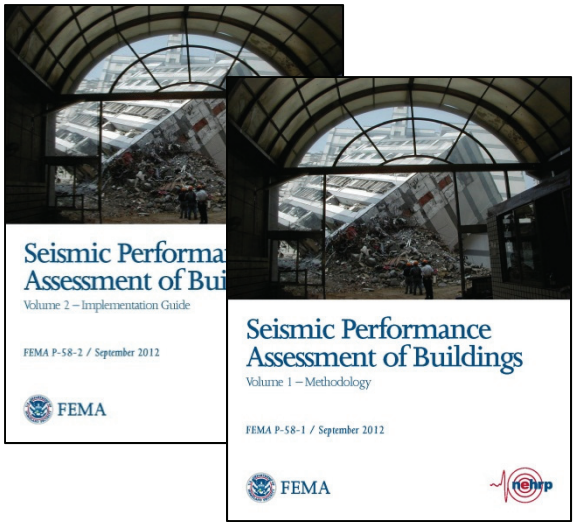

Background Document

FEMA P-58/BD-3.9.15

Fragility of Chillers

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FEMA

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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

Fragility of chillers

Keith Porter (10/04/2009)

Table 1. Summary results

Fragility, damage measures, and consequences for		
Component category:	D3031.011, chiller, well installed: strong anchorage, tight mounting bolts; snubbers on vibration isolators, attached piping is well supported, no large items that could fall on chiller D3031.012, chiller with deficient installation (typ. no snubbers)	
Basic composition:	Chiller. See Figure 1.	
Units:	ea	
Number of damage states:	1	
If multiple damage states:	□ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Keith Porter 19 Oct 2009	
Damage states, fragilities, and consequences for		
	D3031.011, chiller, well installed	**D3031.012, chiller, deficient installation**
Description:	Damaged, inoperative	Damaged, inoperative
Illustration:	Figure 2	
Demand parameter	Peak floor acceleration (geometric mean, g)	Peak floor acceleration (geometric mean, g)
Median demand (θ):	6.1	0.64
Data dispersion (β_d):		
Uncertainty (β_u):		
Total dispersion (β):	0.4	0.6
Probability:		
Correlation:		
Repairs required:	Repair attached piping	Remount chiller & repair attached piping
Possible consequences:		
Repair cost (Y/N/?):	Y	Y
Death or injury (Y/N/?):	N	N
Inoperative facility (Y/N/?):	Y	Y
Red tagging (Y/N/?)	N	N
Comments:		

Table 2. Summary supporting information template

<table>
<tr><td colspan="2">Literature summary
EPRI's eSQUG database (EPRI 2007) offers 43 post-earthquake observations of chiller performance at a number of industrial facilities. See Porter et al. (ND) for detail. In EPRI (1991), Merz of ANCO Engineers offers a single data point from a sequence of tests of a standard commercial 85-ton centrifugal liquid chiller, mounted on neoprene rubber isolators, which were in turn bolted to a retaining plate anchored to the shake table. The chiller was operating during the tests. Since only a single specimen was tested, EPRI (1991) does not offer a generic equipment response spectrum. The specimen survived ZPA = 2.4g. The author felt the test was applicable to chillers meeting the following criteria. These criteria agree with the requirements for the general class of well-installed chillers, so the test is included here.
• The chiller unit must be anchored and the installed anchorage must be evaluated.
• Any vibration isolation incorporated in the chiller or appendage mountings must be evaluated for restraint of lateral (horizontal) seismic loads
• All mounting bolts including appendages and bolts associated with vibration isolation mounts must be checked for tightness.</td></tr>
<tr><td>Number of specimens tested:</td><td>43 from EPRI (2007)
1 from EPRI (1991)</td></tr>
<tr><td>Construction quality:</td><td>□ exceeds □ meets □ does not meet requirements of:
varies</td></tr>
<tr><td>Seismic installation conditions:</td><td>varies</td></tr>
<tr><td>Loading protocols applied:</td><td>eSQUG specimens (EPRI 2007) experienced 6 earthquakes
Tested specimen (EPRI 1991) subjected to triaxial test with peak S_a ≈ 4.7g, ZPA = 2.4g</td></tr>
<tr><td>Method for observing demand:</td><td>Nearby strong-motion instruments (EPRI 2007) or lab instruments (EPRI 1991)</td></tr>
<tr><td>Method for observing damage:</td><td>Data from eSQUG (EPRI 2007) are from first-hand observations by EQE International (e.g., DL McCormick, Nancy Horstman, Sam Swan, Peter Yanev, etc.) and by the Electric Power Research Institute (EPRI), e.g., Bob Kassawara. The investigators also examined facility engineers' records or interviewed them. Observations made during post-earthquake facility surveys on behalf of EPRI, with the intention of documenting failures and non-failures, with installation conditions, etc.</td></tr>
</table>

