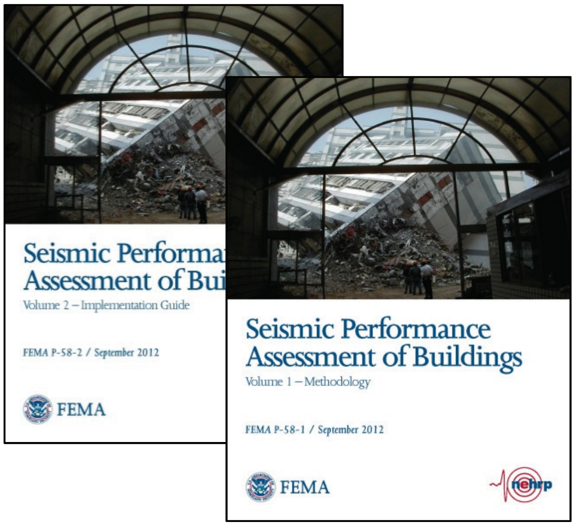

Background Document

FEMA P-58/BD-3.7.6

Fragility Testing and Reporting for ATC-58

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contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology.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

Revision history

1.0	31 Dec 2007	Initial release
1.1	29 Feb 2008	Add math for MECE and simultaneous damage states with probabilities that vary by DP
1.2	30 Mar 2008	Add requirement for describing how DP is observed
1.3	12 May 2008	Add row in Table 5 (test results) to record data type. Added instructions for Table 7 to list the factors that affect fragility and how they affect θ and β, e.g., lack of representation of test setup with as-installed conditions; size effects; variability in installation detail; quality of workmanship. Added rows to Table 7 to list factors affecting θ and β
1.4	11 Aug 2008	Change Table 2 to show residual story drift as a demand parameter Add requirement for type-A data in Table of Test Results: if specimens were subjected to increments of demand and damage state observed after each increment, record failure demand as the midpoint of the increment causing failure. Add requirement to show plot with data, best-fit curve, and final fragility function(s). Add location to place fragility functions (Figure 1) in results section.
1.5	5 Sep 2008	Change equation 2 (fraction of specimens that failed when subjected to demand x_i or less) from y = (n – 0.5)/N to y = n/(N + 1) per Ellingwood preference. Require reporting of β_r, β_u, and β separately, and report to 2 sig figs.

Fragility Testing and Reporting for ATC-58

Keith Porter and Craig Comartin

1 PURPOSE, SCOPE, AND APPLICABLE TYPES OF TEST DATA

ATC-58 is developing tools and procedures for practicing engineers to perform next-generation performance-based earthquake engineering analysis, in which one explicitly estimates the uncertain future seismic performance of buildings in terms of repair costs, fatalities, and repair duration (dollars, deaths, and downtime). The damage-analysis portion of the procedure requires fragility functions, which in this context give the probability that building components with prescribed characteristics will reach or exceed predefined damage states, given the values of demand (for example, drift, acceleration, etc.) to which the building components are subjected. Building components include structural, nonstructural, and contents components included in the NISTIR 6389 (NIST 1999) category system. These fragility functions are derived from laboratory test data, earthquake experience data, or other sources. Methods to analyze these data and produce fragility functions are presented elsewhere.

This specification presents requirements for documenting fragility functions. It applies when specimens have been tested in a laboratory to observe their damage when loaded to simulate earthquake excitation. Of the seven types of damageability data listed in Table 1, this document applies to cases where specimens have been tested to observe damage data of types A, B, C, UA, and UB.

Table 1. Analysis methods and data employed

Method name	**Data used**
A. Actual failure demand	All specimens failed at observed values of demand
B. Bounding demand	Some specimens failed; maximum demand for each is known
C. Capable demand	No specimens failed; maximum demand for each is known
D. Derived fragility	Fragility functions produced analytically
E. Expert opinion	Expert judgment is used
UA. Updating-A	Enhance existing fragility functions with new method-A data
UB. Updating-B	Enhance existing fragility functions with new method-B data

2 NOMENCLATURE AND DEFINITIONS

θ. See median.

β. See dispersion.

Damage state. A condition of a component requiring specified repair measures to restore the component to its undamaged condition; or that has specific consequences with respect to life safety or occupancy or a building.

Dispersion. As used here, the logarithmic standard deviation of the value of demand at which an arbitrary sample of a component will reach or exceed a specified damage state.

Demand: a structural response quantity such as interstory drift, acceleration, force, inelastic deformation, that correlates with component or system damage.

DP. See demand.

DS. See damage state.

Logarithmic standard deviation. The standard deviation of the natural logarithm of an uncertain variable. As used here, refers to the logarithmic standard deviation of the demand parameter associated with reaching or exceeding a specified damage state.

NISTIR 6389. Proposed extension of UNIFORMAT-II component numbering system.

Median. As used here, that value of demand at which there is an estimated 50% probability that an arbitrary sample of a component will reach or exceed a specified damage state.

UNIFORMAT-II. A category system for numbering building systems, developed by the Construction Specification Institute (CSI).

3 DESCRIBE COMPONENTS TESTED

Report the following:

- Category of components tested. This is a brief name for the category. If convenient, use UNIFORMAT-II terminology, available online at http://www.bfrl.nist.gov/oae/publications/nistirs/6389.pdf.

- Basic composition. This is a detailed description of the specimens' physical characteristics (dimensions, weights, material properties) to which the fragility functions provided are applicable.

- Normative quantity. This is the quantity of the component to which the fragility functions apply, generally related to quantity takeoff or repair costs. For example, walls might be measured in square feet.

