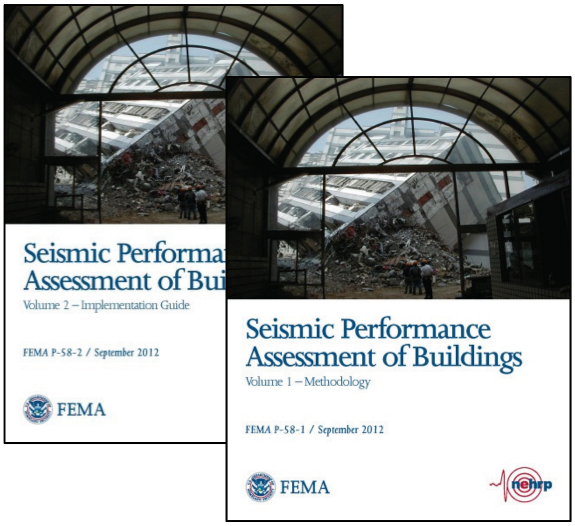

Background Document

FEMA P-58/BD-3.9.11

Development of Seismic Fragilities for MEP Distribution Systems for the ATC-58 Project

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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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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.

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 MEP Distribution Systems for the ATC-58 Project

Robert Bachman
ATC-58 Team Leader, Nonstructural Performance Products
(08/30/2012)

Introduction

This document provides the basis for establishing the seismic fragility values for mechanical, electrical and plumbing (MEP) distribution system components provided in the fragility spreadsheets for the ATC-58 project. MEP distribution system components include: hot and cold water service piping; chilled and steam water piping; sanitary plumbing piping; sprinkler piping; electrical wiring and conduits; and. HVAC ducting including inline coils, fans, drops and diffusers. Included in the scope of distribution systems are their anchorage, lateral bracing and support system.

There has been very limited laboratory research on the seismic performance of distribution systems. This is primarily because the seismic capacity of such systems is very layout-dependent and unique for most buildings. Also, with the exception of sprinkler systems, neither building codes nor standard industry practice specify standard or prescriptive details for installation of these systems. Therefore, anchorage and bracing of these systems and system performance tends to be unique for each building installation. Precise evaluation would require structural analysis of each distributed system considering the unique configuration, support locations, support boundary conditions and input motions. This is an extremely difficult analytical problem. Alternatively, one could perform numerous shake table tests with numerous configurations, an equally impractical task. Research therefore on these systems is lacking. At this point, building codes focus on the anchorage and bracing of these systems prescribing deign forces based on tributary mass since that problem is tractable.

MEP distribution systems have been damaged in past earthquakes and some of this damage has been life threatening while others (particularly pipe breakage or leakage) has resulted in considerable consequential damage and building downtime. Therefore, it was determined important to include seismic fragilities as part of the ATC-58 fragility database. With limited available test data, fragilities were developed by expert opinion.

Expert Opinion Panel

To determine the seismic fragility values for distribution systems, an expert panel was convened to establish values based on observation of damage in past earthquakes and judgment. This panel met on July 24, 2009 in San Francisco, California where it developed the criteria and the judgmental values that serve as the basis for the seismic fragilities in the ATC-58 fragility spreadsheets. The panel included industry experts, members of the ATC-58 project team and representatives of the Applied Technology Council. Table 1 indicates the names and affiliations of participants.

