Fragility of Mechanical, Electrical, and Plumbing Equipment

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A study for the Multidisciplinary Center for Earthquake Engineering Research (MCEER) provides fragility functions for 52 varieties of mechanical, electrical, and plumbing (MEP) equipment commonly found in commercial and industrial buildings. For the majority of equipment categories, the MCEER study provides multiple fragility functions, reflecting important effects of bracing, anchorage, interaction, etc. The fragility functions express the probability that the component would be rendered inoperative as a function of floor acceleration. That work did not include the evidence underlying the fragility functions. As part of the ATC-58 effort to bring second-generation performance-based earthquake engineering to professional practice, we have compiled the original MCEER specimen-level performance data into a publicly accessible database and validate many of the original fragility functions. In some cases, new fragility functions derived by ATC-58 methods show somewhat closer agreement with the raw data. Average-condition fragility functions are developed here; we will address in subsequent work the effect of potentially important—arguably crucial—performance-modifying factors such as poor anchorage and interaction. [DOI: 10.1193/1.3363847]

INTRODUCTION

In a project funded by the Federal Emergency Management Agency, the Applied Technology Council (ATC) is in the process of adapting for professional practice a second-generation performance-based earthquake engineering (PBEE-2) methodology originally developed by the Pacific Earthquake Engineering Research (PEER) Center and others (e.g., Porter 2003). The methodology seeks to estimate the future seismic performance of buildings in terms of probabilistic repair costs, human safety, and functionality (i.e., dollars, deaths, and downtime). A principal objective of the methodology is that each stage of the analysis be objective and documented, with the least practical reliance on expert opinion.

One stage of the analysis—referred to here as the damage analysis—seeks to estimate the probabilistic damage state of every damageable component of significance in the building. The damage analysis follows a series of nonlinear time-history structural analyses, which produce probabilistic estimates of various measures of structural re-

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sponse, referred to here as demands. Demand parameters may include member forces, deformations (including relative displacements between stories), and accelerations, at each story, column line, or node.

In the damage analysis, demands are input to component fragility functions, one or more fragility functions for each damageable component in the building. These fragility functions relate a demand parameter to the probabilistic damage state of a fairly narrowly defined class of component. The level of resolution of the component category system is fairly high: the ATC-58 taxonomy (Porter 2005) adds a subcategory system to the NISTIR 6389 (NIST 1999) proposed extension to the UNIFORMAT-II component numbering system. UNIFORMAT II (ASTM 2002) has 58 categories of building component and NISTIR 6389 has 284, but neither distinguishes important seismic features such as battery racks with or without anchorage or battery spacers—features that can be crucial to making informed seismic risk-mitigation decisions, thus the additional level of the taxonomy to distinguish such features is important.

There are three important implications for using this level of detail: First, one can resolve the difference in seismic performance of a particular building built with and without common seismic deficiencies. Second, one can use laboratory evidence and post-earthquake field observations to support the fragility functions with a degree of objectivity or verifiability. But counterbalancing these two perceived advantages is a problem: at this level of detail a lot of fragility functions are needed—probably hundreds—to represent most of the damageable components in most U.S. buildings and properly inform mitigation decisions. Many of these required fragility functions—perhaps one-third—are mechanical, electrical, and plumbing (MEP) equipment. Where are they to come from? There are several alternatives: laboratory testing, earthquake experience, theory, or expert opinion, but each choice involves time and expense.

Johnson et al. (1999, henceforth referred to as J99, and written largely by two of the present authors) provide a large number of MEP fragility functions: 52 component categories, each with between one and eight variants to reflect seismic conditions, for a total of approximately 170 fragility functions. This is enough potentially to serve a large portion of ATC-58's ultimate need for equipment fragilities.

J99 uses primary source data (some of which were also compiled in the EPRI SQUG database, e.g., EPRI 2003) to develop fragility functions for approximately 15 component categories of MEP equipment, listed in Table 3. Each category has between four and eight fragility functions to reflect installation conditions, for a total of 93 fragility functions. The data used to create fragility functions for these components come from direct observation of equipment exposed to strong motion shaking in 23 earthquakes between 1971 (San Fernando) and 1993 (Guam), including 123 sites experiencing ground motions from 0.12 g to 0.85 g of geometric-mean-direction peak ground acceleration. The fragility functions were published, but the underlying data were not. We refer to this previously unpublished data set as the J99 database. The remaining 80 or so fragility functions—e.g., for breakage of buried pipe and for tank ruptures—were drawn from other authorities and are not addressed here.

