICC, 2003). The different levels were obtained by scaling the input acceleration from those associated with the target horizontal and vertical spectra. Table 3.2 lists the standard series of tests used for each test specimen.

Table 3.2 Test sequence for a complete set of experiments for a sprinkler/ceiling system.

Test No.	**Test name**	**Target S_S (g)**	**Description**
1	I10_wn	--	Triaxial white noise excitation in the horizontal (N-S and E-W) and vertical directions
2	I10_025	0.25	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
3	I10_050	0.50	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
4	I10_075	0.75	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
5	I10_100	1.00	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
6	I10_125	1.25	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
7	I10_150	1.50	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
8	I10_175	1.75	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
9	I10_200	2.00	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
10	I10_225	2.25	Triaxial motion in the horizontal (N-S and E-W) and vertical directions
11	I10_250	2.50	Triaxial motion in the horizontal (N-S and E-W) and vertical directions

3.3 Earthquake Histories

3.3.1 White Noise

White noise was used to find the frequencies of the test frame and the ceiling systems with the FlexHead sprinkler systems. The natural frequencies for the horizontal and vertical directions of each test specimen were obtained by finding the frequency associated with the peak in the acceleration transfer function (Clough and Penzien, 1993). Figure 3.3 shows the records and the Fourier amplitude spectrum of the white noise used in this study to calculate the natural frequencies of each of the ceiling systems for the horizontal and vertical directions, respectively. These frequencies will be presented in a later report to the sponsor, FlexHead Industries.

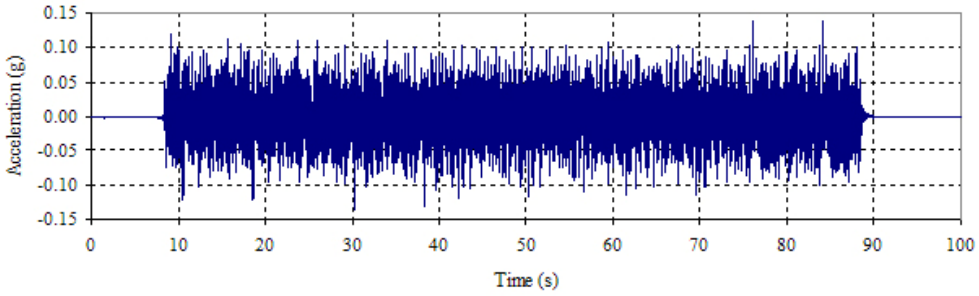
3.3.2 Response Spectrum Matching Procedure and Earthquake Histories

3.3.2.1 Ground Motion Generation

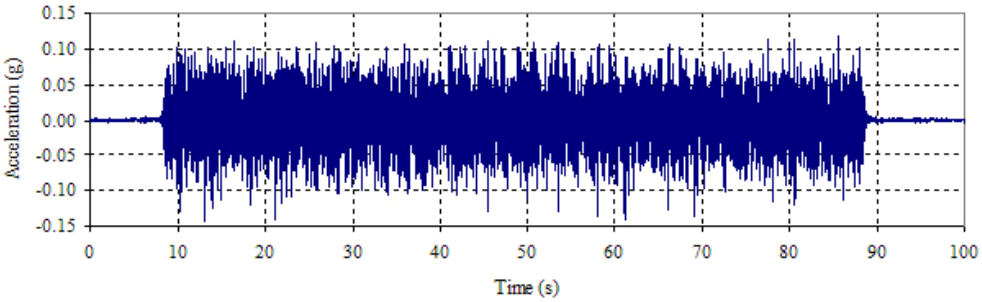
The earthquake excitations used for the qualification of the sprinkler systems were generated according to the requirements of AC156 using a spectrum-matching procedure, namely, the “Inverse Response Spectrum Procedure” (IRSP) routine from the program software STEX (MTS, 1991). STEX utilizes industry-standard algorithms for calculation of shock response spectra and inverse shock response spectra. A damping ratio of 5% (required by AC156) and a frequency resolution of 12 lines per octave (4 times greater than that required by AC156) were used to generate the earthquake records. Independent records were generated for each excited degree of freedom, namely, longitudinal, lateral, and vertical. As specified by AC156, a) the amplitude of the peak vertical acceleration was set equal to 67% of the amplitude of the peak longitudinal and lateral accelerations, and b) 20 seconds of strong motion (with 5 seconds each of ramp-up and ramp-down) was generated for each record.