Table 1 – Expert Panel

Panelist	Affiliation	Category
Robert P. Kennedy	RPK Structural Mechanics Consultants	Industry expert
Greg S. Hardy	Simpson Gumpertz & Heger Inc.	Industry expert
Gayle S. Johnson	Halcrow	Industry expert
David L. McCormick	Simpson Gumpertz & Heger Inc.	Industry expert
Ronald O. Hamburger	Simpson Gumpertz & Heger Inc.	ATC-58 Team Member
William T. Holmes	Rutherford & Chekene	ATC-58 Team Member
John Gillengerten	State of California OSHPD	ATC-58 Team Member
Maryann Phipps	Estructure	ATC-58 Team Member
Robert E. Bachman	R. E. Bachman & Associates	ATC-58 Team Member
Keith Porter	University of Colorado	ATC-58 Team Member
Phillip Caldwell	Square D	ATC-58 Team Member
Jon Heintz	Applied Technology Council	ATC-58 Team Member
Ayse Hortacsu	Applied Technology Council	ATC-58 Team Member
Robert Hanson	Univ. of Michigan Emeritus	ATC-58 Team Member

Attachment A provides background information on qualifications of industry experts who served on the panel. All of the panelists, including those from the ATC-58 project team, have substantial experience in investigating earthquake damage to structures and nonstructural components (including MEP systems). Therefore, panelists could provide opinions based on their personal investigations and observations (as well as other knowledge) of actual earthquake-induced failures of MEP systems (or lack thereof) that had occurred in the past 30 years or so.

Many of the panelists were (and some still are) also involved in the development and maintenance of the Electric Power Research Institute's (EPRI) Seismic Qualification Utility Group (SQUG) database. This nuclear industry-funded database was specifically developed to provide a verifiable and documented source of mechanical and electrical system experiential performance data in actual earthquakes. With knowledge of actual installations in both industrial and commercial facilities along with nearby ground motion measurements, the seismic fragilities of many types of equipment and systems were estimated. Seismic fragilities developed based on this database have been reviewed and accepted by the U.S. Department of Energy and the Nuclear Regulatory Commission as a valid basis for characterizing the performance of MEP systems. Many of the participants also therefore relied upon their knowledge of this proprietary database to guide their expert opinion.

Horizontal Distribution Systems

Panelists agreed that the fragilities they were determining would be for horizontally oriented systems. Their collective experience suggested that vertical distribution system components, that is, risers between floors were typically less vulnerable seismically and their seismic capacity was likely associated with different demand parameters than horizontal systems. Therefore, the seismic fragilities for distribution systems provided in the ATC-58 fragility spreadsheets are applicable only to horizontally oriented distribution systems. The fragilities determined are for assumed generic distribution systems layouts and do not represent any specific layout.

Fragility Demand Parameters

The panel agreed that horizontal distribution systems in buildings are most sensitive to the accelerations of the floor to which the distributed systems are attached. While it is likely that there is a narrow range of frequencies of floor motion where individual distribution systems ceilings are most sensitive, rather than attempting to use floor acceleration spectra, the panel selected peak horizontal floor acceleration of the floor supporting the distribution system as the predictive demand parameter.

Distribution System Types

The panel developed seismic fragility values for the following distribution system types:

- Fire Sprinkler Piping Systems including Sprinkler Drops
- Domestic Cold and Hot Water Piping Systems
- Steam and Chilled Water Piping Systems
- Sanitary Waste Piping Systems
- HVAC Ducting Systems
- HVAC Drops and Diffusers
- HVAC In-line Fans and Coils

For piping systems, separate fragilities were developed for different types of piping materials and piping connectors. Materials and connectors considered included:

- Welded steel
- Threaded steel
- Steel with victaulic type groove couplings
- Cast Iron
- Cooper

Separate fragilities were developed for damage to the piping and/or their connectors, which is not associated with bracing or anchorage failure; and, damage associated with bracing or anchorage failure. Separate fragilities were also established for sprinkler drops that protrude through different types of suspended ceilings.

In addition, separate fragility values were developed considering the degree of seismic design and construction quality assurance associated with the installation. Four seismic installation conditions were assumed based on the treatment of seismic protection of these systems contained in the present edition of the International Building Code. These are:

- Seismic Design Category A & B   (no requirements for seismic design)
- Seismic Design Category C (minimal seismic design)
- Seismic Design Category D, E and F (design of seismic anchorage and bracing)
- Seismic Design Category F with special regulation (anchorage and bracing designed to a higher standard and installation carefully inspected)

Damage States and Consequences

The panel established damages states and consequences for each of the distribution types described above.