The challenge in using the J99 fragility functions for ATC-58 is that, under devel-

Table 1. Sample of failure database

Component	Earthquake	Facility	PGA	Units	Failed	Comments
Air compressor	San Fernando 1971	Glendale Power Plant	0.25	4		
Air compressor	Morgan Hill 1984	IBM/Santa Teresa Facility	0.37	3		
Air compressor	Loma Prieta 1989	Green Giant Foods	0.30	2	2	Burnt windings due to power transients or single phasing

(The table also contains an integer index field, not shown here)

oping ATC-58 guidelines, fragility functions carry little weight if the underlying data are not publicly available for review and validation. We therefore present them here and re-analyze them using ATC-58 procedures as described in ATC's developing *Guidelines for Seismic Performance Assessment of Buildings*. The specimen-by-specimen observations are presented here for the first time.

SUMMARY OF JOHNSON ET AL. SUPPORTING DATA

A database was compiled from the original, unpublished data used to create the J99 fragility functions. The data are available at www.risk-agora.org. The database contains two tables: one showing equipment damage data (the table is named "Damage"), the other summarizing the distribution of equipment through the height of the buildings in which they were observed (table name "Height").

A sample of the damage data is shown in Table 1. Each record of table "Damage" contains observations of a particular class of component at a single facility in a single earthquake. The database also contains the estimated shaking intensity at the facility, the total number of specimens ("units"), the number that failed, and in some cases a comment on the nature of the damage.

A sample of the table "Height" is shown in Table 2. Each record refers to the distri-

Table 2. Sample of table "Height"

Component	Earthquake	Facility	PGA	Units	Bot 1/3	Mid 1/3	Top 1/3
Air compressor	San Fernando 1971	Glendale Power Plant	0.25	4	4		
Air compressor	Morgan Hill 1984	IBM/Santa Teresa Facility	0.37	3	3		
Air compressor	Chile 1985	Rapel Hydroelectric Plant	0.23	8	6		2

(The table also contains an integer index field, not shown here)

Table 3. Summary of data supporting 15 categories of fragility functions in Johnson et al. (1999)

Component category	NISTIR 6389	Events	Sites	Specimens	Failed	Height distr.	Derived functions
Air compressors	D3032?	14	37	158	3	98,0,2	6
Air handling units	D3063	11	23	119	21	10,70,20	7
Batteries in racks	D5092	10	23	168	14	75,8,16	7
Battery chargers	D5092	18	46	156	2	96,4,0	6
Chillers	D3031	6	16	50	12	100,0,0	6
Control panels	D3067?	17	61	326	23	70,16,13	6
Distribution panels	D5012?	15	34	199	3	100,0,0	5
Engine generators	D5092	13	36	157	13	100,0,0	7
Fans	D3041	16	41	402	47	23,3,74	8
Low voltage switchgear	D5012?	19	45	150	7	98,2,0	6
Motor control centers	D5010	19	51	283	5	69,25,6	6
Motor generators	D5012?	12	18	41	0	91,9,0	7
Pumps	D3040?	19	44	551	5	100,0,0	7
Transformers	D5011?	18	46	245	5	100,0,0	5
Valves	D3040?	17	42	914	6	68,17,15	4
Total				3919	166		93

bution through the height of a facility of a given component category in a single earthquake. It shows the component category, earthquake, facility name, estimated PGA, total number of specimens observed, and the number of specimens in each of the bottom, middle, and top one-third of the height of the facility. These data are relevant because excitation is only known in terms of peak ground acceleration (PGA) at the site.

The nature of the buildings in which these specimens were observed is not recorded in the J99 database: not their height, nor lateral force resisting system, nor fundamental period of vibration. Except for components that were installed on the ground floor, only a crude estimate is practical for the peak excitation to which their bases were subjected. While PGA is a reasonable proxy for the acceleration to which specimens at the ground level or perhaps in the lower one-third of a building were subjected, the actual acceleration that specimens in the middle and upper one-third of floors experienced is unknown; amplification is dealt with in an approximate way, described later. (Note that most of the components in the J99 database were installed in the lower third, so PGA is not a bad proxy for the equipment demand parameter.) Note that there is *not* a one-to-one correspondence of records in Table "Height" to records in table "Damage" because the database did not always contain information about height distribution.

Tables 3 and 4 summarize the data examined here. In the table, each row refers to one category of component. "NISTIR 6389" refers to the approximate NISTIR 6389 UNIFORMAT-II label for that category. Note some overlap: batteries in racks and battery chargers both belong to D5092, Emergency Light and Power Systems, but are dis-