3.3.2.2 Ground Motion Scaling and Filtering

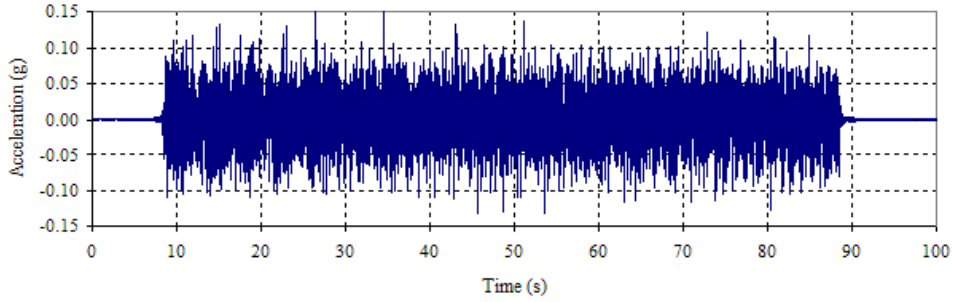
The records obtained using the IRSP were then scaled to match the amplitude requirements of the scaled required (or target) response spectra (RRS). Analysis of the resultant velocity and displacements associated with the acceleration records at each scale factor revealed that the motions scaled to 1.25 times the original RRS would exceed the table limits of +/- 6.0 in (+/- 150 mm) for longitudinal and lateral shaking and +/- 3.0 in. (+/-75 mm) for vertical shaking, at frequencies below 1.0 Hz. Therefore, a high-pass filter with a cutoff value of 1.0 Hz was applied to each motion for all RRS levels scaled to 1.25 times the original RRS and higher. For ground motions scaled to 100% of the original RRS and lower, a high pass filter with a cutoff value of 0.5 Hz was utilized.



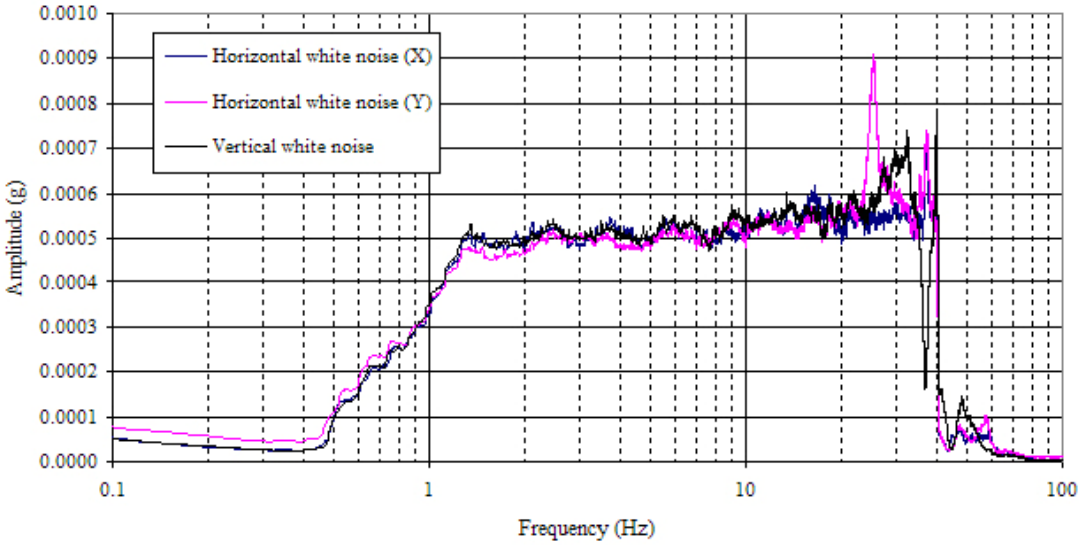
a. horizontal white noise history in X direction (E-W)



b. horizontal white noise history in Y direction (N-S)



c. vertical white noise history



d. Fourier amplitude spectrum of horizontal and vertical white noise

Figure 3.3 White noise records and Fourier amplitude spectra

3.3.2.3 Ground Motion Generation

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3.3.2.4 Ground Motion Scaling and Filtering

