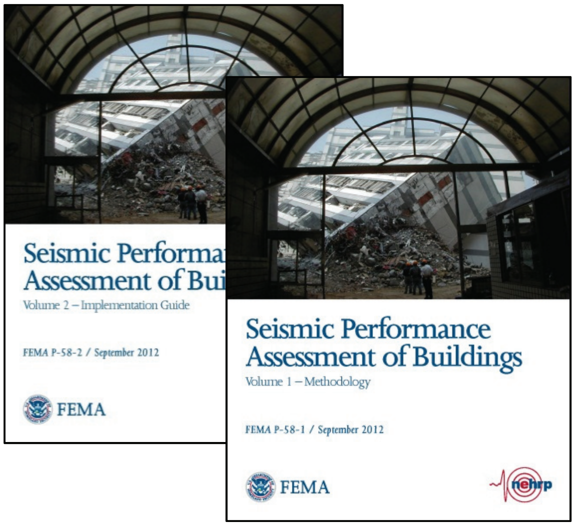

Background Document

FEMA P-58/BD-3.9.27

Fragility of Control Panels

Prepared by

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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

Keith Porter (10/20/2009)

Table 1. Summary results

Fragility, damage measures, and consequences for		
Component category:	D3067.011, Control panel, well installed: well anchored, strong load path to floor, adjacent cabinets within ½ inch are bolted together, no large nearby items that could fall on the control panel D3067.012, Control panel, deficient installation (typ unanchored or poorly anchored)	
Basic composition:	Metal cabinet; see Figure 1	
Units:	**ea**	
Number of damage states:	**1**	
If multiple damage states:	□ ordered; □ mutually exclusive; □ simultaneous	
Author and date:	Keith Porter 20 Oct 2009	
Damage states, fragilities, and consequences for		
	D3067.011, Control panel, well installed	D3067.012, Control panel, deficient installation
Description:	Damaged, inoperative	Damaged, inoperative
Illustration:	NA	NA
Demand parameter	Peak floor acceleration (geometric mean, g)	Peak floor acceleration (geometric mean, g)
Median demand (θ):		
Data dispersion (β_d):	0.6	
Uncertainty (β_u):		
Total dispersion (β):	0.6	
Probability:		
Correlation:		
Repairs required:	Replace components (relays, circuit boards)	
Possible consequences:		
Repair cost (Y/N/?):	Y	Y
Death or injury (Y/N/?):	Y	Y
Inoperative facility (Y/N/?):	Y	Y
Red tagging (Y/N/?)	N	N
Comments:	Re death or injury, one case was noted of a technician being injured by a burned breaker, but probably too rare to be worth addressing here; it is noted for completeness only.	Ditto