Table 4. Fragility functions derived from Johnson et al. (1999) data

Component	h	*New* θ	*New* β	*MCEER* θ	*MCEER* β	*Diff in* ε^2	*Comment*
Air compressor	1.02	2.2	0.6	2.5	0.4	−0.01	
Air handling unit	1.55	1.4	0.6	1.9	0.5	−0.27	
Batteries in rack	1.21	3.0	0.6	2.5	0.4	−0.15	
Battery charger	1.02	4.2	0.6	2.0	0.4	−0.01	
Chiller	1.00	0.7	0.6	2.1	0.5	−0.12	
Control panel	1.21	2.3	0.4	2.3	0.4	−0.20	
Distribution panel	1.00	3.4	0.6	2.8	0.4	−0.00	
Engine generator	1.00	1.6	0.6	2.0	0.4	−0.01	
Fan	1.75	1.4	0.6	1.6	0.5	−0.44	
Low voltage switchgear	1.01	1.2	0.6	1.3	0.4	−0.30	
Motor control center	1.18	1.8	0.6	1.5	0.4	−0.10	
Motor generator	1.05	1.5	0.4	2.0	0.4	N/A	No failures; method C used
Pump	1.00	2.6	0.6	3.0	0.4	−0.01	
Transformer	1.00	1.3	0.6	1.6	0.4	−0.72	
Valve	1.23	4.5	0.6	4.0	0.4	−0.00	

tinct components with distinct seismic installation and fragility features. The column labeled "Events" indicates the number of earthquakes after which various specimens were observed. The column labeled "sites" indicates how many different facilities were examined; "specimens" indicates how many unique specimens were examined, and "failed" indicates distinct failures of those specimens.

The column labeled "Height distribution" recaps the percentage of observed specimens that were in the lower, middle, and upper one-third of buildings. The column labeled "Derived functions" indicates how many fragility functions were derived from the EPRI data. As will be shown later, one basic fragility function was developed for each class of component, along with three or more additional fragility functions to reflect different installation conditions, referred to in J99 as performance modification factors, or PMFs. For example, 6 fragility functions are derived for air compressors: (1) basic conditions, (2) no anchorage, (3) poor anchorage, (4) vibration isolator concerns, (5) rigid attachments, and (6) interaction concerns.

Few records in the J99 data actually indicate the presence or absence of PMFs. The fragility functions for PMFs were developed using a methodology referred to in J99 as "survival analysis," which involves observations of damage to component where PMF information is available. The effect on fragility from some of these PMFs is profound, increasing the failure probability in some cases by an order of magnitude or more. This implies that in many cases the equipment itself is fairly rugged, but that anchorage, interaction, and other installation conditions should be the focus of remedial action.

The methodology is explained in J99, but it involves assuming the lowest observed PGA associated with failure is the HCLPF (high confidence of low probability of failure) PGA, defined as the PGA where the authors have 95% confidence that no more than 5% of samples of the component would fail. With the addition of two beta values, one can find the median failure PGA from the HCLPF PGA; the authors used

$$\theta = r_{HCLPF} \exp(1.65(\beta_u + \beta_r)) \tag{1}$$

where β_u reflects modeling uncertainty (uncertain median) and β_r represents uncertainty given a known median.

Equation 1 is rational, but is not used here for two reasons: (1) it has not yet been accepted as an ATC-58 standard, and (2) some of the r_{HCLPF} values are based on judgment. For example, r_{HCLPF} for motor control centers with interaction concerns is noted in the J99 authors' calculations as 0.2 g, but no specimens were actually observed where interaction was noted as contributing to failure. For this reason, the present manuscript addresses only average-condition fragility functions; PMFs will be dealt with in a separate work. It is valuable to know how equipment will perform when one knows installation conditions, but it is also valuable to know something about performance under average conditions, where the details of installation are unknown. Hence the average-condition fragility functions are worthy of consideration.

DEVELOPING FRAGILITY FUNCTIONS FOR HVAC EQUIPMENT

Methodology for height modifiers. J99 estimated the average floor acceleration of equipment by increasing PGA by a factor to account for building response. Let M denote the total number of specimens of a component class, M_L the total number in the bottom one-third of the facilities they are in, M_M the total number in the middle one-third, and M_H the total number in the top one-third. Let PGA_i denote the estimated geometric-mean peak ground acceleration of the facility in which specimen i was observed, and let r_i denote the estimated floor acceleration of the specimen. It is estimated as

$$h = \frac{1}{M}(M_L + 1.5 \cdot M_M + 2M_H)$$

$$r_i = h \cdot PGA_i \tag{2}$$

Method B for developing fragility functions. A methodology is proposed in *Guidelines for Seismic Performance Assessment of Buildings* (also shown in Porter et al. 2007) to estimate the fragility function of a component category where the available data are groups (or bins) of components assumed to have experienced the same demand, where bins contain varying number of specimens, and where at least some specimens failed. One performs a weighted least-squares fit to failure-rate data, using the number of specimens in each bin as the bin weight. Let