For piping systems, the damage states ranged from minor leaks where repair consists of retightening joints to major breaks resulting large scale release of contents and replacement of damaged piping. For pipe system bracing and anchorage, the damage states ranged from isolated brace failure where repair consists of repair of the damaged brace to to multiple support failures causing the pipe to fall resulting in major pipe breakage and replacement of large sections of piping and its bracing and anchorage. Separate fragility damage states were determined for sprinkler drops and heads as minor leaks and major breaks.

For HVAC ducting, the damage states ranged from individual support failure where individual supports needed to be replaced to several support failures where large sections of ducting and their supports require replacement. In addition separate fragilities were provided for in-line fans depending on whether their support conditions could result in their becoming dislodged and falling and for drops and diffusers depending on whether they had independent safety wires connected to them. The in-line coil damage state was based on the failure of plumbing coil connections resulting in significant leakage.

Floor Flooding

Floor flooding was established as a separate fragility with consequences associated with individual occupancy types. Because the consequences associated with floor flooding can be significant in some occupancies, and to prevent double counting, fragility parameters associated with floor flooding are taken the same as those for the most vulnerable piping system present in an individual building. Because the damage caused by floor flooding is primarily associated with the floor covering which are highly dependent on building occupancy type, floor flooding fragilities are assigned NSITR identification numbers associated with floor coverings.

Fragility Normative Quantities (Units of Measure) and Repair Quantities

For horizontal piping systems, the leakage fragility damage state established was associated with one leak per 1000 linear feet of piping. This measure was selected by the panel based on their experience that when leaks occur, they are limited in quantity and also to reduce PACT run times. For small leaks, the number of leaks requiring repair is used to establish the consequence. For major leaks and breaks, a 20 foot section of pipe per major leak was selected as the repair action since pipes typically come in 20 foot lengths. For individual bracing failures, the failure was taken as one per 100 supports based on the panel's experience. For multiple support failures, the fragility quantity was associated with 1000 feet of piping with the repair action being 60 feet of pipe and supports and bracing. For sprinkler drops, the quantity was taken as sprinkler drop damaged per 100 drops.

For HVAC ducting, the quantities were similarly and based on 1000 feet lengths of ducting for anchorage and support damage. Damage to drops, diffusers, fans and coils were based on number of drops and diffusers per floor.

Fragility Parameter Determination Procedure

The panel used the following procedure to establish median values and dispersions:

1. Based on consensus judgment a High Confidence Low Probability of failure (HCLPF) values of peak ground acceleration (PGA) was established for each installation type and damage state. HCLPF values are associated with a 1% conditional probability that a given damage state will occur, given the occurrence of the HCLPF value of acceleration. Median PGA values were taken as 2.5 times the HCLP value when a low value of dispersion (0.4) was assigned or 3.2 times the HCLPF value if the assigned dispersion is 0.5.

2. A dispersion value of 0.4 was assigned if the group felt confident in their selection of the HCLPF value, and also believed that the particular damage state had low correlation with the individual details of construction. A dispersion value of 0.5 was assigned when the panel had less confidence in the HCLPF value or felt that the occurrence of damage was highly correlated with the individual, building-specific details of installation. Note that these dispersions are not intended to include uncertainty associated with ground motion intensity.

3. The fragilities were grouped by system type (i.e. welded steel, threaded connections, etc.) The attached excel spreadsheet provides the raw data agreed to at the meeting.

4. Attendees agreed to convert the median values of peak ground acceleration to peak floor acceleration demand, using a factor of 1.5 to account for in-structure amplification effects. Accordingly a HCLPF PGA value is factored by 2.5 x 1.5 = 3.75 for a dispersion of 0.4 and 3.2 x 1.5 = 4.8 for a dispersion of 0.5 to obtain median values of floor acceleration capacity.