Table 3. Failure data for chiller 0 installation deficiencies (EPRI data)

r, g	Units, M	Failed, m	Comment
0.2	4	0	EPRI (2007) UNO
0.35	1	0	
0.35	4	0	
0.37	4	0	
0.4	3	0	
0.4	2	0	
0.42	4	0	
0.5	2	0	
0.6	2	0	
0.8	2	0	"The [failed] chiller is supported on four spring mounts encased in steel brackets. Campus engineers indicated that the roof-mounted chiller dismounted from its springs, but was otherwise undamaged and operable once it was re-mounted." Because the failure was damage to a snubbed isolator, it is ignored for present purposes.
2.4	1	0	EPRI (1991) pg. D-10
Sum	29	0	

Table 4. Failure data for specimens with deficient installation (typ. isolators w/o snubbers or rigid attachments)

r, g	Units, M	Failed, m	Comment
0.3	3	0	
0.50	9	8	"According to the facility engineers, all pad-mounted refrigerant compressors of this type located on the site rolled off their isolation mounts. The compressor units were undamaged and operational once they were remounted. Attached piping appears to have sufficient flexibility to have accommodated the displacement; there were no reports of water or refrigerant leaks. The site did not loose power, so some of the compressors were probably in operation at the time of the earthquake and subsequent dismount."
0.8	1	1	Chiller experienced substantial rocking on its rubber pads during the earthquake. The expansion bolts anchoring the seismic bumpers were partially pried out of the concrete floor. Displacement of the chiller fractured an attached 1/2-inch tube for makeup water. The tube was rigidly supported adjacent to the chiller and lacked adequate flexibility to accommodate the imposed chiller displacement. The four-inch chilled water lines attached to the chiller fractured the impeller casing of a horizontal pump on the opposite end of the piping. The anchor point displacement on the 4-inch lines imposed by the chiller may have aggravated this failure in the pump casing.
0.80	2	0	"Both units shifted off their spring mounts. One unit shifted as much as four inches, pulling the attached chilled water piping with it. Nearby chilled water pumps were offset on their spring mounts due to the imposed displacement of the piping tying the pumps to the chillers. In spite of the dismounts the chillers remained operational. The need for air conditioning required that the HVAC equipment be restarted prior to replacing it on its mounts." Failures of isolators are ignored for present purpose.
0.84	2	1	"Rocking of the [first] chiller on its spring mounts during the earthquake imposed sufficient anchor point displacements to fracture the attached PVC water lines. The chiller was operable once the piping damage was repaired following the earthquake. The photo shows the chiller following repair of the attached piping. The [second] chiller dismounted from its spring isolators and shifted several inches. The imposed displacement pulled the attached insulated chilled water lines from their ceiling spring hangers. The degree of displacement imposed on the water lines was illustrated by the cracked sheet rock where the lines penetrated the wall of the mechanical room. A soldered copper inlet water line also failed due to the imposed displacement of the chiller. The chiller was operable once it was replaced on new isolation mounts, and the damaged piping repaired. The photos show the chiller and attached piping following repair." Failure of the 2nd chiller is ignored for present purposes
Sum	15	9	