M = number of specimens observed
i = index of specimens, $i \in \{1, 2, \ldots M\}$
r_i = demand to which specimen i was subjected
f_i = failure indicator for specimen i
= 1 if specimen i failed (reached or exceeded damage state dm)
= 0 otherwise
N = number of bins
j = index of bins, $j \in \{1, 2, \ldots N\}$
M_j = number of specimens in bin j
m_j = number of failed specimens in bin j
y_j = failure rate in bin j

$$y_j = \frac{m_j}{M_j} \tag{3}$$

One finds θ and β_r to minimize ε^2 such that:

$$\varepsilon^2 = \frac{1}{M}\sum_{j=1}^{M} M_j\left(y_j - \Phi\left(\frac{\ln(r_j/\theta)}{\beta_r}\right)\right)^2$$

$$\theta > 0$$

$$0.2 \leqslant \beta_r \leqslant 0.6 \tag{4}$$

then calculates β:

$$\beta = \sqrt{\beta_r^2 + \beta_u^2} \tag{5}$$

where $\beta_u = 0.25$ if any of the following is true, 0 otherwise:

All specimens were observed to be in the same configuration (if applicable)
All specimens were observed to have the same installation conditions
All specimens experienced the same loading history
$M < 5$

Method C for developing fragility functions. In cases were no specimens failed, the Guidelines propose the following procedure for creating fragility functions. Given no damage among M observations, let

$F_{dm}(r)$ = failure probability given demand r
r_i = demand experienced by specimen $i (i = 1, 2, \ldots M)$
r_{max} = $max_i\{r_i\}$
r_d = minimum demand experienced by any specimen with distress
r_a = the smaller of r_d and $0.7 \cdot r_{max}$
M_A = number of specimens without apparent distress and with $r_i \geqslant r_a$
M_B = number of specimens at any level of r_i with distress not suggestive of imminent failure

M_C = number of specimens at any level of r_i with distress suggestive of imminent failure
r_m = r_{max} if $M_B+M_C=0$
= $0.5\cdot(r_{max}+r_a)$ otherwise
S = subjective failure probability at r_m

$$S=(0.5M_C+0.1M_B)/(M_A+M_B+M_C) \tag{6}$$

One uses Table 5 to determine $F_{dm}(r_m)$ and Equation 7 to determine β and θ.

$$\beta=0.4$$
$$z=\Phi^{-1}(F_{dm}(r_m))$$
$$x_m=r_m\exp(-z\beta) \tag{7}$$

RESULTS

New fragility functions and comparison with original. The J99 data were analyzed to produce values of h for each component category; the results are shown in Table 4. They agree in every case with the height modifier calculated in J99. The table also shows results of the fragility analysis described above. The columns labeled "new" are parameters for the fragility function re-derived from the raw data. The columns labeled "MCEER" are the fragility function parameters from J99. The difference between the two fragility functions is measured here by the relative difference in ε^2 calculated using the two sets, i.e., if we denote by ε_0^2 and ε_1^2 respectively the values of ε^2 as calculated using the MCEER parameters and using the new parameters, then the difference noted in the table is calculated by

$$Diff=\frac{\varepsilon_0^2-\varepsilon_1^2}{\varepsilon_1^2} \tag{8}$$

In only a few cases are there significant differences between the perceived accuracy of the newly derived versus original J99 fragility functions. Most notable among these are the fragility functions for transformers and for fans, with 72% lower and 44% lower ε^2 values (equal to the reduction in residual variance). These differences are attributable

Table 5. Example values of $\exp(-z\beta)$

Conditions	$F_{dm}(r_m)$	Z	$\exp(-z\beta)$, $\beta=0.4$
$M_A\geqslant 3$ and $S=0$	0.01	−2.326	2.54
$M_A<3$ and $S\leqslant 0.075$	0.05	−1.645	1.93
$0.075<S\leqslant 0.15$	0.10	−1.282	1.67
$0.15<S\leqslant 0.3$	0.20	−0.842	1.40
$S>0.3$	0.40	−0.253	1.11

to the fact that the authors of J99 constrained their β values to 0.4 or 0.5. The $\beta=0.5$ value is reserved for components where a majority of the observed specimens were in the middle and upper one-third of the building. In this work we have allowed β to vary between 0.2 and 0.6 regardless of height. This greater latitude allows for a closer fit to the data.

Figure 1 through Figure 15 show the derived fragility functions and the underlying data points, one point for each level of intensity (which can reflect one or more facilities). In the figures, "floor acceleration" means the geometric-mean peak horizontal acceleration applied at the base of the equipment, i.e., the floor slab on which the equipment stood. The figures all show a smooth curve for a fragility function between 0 and 1.5 g, but with a dashed line above 1.5 times the maximum acceleration any of the specimens experienced. To use the curve extrapolated beyond that point is probably inappropriate. Table 6 through Table 20 contain summary exposure and damage data for the

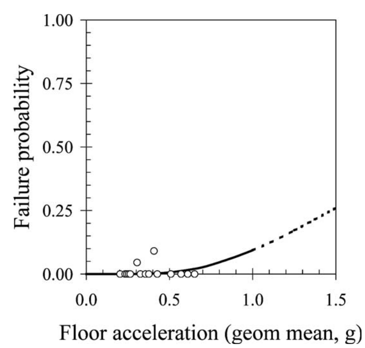

Figure 1. Air compressors.