5. For situations where damage states for the same fragility have different dispersions (some 0.4 and others 0.5), it was subsequently agreed to use a dispersion value of 0.45 resulting in a HCLPF adjustment factor of 2.85 and an overall adjustment factor of 2.85 x 1.5 = 4.275. In all cases, rounding to the nearest 0.05g was conducted.

6. It was agreed that piping support failure and pipe leakage damage states should be treated as independent events.

Table 2 summarizes the HCLPF pga values and floor acceleration values provided. The full spreadsheet presenting the values for all of the distributed system components is presented as Attachment B.

Table 2 Conversion Between HCLPF Peak Ground Acceleration and Median Floor Acceleration Values

HCLPF Peak Ground Acceleration - g	Dispersion	Median Peak Floor Acceleration - g
0.15	0.40	0.55
0.20		0.75
0.25		0.95
0.30		1.15
0.35		1.30
0.40		1.35
0.45		1.50
0.50		1.70
0.55		1.90
0.60		2.05
0.70		2.25
0.80		2.65
0.90		3.00
1.10		3.40
1.20		4.15
0.30	0.45	1.30
0.50		2.15
0.25	0.50	1.20
0.50		2.40

ATTACHMENT A

Invited Expert Opinion Panelists

Robert Kennedy

Bob is a structural engineer who has been involved in the development and review of probabilistic seismic fragilities for MEP equipment and systems for over 30 years with an emphasis on MEP equipment associated with nuclear facilities. He co-authored landmark papers on probabilistic seismic hazard evaluations with Allen Cornell and others. He was heavily involved in the review of fragilities developed from the SQUG database and currently serves as a senior seismic reviewer for both NRC and DOE. He has participated in many earthquake damage investigations. He has been a contributing member of the ATC-58 Nonstructural Performance Products Team since its inception in 2002.

Greg Hardy

Greg is a mechanical engineer who has been heavily involved in the development and review of probabilistic seismic fragilities for the MEP equipment and systems for 25 years with an emphasis on MEP equipment associated with nuclear facilities. He has been heavily involved in the development of the SQUG database including the development of MEP equipment fragilities derived from them. He has participated in many earthquake damage investigations.

Gayle Johnson

Gayle is a structural engineer who has been heavily involved in the development of the SQUG database including the development of MEP equipment fragilities derived from them. He has participated in many earthquake damage investigations. He was the primary author of a document prepared for MCEER in Buffalo that applied to the SQUG database to the probabilistic evaluation of critical non-nuclear facilities such as hospitals.

Dave McCormick

Dave is a structural engineer who has been heavily involved in the development of the SQUG database including the development of MEP equipment fragilities derived from them. He has participated in many earthquake damage investigations.

Pipe Class

- Threaded steel
- Welded steel
- Victaulic
- Plastic
- Cast Iron
- Ductile Iron
- Copper
- PEX