The records obtained using the IRSP were then scaled to match the amplitude requirements of the scaled required (or target) response spectra (RRS). Analysis of the resultant velocity and displacements associated with the acceleration records at each scale factor revealed that the motions scaled to 1.25 times the original RRS would exceed the table limits of +/- 6.0 in (+/- 150 mm) for longitudinal and lateral shaking and +/- 3.0 in. (+/-75 mm) for vertical shaking, at frequencies below 1.0 Hz. Therefore, a high-pass filter with a cutoff value of 1.0 Hz was applied to each motion for all RRS levels scaled to 1.25 times the original RRS and higher. For ground motions scaled to 100% of the original RRS and lower, a high pass filter with a cutoff value of 0.5 Hz was utilized. This high-pass cutoff frequency is also the default high pass frequency used by the MTS earthquake simulator controllers in acceleration control mode.

3.3.2.5 Earthquake Simulator Motion Verification and Analysis

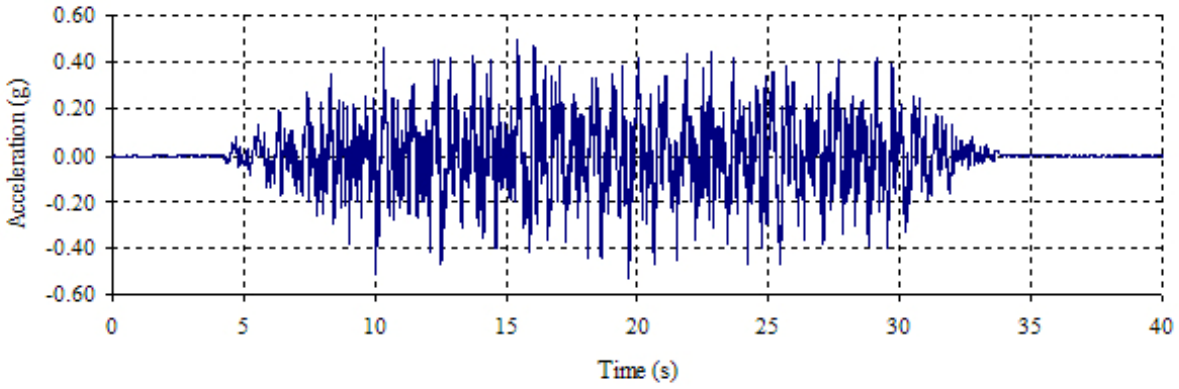
The earthquake simulator with only the test frame installed was excited along each degree of freedom using a low amplitude random motion with frequency content from 0.5 Hz. to 40 Hz. A performance model was determined by generating a system transfer function. Subsequently, the generated ground motions were applied to the earthquake simulator at 75% of the target amplitude for each RRS level. The RMS error between the desired and achieved ground motions was determined by STEX. Using an iterative procedure provided by STEX, the system performance model was used to apply a correction to the earthquake simulator drive signals based on amplitude fidelity over the target frequency span. The procedure was repeated to provide a convergence between the desired and achieved ground motions until the RMS error reported by STEX was less than 2 percent in each degree of freedom. This procedure was

repeated for each scale factor and the corrected motions were used as the baseline motions for the testing of all ceiling systems.

