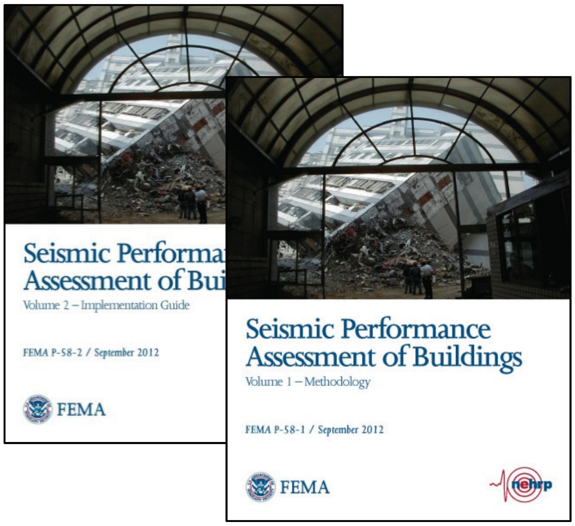

Background Document

FEMA P-58/BD-3.9.26

Fragility of Battery Racks

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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

Keith Porter (10/18/2009)

Table 1. Summary results

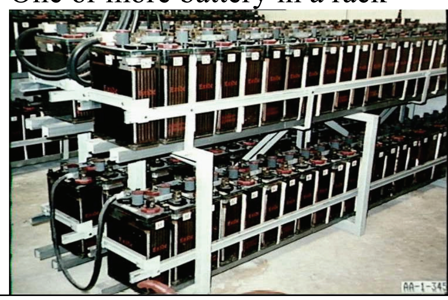
Fragility, damage measures, and consequences		
Component category:	D5092.011, battery rack, well installed: anchors on each frame, stiff spacers between batteries, batteries restrained from falling off rack, longitudinal cross braces, no nearby large items that could fall on batteries D5092.012, battery rack, one or more installation deficiency	
Basic composition:	One or more battery in a rack 	
Units:	**ea**	
Number of damage states:	**1**	
If multiple damage states:	simultaneous	
Author and date:	Keith Porter 18 Oct 2009	
Damage states, fragilities, and consequences for 2 cases:		
	D5092.011: well installed	**D5092.012: 1+ deficiencies**
Description:	Damaged, inoperative	Damaged, inoperative
Illustration:	Not available	Not available
Demand parameter	Peak floor acceleration (geometric mean, g)	Peak floor acceleration (geometric mean, g)
Median demand (θ):	5.0g	1.0g
Data dispersion (β_d):	0.25	0.6
Uncertainty (β_u):		
Total dispersion (β):	0.6	0.6
Probability:		
Correlation:		
Repairs required:	Replace batteries (100% of cases), plus: clean acid (50% of cases) and replace rack (33% of cases)	Same
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:	Max tested PFA ≈ 5g, so okay to use at high demand	Max observed PFA ≈ 0.8g, so do not use for PFA > 1.2g

Table 2. Summary supporting information

Discussion. Johnson et al. (1999) proposed a number of fragility functions, including battery racks, based on earthquake experience data in the EPRI eSQUG database (EPRI 2007). For a discussion, see Porter et al. (ND). In EPRI (1991), ANCO Engineers compiled shake-table tests of various mechanical and equipment, and based on the results of those tests recommends generic equipment ruggedness spectra (GERS), a response spectrum that a component that has not been tested can be expected to survive, if it meets certain requirements specified in a checklist. In the case of battery racks, the zero-period acceleration (ZPA) of that GERS is 2.0g. In an October 2009 ATC-58 FRP meeting, Bob Kennedy advised using the GERS tests solely to check that the median value calculated from the data in the eSQUG database was not too high, unless the qualified equipment were not more restrictive than the conditions for our zero-deficiency fragility functions. The tests of battery racks in the GERS report only included batteries ≤ 10 yr old, and the GERS is therefore restricted to batteries of ≤ 10 yr old, because one manufacturer only qualified its batteries for a 10-yr life. This is more restrictive than the conditions for our zero-deficiency fragility functions, so I examined the effect of removing the tests reported in the GERS report from the fragility function for well installed battery racks. Doing so eliminated all failures from the zero-deficiency dataset and switched the analysis from type B to type C. (Type B means some specimens failed, others did not, and the maximum demand is known for each specimen. Type C means that no specimens failed and the maximum demand is known for each specimen. Different analytical approaches are used to develop fragility functions in the two cases.) The change reduced the median capacity from 2.2g to 1.8g. Either median appears reasonable, and since the GERS data do add some failures and seems to make the fragility function more robust, the figure with GERS data is recommended. Note also that 9 of the 10 observed failures in the eSQUG database (specimens that had deficient installation) included failures other than cell cracking or dislodging of conductors inside cells > 10 yr old. The remaining, 10th failure may or may not have been age related. I conclude that battery age may or may not be a contributor to failure, but the evidence suggests it is not much of a contributor—that restraint and spacers are a much bigger issue—at least at the levels of excitation common in earthquakes.	
Number of specimens tested:	114 from eSQUG (EPRI 2007), 18 from GERS data set (EPRI 1991).
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: <u>varies</u>
Seismic installation conditions:	varies
Loading protocols applied:	22 earthquakes (eSQUG data)
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 specimens with no deficiencies