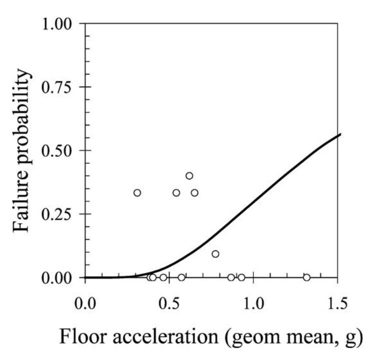

Figure 2. Air handling units.

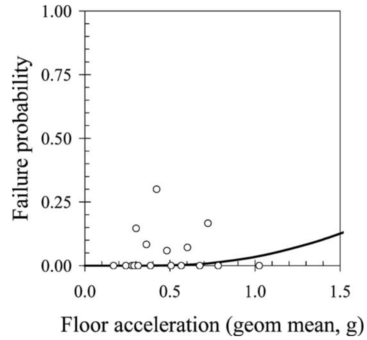

Figure 3. Batteries in racks.

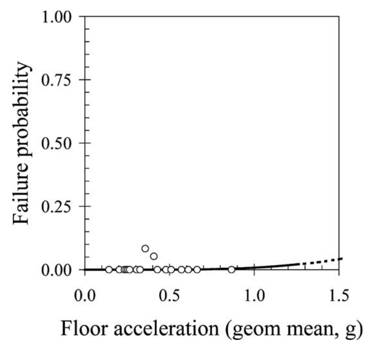

Figure 4. Battery chargers.

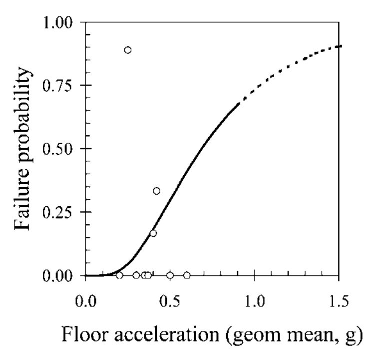

Figure 5. Chillers.

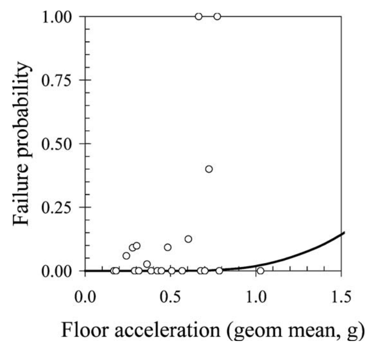

Figure 6. Control panels.

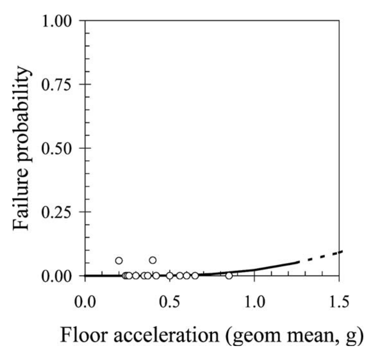

Figure 7. Distribution panels.

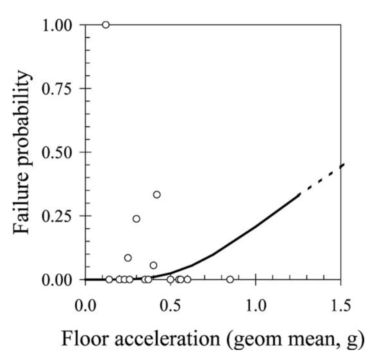

Figure 8. Engine generators.

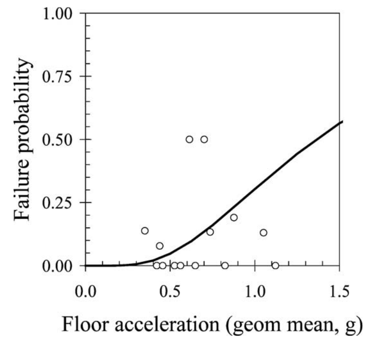

Figure 9. Fans.

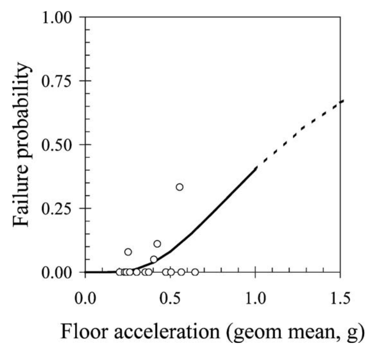

Figure 10. Low voltage switchgear.