Table 2. Summary supporting information template

Literature summary Johnson et al. (1999) present fragility functions for battery chargers under various conditions, based in large part the post-earthquake observations of the seismic performance of MEP equipment in commercial and industrial facilities during 1971-1991. Much of the data is shown in tables in Porter et al. (1993), and also appears in EPRI's eSQUG database (EPRI 2007). See Porter et al. (ND) for discussion of the Johnson et al. (1999) fragility functions. EPRI's eSQUG database (EPRI 2007) includes detail about individual specimens that does not appear in Porter et al. (1993) or Porter et al. (ND), particularly details about installation conditions, component elevation, manufacturer, model number, weight, photographs, etc. EPRI (2007) does not offer fragility functions. ANCO Engineers (EPRI 1991) offers generic equipment ruggedness spectra (GERS) for a number of equipment classes, based on shake-table tests of small numbers of specimens. The purpose of the report is to propose simplified response spectra that a generic piece of equipment can be assumed to survive, if it meets a set of constraints proposed by the author, even if that particular model has not been tested. The GERS generally includes a zero-period acceleration associated with the response spectrum, although there is some concern about using the ZPA. Reason is that the tests were performed using older equipment that might have somewhat higher ratios of ZPA to spectral response at the equipment's natural periods of vibration. The implication is that under real earthquake excitation, the equipment would experience spectral acceleration response that is higher for a given ZPA than that of the tests, and might therefore fail at lower ZPAs than would be predicted based on the tests. In an October 2009 ATC-58 FRP meeting, Bob Kennedy recommended that the GERS data be used only to check that the medians using the EPRI data are not too high, unless the GERS checklists correspond exactly with the "well installed" conditions to be used for ATC-58. This approach has produced some median capacities that look too low. In this and other fragility specifications, therefore, Kennedy's recommendation is followed with some flexibility, leaving open the possibility of including the GERS data, even if there are more constraints, based generally on 3 questions: a. How significant are the additional constraints in the GERS report, relative to the well-installed conditions? For example, what fraction of the failures in the eSQUG well-installed dataset occurred in specimens that seemed not to meet the GERS constraints? Do the additional constraints seem to be as important in preventing failures as the other conditions for well-installed equipment? b. If the GERS data are not used to create the fragility function, does the well-installed fragility function lie close to the deficient-installation function, and if so does the fragility function with the GERS data look more realistic? c. Do the eSQUG data seem consistent with the GERS tests, e.g., with few if any failures at low levels of excitation where the GERS data show success at much higher levels? In the present case, ANCO Engineers (EPRI 1991) attempted to create GERS, but found that the specimens were too diverse to offer a "generic" class, though the study offers data on 9 specimens. The relevance criteria are that a control panel is low voltage, with wall- or floor-mounted enclosure with average weight per vertical section ≤ 60 lb/in depth; control panel anchored and installed anchorage must be evaluated; all door latches secured with locking

devices; and	
Number of specimens tested:	Avg condition: 326 from data set 1 (broader EQE data set) Known deficiencies: 139 from data set 2 (EPRI database) GERS report: 9 specimens
Construction quality:	□ exceeds □ meets □ does not meet requirements of: varies
Seismic installation conditions:	varies
Loading protocols applied:	17 earthquakes
Method for observing demand:	Nearby strong-motion instruments
Method for observing damage:	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.

Table 3. Failure data of all specimens (data set 1: EQE + EPRI)

r, *g*	Units, *M*	Failed, *m*	*w* =*M*/Σ*M*	*y* = *m*/*M*	Φ
0.17	6	0	0.018	0.000	0.000
0.18	3	0	0.009	0.000	0.000
0.24	17	1	0.052	0.059	0.000
0.28	11	1	0.034	0.091	0.000
0.29	10	0	0.031	0.000	0.000
0.30	61	6	0.187	0.098	0.000
0.31	18	0	0.055	0.000	0.000
0.36	38	1	0.117	0.026	0.000
0.39	10	0	0.031	0.000	0.000
0.42	16	0	0.049	0.000	0.000
0.45	1	0	0.003	0.000	0.000
0.48	65	6	0.199	0.092	0.000
0.51	8	0	0.025	0.000	0.000
0.57	2	0	0.006	0.000	0.000
0.60	32	4	0.098	0.125	0.000
0.66	1	1	0.003	1.000	0.001
0.68	8	0	0.025	0.000	0.001
0.70	1	0	0.003	0.000	0.001
0.73	5	2	0.015	0.400	0.002
0.77	1	1	0.003	1.000	0.003
0.79	3	0	0.009	0.000	0.004
1.03	9	0	0.028	0.000	0.022
Sum	326	23			

Table 4. Failure data of specimens with no deficiencies (data set 2, EPRI)

r, g	Units	Failed	Comment
0.17	1	0	EPRI (2007) UNO
0.17	1	0	

0.17	1	0	
0.24	1	0	
0.24	1	0	
0.24	1	0	
0.24	1	0	
0.24	1	0	
0.24	2	0	
0.28	1	0	
0.28	5	1	Five of approximately 100 protective relays mounted on the panels were damaged. Three relays were burned by internal short circuits. A small torsional spring which also serves as a conductor detached and touched ground. Two directional impedance relays suffered internal damage when their armatures exceeded their rotational range of travel. Spilled ink found in an oscill-perturbograph strip chart recorder. Loosened or bent mounting screws were found on several components.
0.30	3	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	1	1	Rack has high COG; large rectifier near the top. Rack pulled its anchor bolts and overturned, damaging some components. The rack was rebuilt
0.30	1	1	Drawer-mounted circuit boards slid out of cabinets and hit the floor. Repairs were later required in circuit boards.
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.31	1	0	
0.31	1	0	
0.31	1	0	
0.31	1	0	
0.31	1	0	
0.31	1	0	
0.36	1	0	
0.36	2	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.36	1	0	
0.42	1	0	
0.42	1	0	
0.45	1	0	