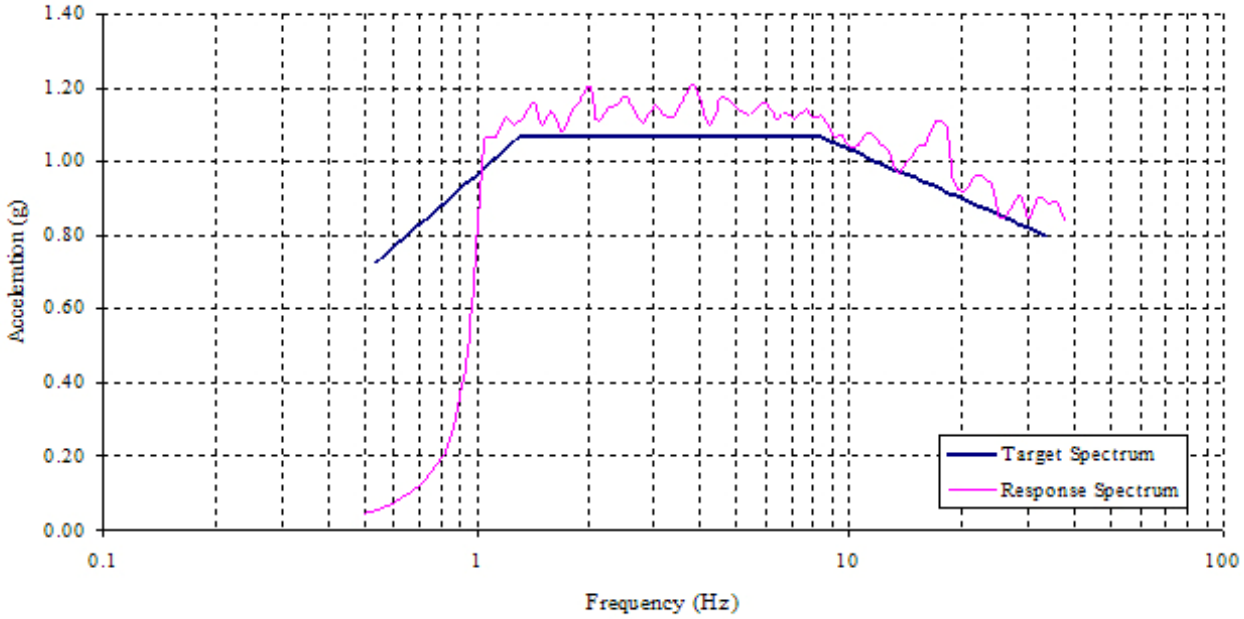
For each installed ceiling and sprinkler system, the table was excited at each scale factor (using the previously determined motions) and the test response spectrum (TRS) was calculated for each degree of freedom. For most systems, the excitation levels used were 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, 2.00, 2.25 and 2.50 times the original RRS. When the TRS deviated from the RRS by more than 10% during the course of testing and analysis, the ground motions were corrected using additional STEX iterations as described earlier. Each system imposed slightly different dynamic characteristics on the earthquake simulator, requiring minor adjustments to the motions in most cases.

ICC (2004) requires the test response spectrum (TRS) associated with the earthquake histories used for qualification must envelope the required (or target) response spectrum (RRS) using a maximum-one-third-octave bandwidth resolution over the frequency range from 1 to 33 Hz, or up to the limits of the simulator. A damping ratio of 5% and a resolution of 12 lines per octave (4 times greater than that required by AC156) were used to generate TRS from the achieved earthquake histories.

Figure 3.4 shows the earthquake history created after performing the spectrum-matching procedure and the response spectrum of this record for a target spectrum with $S_s = 1.0\ g$.



a. scaled record



b. response spectrum for the scaled record and the target spectrum for $S_s = 1.0\ g$

Figure 3.4 Scaled earthquake history for $S_s = 1.0\ g$

4. SUMMARY RESULTS

Two FlexHead sprinkler systems were subjected to the various levels of combined horizontal and vertical earthquake shaking for the purpose of seismic qualification. The sprinkler systems were tests as part of an integrated ceiling-sprinkler system. The experimental studies were performed using the earthquake simulator of the Structural Engineering and Earthquake Simulation Laboratory (SEESL) of the University at Buffalo (State University of New York). The results of the testing program of Table 3.2 are summarized in Table 4.1 below, using the target short period spectral acceleration S_s as the seismic demand parameter. Three performance limit states were defined, namely, 1) water leakage from any part of the sprinkler system, 2) movement of a sprinkler head from its intended location, and 3) damage to the suspension grid of the ceiling system. No leakage of water was observed, all sprinkler heads remained in their installed locations, and the suspension grids of the ceiling systems suffered no damage for all tests described in this report.

Table 4.1 Performance of FlexHead sprinkler systems

Testing Series	FlexHead system ID	System description	Qualification level (g)
I10	1	Standard schedule 40 piping system with seismic bracing, FlexHead bracket MP24BKT, two FlexHead Model #2036 units on the east side and two Model #2048 units on the west side of the test frame, with Armstrong Standard Seismic Design Category D, E and F ceiling system	2.50
J10	2	Standard schedule 40 piping system with one horizontal sway brace, FlexHead bracket MP24BKT, two FlexHead Model #2036 units on the east side and two Model #2048 units on the west side of the test frame, with an Armstrong Standard Seismic Design Category C ceiling system	1.75

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