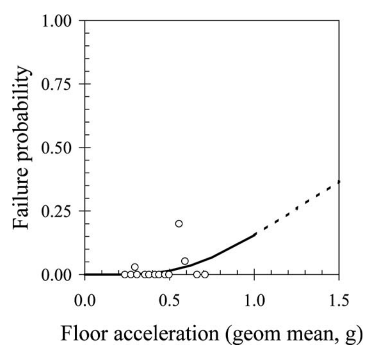

Figure 11. Motor control centers.

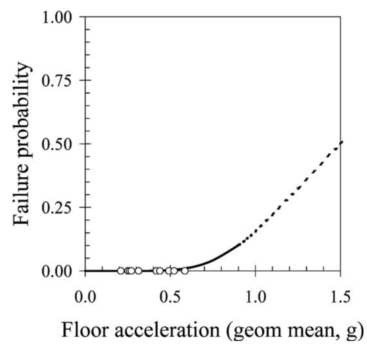

Figure 12. Motor generators.

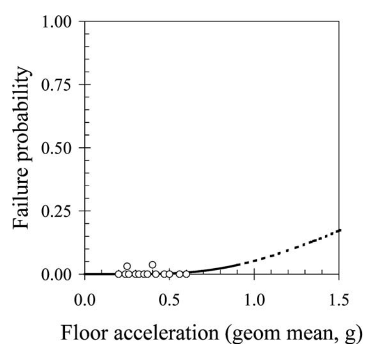

Figure 13. Pumps.

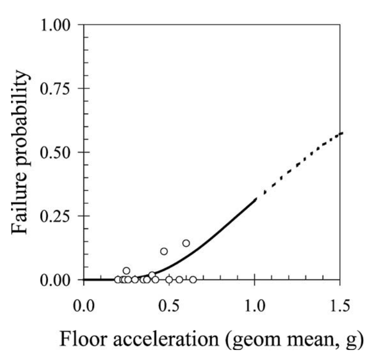

Figure 14. Transformers.

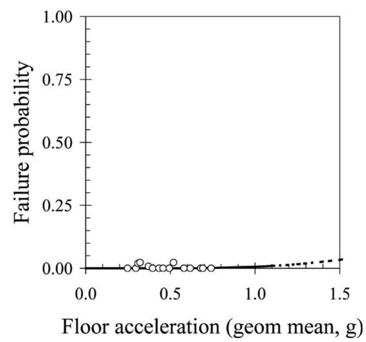

Figure 15. Valves.

Table 6. Failure data of air compressors

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.20	16	0	0.101	0.000	0.000
0.23	8	0	0.051	0.000	0.000
0.24	4	0	0.025	0.000	0.000
0.25	25	0	0.158	0.000	0.000
0.26	11	0	0.070	0.000	0.000
0.31	44	2	0.278	0.045	0.000
0.33	3	0	0.019	0.000	0.001
0.36	4	0	0.025	0.000	0.001
0.38	3	0	0.019	0.000	0.002
0.41	11	1	0.070	0.091	0.002
0.43	7	0	0.044	0.000	0.003
0.51	8	0	0.051	0.000	0.007
0.57	2	0	0.013	0.000	0.012
0.61	10	0	0.063	0.000	0.016
0.65	2	0	0.013	0.000	0.021

Table 7. Failure data of air handling units

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.31	3	1	0.025	0.333	0.000
0.39	7	0	0.059	0.000	0.001
0.40	2	0	0.017	0.000	0.001
0.46	2	0	0.017	0.000	0.002
0.54	3	1	0.025	0.333	0.006
0.57	3	0	0.025	0.000	0.008
0.62	30	12	0.252	0.400	0.013
0.65	6	2	0.050	0.333	0.016
0.77	54	5	0.454	0.093	0.036
0.87	2	0	0.017	0.000	0.058
0.93	6	0	0.050	0.000	0.076
1.32	1	0	0.008	0.000	0.232

Table 8. Batteries in racks failure data

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.17	5	0	0.030	0.000	0.000
0.24	18	0	0.107	0.000	0.000
0.28	5	0	0.030	0.000	0.000
0.29	6	0	0.036	0.000	0.000
0.30	41	6	0.244	0.146	0.000
0.31	10	0	0.060	0.000	0.000
0.36	24	2	0.143	0.083	0.000
0.39	1	0	0.006	0.000	0.000
0.42	10	3	0.060	0.300	0.000
0.48	17	1	0.101	0.059	0.000
0.51	2	0	0.012	0.000	0.000
0.57	2	0	0.012	0.000	0.000
0.60	14	1	0.083	0.071	0.000
0.68	4	0	0.024	0.000	0.001
0.72	6	1	0.036	0.167	0.001
0.78	1	0	0.006	0.000	0.002
1.02	2	0	0.012	0.000	0.013