0.48	1	0	
0.48	1	0	
0.48	1	0	
0.48	12	0	
0.48	2	0	
0.48	1	0	
0.48	1	0	
0.48	7	0	
0.48	4	1	Anchoring Unistrut bolts were not equipped with washers. During the earthquake, yielding and tearing of the light gauge angle framing surrounding the bolts at the base of the cabinet allowed the bolt heads to pull through the framing. The cabinet overturned, hitting the mimic panel in front and pushing it over. The glass cover shattered on a large relay
0.48	1	0	
0.51	1	0	
0.51	1	0	
0.51	1	0	
0.51	1	0	
0.61	17	0	
0.73	1	0	
1.03	1	0	
1.03	1	0	
1.03	1	0	
1.03	1	0	
1.03	1	0	
1.03	1	0	
1.2	2	0	EPRI (1991) GERS data
1.7	1	0	Ditto
1.9	1	0	Ditto
2.0	1	0	Ditto
3.9	1	0	Ditto
2.5	1	0	Ditto. Wire chafing & loose screws, ignored here
3.0	1	0	Ditto. Relay chatter ignored here
3.3	1	0	Ditto. Loose washer ignored here
Sum	125	4	

Table 5. Failure data of specimens with 1 deficiency, typ. unanchored or poorly anchored (data set 2, EPRI)

***r*, g**	**Units, *M***	**Failed, *m***	**Comment**
0.24	1	0	
0.24	1	0	
0.30	1	0	
0.30	1	1	Portions of the mimic board face came apart, with the color-coded plastic chips popping out of the supporting steel mesh. Unrestrained strip chart recorders mounted in drawers slid out the front of the board and hit the floor. Repaired circuit boards for components that hit the floor.
0.36	1	0	
0.36	1	0	
0.39	1	0	
0.42	1	0	
0.42	1	0	
0.48	1	0	
0.48	2	2	Mimic panels damaged by impact with adjacent relay cabinet. The relay cabinet, located behind the mimic panels, was anchored with Unistrut. Bolts had no washers. Yielding and tearing of the light gauge angle framing surrounding the bolts at the

			base of the relay cabinet allowed the bolt heads to pull through the framing. The cabinet overturned, hitting the mimic panels and pushing them over.
0.48	1	1	Anchoring Unistrut bolts were not equipped with washers. Yielding and tearing of the light gauge angle framing surrounding the bolts at the base of the cabinet allowed the bolt heads to pull through the framing. The cabinet overturned, hitting the mimic panel in front and pushing it over. The glass cover shattered on a large relay, but operators reported that the internals were not damaged.
0.48	1	0	
0.57	1	0	
0.61	2	0	
0.61	1	0	
0.67	1	1	The section of the ground floor slab that supports the control panel settled up to 8 inches with respect to the end sections of the floor. Because the panel is rigidly tied to the building columns it was forced to flex with the building. The porcelain base of one of the circuit breakers shattered. When the plant was restarted and the circuit breaker closed, it grounded out due to loss of insulating capability in the broken porcelain. The breaker burned and apparently injured the operating technician.
0.68	1	0	
0.73	1	0	
1.03	1	0	
1.03	1	0	
Sum	23	5	