Table 5. Quality tests

Quality test	D3031.011, chiller, well installed	D3031.012, chiller, deficient installation
Passes Lilliefors goodness of fit test? (Type A only)	NA	NA
Are θ and β within 20% of past results? If not discuss.	NA	θ: Y, β: Y
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y	Y
Do you believe the demand with 10% failure probability?	Y	Y
Discussion. Prior vulnerability functions are from Johnson et al. (1999), whose θs for deficient installation vary between 0.8 to 2.1; compare with 0.64 to 1.4 here.		

Figure 1. Chiller

Figure 2. Chiller shifted from rubber pad isolation mount (EPRI)

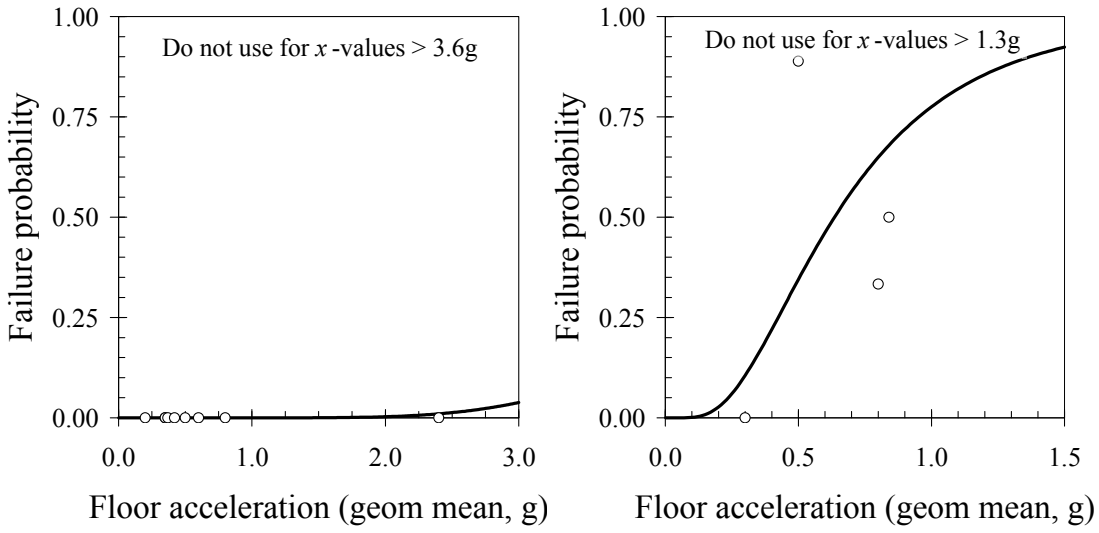

Figure 3. Chiller fragility (a) strong anchorage, snubbers on vibration isolators, attached piping is well supported, (b) deficient installation, typically isolators without seismic restraint

REFERENCES CITED

(EPRI) Electric Power Research Institute, 1991. *Generic Seismic Ruggedness of Power Plant Equipment. EPRI NP-5223-SL Revision 1*. Oakland, CA, 248 pp.

(EPRI) Electric Power Research Institute, 2007. *Seismic Experience Database WWW Version 2.3*.

Johnson, G.S., R.E. Sheppard, M.D. Quilici, S.J. Eder, and C.R. Scawthorn, 1999. *Seismic Reliability Assessment of Critical Facilities: A Handbook, Supporting Documentation, and Model Code Provisions, MCEER-99-0008*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY, 384 pp.

Porter, K.A., G. Johnson, R. Sheppard, and R.E. Bachman, ND. Fragility of mechanical, electrical, and plumbing equipment. Approved Aug 2009 for publication to *Earthquake Spectra*.