Table 9. Failure data for battery chargers

r, *g*	Units. *M*	Failed, *m*	$w=M/\Sigma M$	$y=m/M$	Φ
0.14	4	0	0.026	0.000	0.000
0.20	18	0	0.115	0.000	0.000
0.23	10	0	0.064	0.000	0.000
0.24	6	0	0.038	0.000	0.000
0.25	27	0	0.173	0.000	0.000
0.26	4	0	0.026	0.000	0.000
0.31	21	0	0.135	0.000	0.000
0.33	3	0	0.019	0.000	0.000
0.36	12	1	0.077	0.083	0.000
0.41	19	1	0.122	0.053	0.000
0.43	4	0	0.026	0.000	0.000
0.48	2	0	0.013	0.000	0.000
0.51	10	0	0.064	0.000	0.000
0.57	5	0	0.032	0.000	0.000
0.61	7	0	0.045	0.000	0.000
0.66	1	0	0.006	0.000	0.000
0.87	3	0	0.019	0.000	0.000

Table 10. Failure data for chillers

r, *g*	Units, *M*	Failed, *m*	$w=M/\Sigma M$	$y=m/M$	Φ
0.20	4	0	0.080	0.000	0.000
0.25	9	8	0.180	0.889	0.000
0.30	5	0	0.100	0.000	0.000
0.35	6	0	0.120	0.000	0.000
0.37	4	0	0.080	0.000	0.000
0.40	12	2	0.240	0.167	0.000
0.42	6	2	0.120	0.333	0.001
0.50	2	0	0.040	0.000	0.002
0.60	2	0	0.040	0.000	0.006

Table 11. Failure data for control panels

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	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

Table 12. Failure data for distribution panels

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.20	17	1	0.085	0.059	0.000
0.24	19	0	0.095	0.000	0.000
0.25	39	0	0.196	0.000	0.000
0.26	10	0	0.050	0.000	0.000
0.30	31	0	0.156	0.000	0.000
0.35	7	0	0.035	0.000	0.000
0.37	1	0	0.005	0.000	0.000
0.40	33	2	0.166	0.061	0.000
0.42	14	0	0.070	0.000	0.000
0.50	12	0	0.060	0.000	0.001
0.56	5	0	0.025	0.000	0.001
0.60	5	0	0.025	0.000	0.002
0.65	2	0	0.010	0.000	0.003
0.85	4	0	0.020	0.000	0.011

Table 13. Failure data for engine generators

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.12	1	1	0.006	1.000	0.000
0.14	1	0	0.006	0.000	0.000
0.20	24	0	0.153	0.000	0.000
0.23	4	0	0.025	0.000	0.000
0.25	47	4	0.299	0.085	0.000
0.26	1	0	0.006	0.000	0.000
0.30	21	5	0.134	0.238	0.000
0.35	5	0	0.032	0.000	0.000
0.37	3	0	0.019	0.000	0.000
0.40	18	1	0.115	0.056	0.000
0.42	6	2	0.038	0.333	0.000
0.50	5	0	0.032	0.000	0.000
0.55	1	0	0.006	0.000	0.001
0.56	1	0	0.006	0.000	0.001
0.60	18	0	0.115	0.000	0.001
0.85	1	0	0.006	0.000	0.016

Table 14. Failure data for fans

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.35	58	8	0.144	0.138	0.000
0.42	5	0	0.012	0.000	0.000
0.44	64	5	0.159	0.078	0.000
0.46	26	0	0.065	0.000	0.000
0.53	112	0	0.279	0.000	0.000
0.56	4	0	0.010	0.000	0.001
0.61	6	3	0.015	0.500	0.002
0.65	2	0	0.005	0.000	0.002
0.70	40	20	0.100	0.500	0.004
0.74	30	4	0.075	0.133	0.006
0.82	6	0	0.015	0.000	0.013
0.88	21	4	0.052	0.190	0.020
1.05	23	3	0.057	0.130	0.054
1.12	5	0	0.012	0.000	0.074

Table 15. Failure data for low voltage switchgear

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.20	17	0	0.114	0.000	0.002
0.23	6	0	0.040	0.000	0.004
0.24	5	0	0.034	0.000	0.005
0.25	38	3	0.255	0.079	0.005
0.26	6	0	0.040	0.000	0.007
0.30	26	0	0.174	0.000	0.013
0.35	6	0	0.040	0.000	0.024
0.37	2	0	0.013	0.000	0.029
0.40	20	1	0.134	0.050	0.039
0.42	9	1	0.060	0.111	0.047
0.47	1	0	0.007	0.000	0.068
0.50	5	0	0.034	0.000	0.083
0.56	3	1	0.020	0.333	0.110
0.57	3	0	0.020	0.000	0.115
0.65	2	0	0.013	0.000	0.164