Table 6. Quality tests

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	NA		
Are θ and β within 20% of past results? If not discuss.	θ: N, β: ~Y		
Are $0.2 \leq \beta \leq 0.6$? If not discuss.	Y		
Do you believe demand with 10% failure probability?	Y		
Discussion. Prior functions: Johnson et al. (1999) basic conditions, whose θ ≈ 0.8 - 2.3. Compare with θ = 1.1 - 3.9. Re believing 10% failure probability, yes. Take the weighted average of all data and run a curve through it: r = 0.47g, P_f = 0.08, fairly close to 10th percentile from a curve through all the data as separate data points (r = 0.6g, P_f = 0.08). Re β within 20% of past results, compare w/J99: β = 0.4 for all data, 0.5 for 1+ deficiency			

Table 7. Extrapolation to other detailed conditions and to average conditions

Condition (describe)	From tests?	DS1		J99	
		θ	***β***	**θ**	***β***
Best: well anchored, no concerns re pounding or impact, interaction, or inflexible attachments. After adding GERS data, method B3 produced very high θ (θ = 10g), so used Method C instead. (Without GERS, θ = 3.9, β = 0.6)	Y	5.3	0.40	NA	
Moderate: 1 deficiency, typ unanchored or poorly anchored	Y	1.1	0.60	0.9	0.5
Worst: two or more deficiencies	N	0.7	0.60		
Average or unknown	Y	1.4	0.60	2.3	0.4
Do not use fragility functions for PFA > 1.5 times maximum value in the observations. Basis for extrapolation. For moderate, average, and best conditions, from data shown above. For worst conditions, 2/3rd x moderate. What factors affect θ and β? See "best" conditions.					

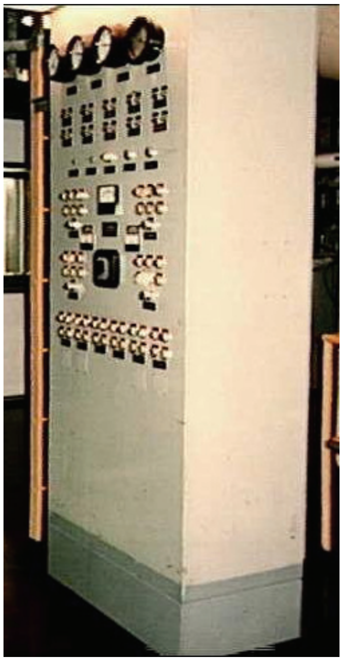

Figure 1. Control panel (EPRI)

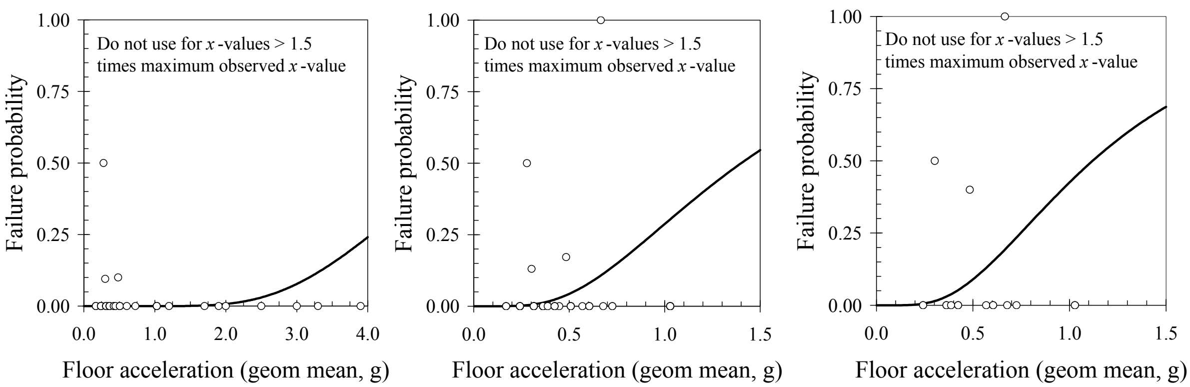

Figure 2. Control panel seismic fragility: (a) well anchored, strong load path to floor, adjacent cabinets within ½ inch are bolted together, no large nearby items that could fall on the control panel, (b) average or unknown conditions, (c) 1 deficiency, typ. no anchorage or poor load path.

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*. http://www.epriq.com/esqug/

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. Submitted to *Earthquake Spectra*.