r, g	Units, M	Failed, m	Comment
0.30	4	0	EPRI (2007) data UNO
0.30	1	0	
0.30	1	0	
0.30	4	0	
0.30	2	0	
0.30	2	0	
0.31	1	0	
0.31	2	0	
0.36	1	0	
0.36	4	0	
0.36	1	0	
0.36	1	0	1 failure: 2-tier rack pulled expansion anchors and overturned. Spilled battery acid. Replacement batteries obtained and a new rack built. Failure ignored for ATC-58
0.39	1	0	
0.42	4	0	
0.48	6	0	
0.48	1	0	
0.48	2	0	
0.48	1	0	
0.48	1	0	
0.48	1	0	
0.48	5	0	
0.57	2	0	
0.60	1	0	
0.68	3	0	
0.68	1	0	
0.73	1	0	
1.03	1	0	
1.03	1	0	
0.28	1	0	GERS (EPRI 1991) non-failures; not labeled
0.48	1	0	Ditto
1.04	1	0	Ditto
1.16	1	0	Ditto
1.28	1	0	Ditto
1.48	1	0	Ditto
1.48	1	0	Ditto
1.68	1	0	Ditto
1.72	1	0	Ditto
2.2	1	0	Ditto
2.28	1	0	Ditto
1.68	1	1	GERS (EPRI) failed specimens, labeled E
2.28	1	1	Ditto, D
2.56	1	1	Ditto, A3
2.8	1	1	Ditto, A1
2.8	1	1	Ditto, C
3.08	1	1	Ditto, A2
3.2	1	1	Ditto, B
Sum	74	7	

Table 4. Failure data of specimens with deficient installation

r, g	Units, M	Failed, m	Comment
0.30	1	0	EPRI (2007) data UNO
0.30	1	0	
0.30	1	0	
0.30	1	0	
0.30	2	2	Batteries undergoing a process of changeout at the time of the earthquake. Normal wrap-around enclosure had been removed to allow access. Portion of the cells had to remain energized to supply power to the operating units. About 50 batteries toppled to the floor at the time of the earthquake, cracking the jars and spilling acid.
0.30	2	2	Unrestrained batteries toppled from shelves. Portion of the toppled batteries cracked their casings, spilling acid onto the floor. Batteries replaced.
0.30	3	0	
0.30	4	1	Wall behind the battery racks was originally unreinforced brick, and suffered a partial collapse in the earthquake, with debris falling on the batteries. Whether or not individual batteries also fell off the rack was not determined.
0.31	2	0	
0.31	2	0	
0.36	1	1	Eleven out of a total of twenty-four batteries on the rack were reported to have internal damage. Apparently impact of batteries, or reaction of lateral loads through the bus bar connections dislodged plates within the battery jars. The plates reportedly dislodged from their connections with the battery terminals, thus breaking electrical contact. Replacement batteries were obtained.
0.36	1	0	
0.36	2	0	
0.36	2	0	
0.36	2	0	
0.36	3	0	
0.42	6	1	A portion of the unrestrained cells toppled from their shelves and came to rest against the compartment doors, or fell all the way to the compartment floor. Toppling resulted in broken bus bar connections and cracked cells in some batteries. DC power supply was restored the day of the earthquake. Bracing to restrain the row of batteries was added.
0.48	1	0	
0.48	1	1	The combination of gaps between the battery cells and flexible cable connections allowed the cells to rock and pound during the earthquake. Apparently the loss of voltage was caused by dislodging of the positive plates within the battery jars. The manufacturer attributed this failure of the internal plate structure to deterioration with age. The cells were eight years old at the time of the earthquake.
0.51	2	0	
0.51	5	0	
0.60	1	0	
0.60	2	1	Five batteries on the bottom step, mounted beyond the end beyond the restraining rail toppled from the rack, cracking the cell containers. The fallen batteries required replacement.
0.60	5	0	
0.73	1	1	Batteries toppled from their rack due to a lack of restraining bracing to hold them in place.
0.73	3	0	
0.79	1	0	
Sum	58	10	