	note use 1.5 factor to get to ZPA	pga (1%)							
Systems	**Description**	**SDC A, B**		**SDC C**		**SDC D,E,F**		**Special Regulati**	
Fire Sprinkler	thin wall, old style victaulic large diameter pipe - spraying during earthquake & dripping after	.3g	0.4	.3g	0.4	.4g	0.4	.5g	0.4
	poorly designed braced old style victaulic pipe - spraying during earthquake & dripping after	n/a		n/a		.4g	0.4	n/a	
	thin wall, old sytle victaulic large diameter pipe - 1 break per 1,000 ft	.5g	0.5	.5g	0.5	.7g	0.4	.9g	0.4
	threaded fire sprinkler drop lines - per 100 heads								
	unbraced laid-in tiles standard drop (up to 6') - leak	.2g	0.4			.25g	0.4	.35g	0.4
	hard ceiling standard drop (up to 6') - - leak	.15g	0.4			.15g	0.4	..3g	0.4
	braced laid in ceilng standard drop (up to 6') - - leak	n/a				.4g	0.4	.5g	0.4
	no ceiling - - leak	.4g	0.4			.7g	0.4	1g	0.4
	unbraced laid-in tiles standard drop (up to 6') - break	.25g	0.4			n/a			
	braced laid in ceilng standard drop (up to 6') - -break	n/a				.6g	0.4	.8g	0.4
	hard ceiling standard drop (up to 6') - - break	.25g	0.4			.35g	0.4	.6g	0.4
	no ceiling - -break	.6g	0.4			.8g	0.4	1.2g	0.4
Fire sprinkler	plastic horizontal distribution								
Domestic Water	**welded large diameter + threaded small diameter (one per thousand feet)**								
Steam & Chilled Water	Threaded small diameter (2-1/2" & smaller)								
	samll leak w/ retighten joint - 1/per thousand ft	.15g	0.4	.15g	0.4	.15g	0.4	.15g	0.4
	large leak w/ retighten joint								
	large leak w/ major repair - replace section of pipe (1 per 1,000)	.3g	0.4	.3g	0.4	.3g	0.4	.3g	0.4
	isolated support failure w/o pipe damage (1/100 supports)	.25g	0.5	.25g	0.5	0.6	0.4	.8g	0.4
	multiple support failure and pipe system falls (60 feet per 1,000 ft)	.5g	0.5	.5g	0.5	rugged		rugged	
	Welded Large diameter - 1 break per 1,000 ft	.7g	0.4	.7g	0.4	1.1g	0.4	1.1g	0.4
	Minor leak in large diameter flange connection (per 1,000 ft)	.4g	0.4	.4g	0.4	.6g	0.4	.6g	0.4
	lateral braces	n/a				.4g	0.4	.6g	0.4
	vertical braces	.6g	0.4			.6g	0.4	.8g	0.4
Domestic Water	plastic	Buffalo							
Gas	Plastic	Buffalo							
Santiray Waste	Cast iron w/ flexible coupling sleeves								
	support failure same as steel								
	breaks	rugged		rugged		rugged			
Sanitary Waste	Cast Iron w/ bell & spigot								
	support failure same as steel								
	breaks	.6g	0.4			.8g	0.4		
Sanitary Waste	Plastic (ABS)	Buffalo							
Roof Drain	Plastic	Buffalo							
Roof Drain	Cast Iron w/flexible coupling sleeves								
Steam and/or chilled water	Welded steel + bolted flanged fittings at equipment								
HVAC Ducts									
	6sq ft or larger								
	Support failure (sagging duct)	.5g	0.4	.5g	0.4	1g	0.4	1.1g	0.4
	Falling	.6g	0.4	.6g	0.4	1.2g	0.4	1.3g	0.4
	smaller than 6 sq ft								
	Support failure (sagging duct)	.4g	0.4	.4g	0.4	.4g	0.4	.45g	0.4
	Falling (60 feet of duct down)	.5g	0.4	.5g	0.4	.5g	0.4	.55g	0.4
HVAC Drops & Diffusers									
	with safety wires or rivets - drops	rugged		rugged		rugged		rugged	
	without safety wires or rivets- drops	.35g	0.4	.35g	0.4	n/a		n/a	
	without ceilings - drops	.4g	0.4	.4g	0.4	.4g	0.4	.4g	0.4
HVAC in-line Fans									
independently supported	on isolators - flying and dropping	.5g	0.5			.7g	0.4		
	isolated - bellows fails	.4g	0.5			.6g	0.4		
	not isolated - dropping	rugged		rugged		rugged			
	not isolated - bellows fails	.5g	0.4			.6g	0.4		
HVAC In-line Coils	busted loose of plumbing	.5g	0.4			rugged		rugged	

Note this is based On 1994 Olive View Experience