Table 16. Failure data for motor control centers

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.24	37	0	0.131	0.000	0.000
0.27	5	0	0.018	0.000	0.001
0.30	68	2	0.240	0.029	0.001
0.31	6	0	0.021	0.000	0.001
0.35	49	0	0.173	0.000	0.003
0.38	9	0	0.032	0.000	0.004
0.41	12	0	0.042	0.000	0.006
0.44	3	0	0.011	0.000	0.008
0.47	35	0	0.124	0.000	0.012
0.50	11	0	0.039	0.000	0.014
0.56	10	2	0.035	0.200	0.023
0.59	19	1	0.067	0.053	0.029
0.66	4	0	0.014	0.000	0.044
0.71	15	0	0.053	0.000	0.056

Table 17. Failure data for motor generators

r, g	Units, M	Failed, m	$w = M/\Sigma M$	$y = m/M$	Φ
0.21	4	0	0.098	0.000	0.000
0.25	2	0	0.049	0.000	0.000
0.26	11	0	0.268	0.000	0.000
0.27	3	0	0.073	0.000	0.000
0.31	6	0	0.146	0.000	0.000
0.42	3	0	0.073	0.000	0.000
0.44	1	0	0.024	0.000	0.000
0.49	6	0	0.146	0.000	0.000
0.52	3	0	0.073	0.000	0.000
0.59	2	0	0.049	0.000	0.000

Table 18. Failure data for pumps

r, g	Units, M	Failed, m	$w = M/\Sigma M$	$y = m/M$	Φ
0.20	81	0	0.147	0.000	0.000
0.24	18	0	0.033	0.000	0.000
0.25	96	3	0.174	0.031	0.000
0.26	24	0	0.044	0.000	0.000
0.30	116	0	0.211	0.000	0.000
0.32	13	0	0.024	0.000	0.000
0.35	18	0	0.033	0.000	0.000
0.37	14	0	0.025	0.000	0.001
0.40	54	2	0.098	0.037	0.001
0.42	39	0	0.071	0.000	0.001
0.47	14	0	0.025	0.000	0.002
0.50	22	0	0.040	0.000	0.003
0.56	2	0	0.004	0.000	0.005
0.60	40	0	0.073	0.000	0.007

components listed in Table 4. The field labeled "Φ" indicates the cumulative distribution function that minimizes the weighted squared error, ε^2. In the tables, "r" means the same thing as "floor acceleration."

CONCLUSIONS

Johnson et al. (1999) present in an appendix a potentially valuable set of fragility functions for 15 categories of mechanical, electrical, and plumbing (MEP) equipment, based on damage observations of 3,919 pieces of equipment from 123 sites and 23 earthquakes. The underlying data are presented here for the first time and are re-examined to develop fragility functions for use in ATC-58. The newly derived fragility functions generally agree with the originals. In a few cases, significant reduction in re-

Table 19. Failure data for transformers

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.20	22	0	0.090	0.000	0.001
0.23	1	0	0.004	0.000	0.002
0.24	7	0	0.029	0.000	0.002
0.25	57	2	0.233	0.035	0.002
0.26	12	0	0.049	0.000	0.003
0.30	42	0	0.171	0.000	0.006
0.35	3	0	0.012	0.000	0.012
0.37	4	0	0.016	0.000	0.016
0.40	57	1	0.233	0.018	0.021
0.42	14	0	0.057	0.000	0.026
0.47	9	1	0.037	0.111	0.039
0.50	6	0	0.024	0.000	0.049
0.56	2	0	0.008	0.000	0.071
0.60	7	1	0.029	0.143	0.088
0.64	2	0	0.008	0.000	0.107

sidual uncertainty was achieved by relaxing restrictions on the logarithmic standard deviation of capacity (the so-called dispersion parameter). The next step is to refine these fragilities based upon differences in installation and other conditions called performance modification factors (PMFs), which in many cases may be key to understanding and mitigation of equipment failure risk.

Table 20. Failure data for valves

r, g	Units, M	Failed, m	$w=M/\Sigma M$	$y=m/M$	Φ
0.25	175	0	0.191	0.000	0.000
0.30	33	0	0.036	0.000	0.000
0.31	157	3	0.172	0.019	0.000
0.32	44	1	0.048	0.023	0.000
0.37	129	1	0.141	0.008	0.000
0.40	52	0	0.057	0.000	0.000
0.43	31	0	0.034	0.000	0.000
0.46	9	0	0.010	0.000	0.000
0.49	72	0	0.079	0.000	0.000
0.52	44	1	0.048	0.023	0.000
0.58	14	0	0.015	0.000	0.000
0.62	19	0	0.021	0.000	0.000
0.68	5	0	0.005	0.000	0.000
0.69	9	0	0.010	0.000	0.000
0.74	121	0	0.132	0.000	0.000

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