Table 5. Quality tests

Quality test	D5092.011: well installed	D5092.012: 1+ deficiencies
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 demand with 10% failure probability?	Y	Y
Discussion. Johnson et al. (1999) propose θs between 0.8 and 1.1g for deficient installation, vs. 1.0 here. They do not offer a zero-deficiency fragility function for comparison with the 2.2g value offered here. EPRI (1991) does not offer a median, but it does offer a GERS value of 2.0g, but this is a lower fractile of capacity. Re believing 10% failure probability, yes. This is easier to support for the deficient installation conditions because there are several data points with 5 ~ 30% failure and the curve seems to run through the cloud.		

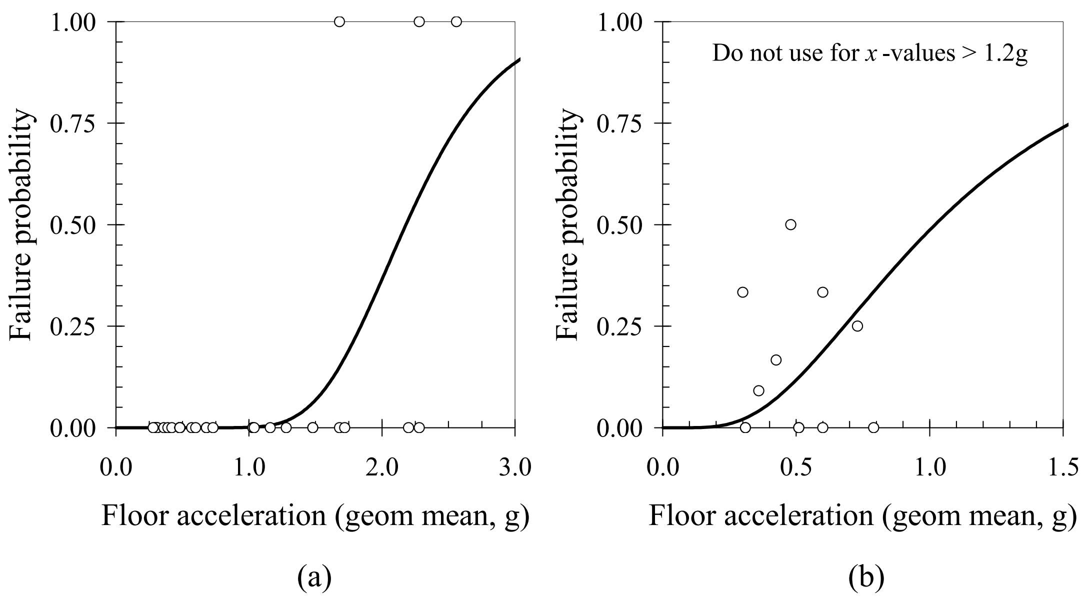


Figure 1. Battery rack seismic fragility: (a) well installed, with anchors on each frame, stiff spacers between batteries, batteries restrained from falling off rack, longitudinal cross braces, no nearby large items that could fall on batteries, (b) deficient installation, typ. no spacers between batteries, and some combination of no anchorage, no restraints, and no longitudinal cross braces.

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