4 SELECT DEMAND PARAMETER

Select among the demand parameters listed in Table 2 or clearly define new ones that will be tested for their ability to relate structural response to physical damage. This specification allows for reporting multiple competing demand parameters. Only peak transient drift ratio and peak diaphragm acceleration are currently available in PACT, and so if possible provide at least one of these. If appropriate, also use others listed in Table 2, or clearly and unambiguously define new ones. PACT currently allows only scalar demand parameters (i.e., demand cannot be a measured in terms of a two or more simultaneous measures of structural response, such as horizontal and vertical acceleration).

Table 2. Demand parameters

DP	Name	Definition
PTD	Peak transient drift ratio	Specified for a story, column line, and direction. PTD = |xi – xi-1|/hi, where xi = displacement of floor i, xi-1 = displacement of floor i-1, hi = height of story i, and the ratio is taken as the maximum over time during seismic loading.
PDA	Peak diaphragm acceleration	Peak diaphragm acceleration, max of two horizontal directions (specified for story).
RD	Residual drift ratio	Specified for story, column line, and direction. RD = |xi – xi-1|/hi, where xi = displacement of floor i after seismic loading, xi-1 = displacement of floor i-1 after seismic loading, and hi = height of story i before seismic loading
CDR	Curvature ductility ratio	CDR = (fm – fy)/(fu – fy), where fr = recoverable curvature of flexural member (i.e., curvature when yield moment occurs), fu = curvature of flexural member when ultimate moment occurs, fm = maximum curvature of flexural member attained during seismic loading
D	Peak transient drift ratio at connection	D = 100*|xa - xb|/(0.5*(ha + hb), where xa = displacement of the mid-height of the column above the connection, xb = displacement of the mid-height of the column below the connection, ha = height of the column above the connection, and hb = height of the column below the connection
FDN	Nonlinear function of drift and cycles	FDN = a*D^b + c*NLL^d, where D = peak transient drift ratio at connection, in percent, NLL = number of cycles, a = 7.7, b = 0.85, c = 0.87, and d = 0.8
FGN	Nonlinear function of joint strain and cycles	FGN = a*G^b + c*NLL^d, where G = maximum shear strain, NLL = number of cycles (Lowes 1999), a = 20, b = 0.25, c = 7.12, and d = 0.36
G	Maximum shear strain	Maximum shear strain
MDCR	Moment demand-capacity ratio	MDR = M/My, where M = moment applied at critical section and My = moment corresponding to yield of extreme fiber
MHR	Maximum hinge rotation	The angle (in radians) subtended by member centerline at joint center and member centerline at distance d from joint face, where d is member depth
NLL	Number of cycles	NLL = Sum[i=i..n](|Dui|/(4*umax)), where umax = historic maximum displacement, Dui = current displacement increment, and n = number of displacement increments
PADI	Modified Park-Ang Damage Index	Specified for member and direction. PADI = (fm - fr)/(fu - fr) + b*(At/(fu*My)), where fr = recoverable curvature of flexural member (i.e., curvature when yield moment occurs), fu = curvature of flexural member when ultimate moment occurs, fm = maximum curvature of flexural member attained during seismic loading, b = strength deterioration parameter, At = total area contained in M-f loops, and My = yield moment of flexural member.

Shaded DPs are not currently treated in PACT.

5 DEFINE DAMAGE STATES AND DAMAGE EVIDENCE

5.1 DEFINE DAMAGE STATES

Define the damage states of interest in terms of physical evidence of damage. For each damage state, define the (most likely) repair measures required as quantitatively as possible as well as identifying the possible consequences of damage in terms of life loss or effect on occupancy. If there are 2 or more damage states, indicate whether they are ordered, mutually exclusive, or simultaneous, defined as follows:

1. ***Ordered damage states.*** There are at least two possible damage states in addition to the undamaged state ($N \geq 2$). Damage state i must be reached before reaching damage

state $i + 1$ or repair of a component in damage state $i + 1$ necessarily repairs it from damage state i. Generally, the demand at which damage state i is reached is less than the demand at which damage state $i + 1$ is reached.

2. ***Mutually exclusive damage states***. There are at least two possible damage states in addition to the undamaged state ($N \geq 2$). Damage state i does not coexist with damage state j. The repair efforts and consequences for occupancy and life safety for damage state i are generally different from those of damage state j. These statements are true for all $1 \leq i \leq N$, $1 \leq j \leq N$, and $i \neq j$. In such a case, provide a single fragility function for the combined probability of occurrence of any of the damage states (that is that the component will be damaged), and then provide the conditional probability of each damage state given the occurrence of damage, either independent of demand, or as a function of demand. (These conditional probabilities must sum to 1.0.) No procedures are provided here evaluating either case.
3. ***Simultaneous damage states.*** There are at least two possible damage states in addition to the undamaged state ($N \geq 2$), and damage state i can coexist with damage state j, and the repair efforts, occupancy, or life consequences for damage state i are different from those of damage state j, for $i \neq j$ and i, j are in $\{1, 2, \ldots N\}$. In such a case, provide a single fragility function for the probability that the component will be damaged, and then provide the conditional probability of each damage state given the occurrence of damage, either independent of demand, or as a function of demand. (The conditional probabilities can sum to more than 1.0.) No procedures are provided here evaluating either case.

5.2 INDICATE POSSIBLE CONSEQUENCES

For each damage state, indicate (yes, no, or do not know) whether the damage could realistically:

- Involve significant repair cost
- Cause death or injury
- Threaten post-earthquake building operability
- Cause red-tagging

5.3 PROVIDE PHOTO OF EACH DAMAGE STATE

Provide at least one photo or other illustration clearly depicting each damage state, preferably from actual earthquake experience. Photos shall be at least 600 dpi resolution, at least 2.5 in x 2.5 in.

5.4 PROVIDE FRAGILITY FUNCTION PARAMETERS FOR EACH DAMAGE STATE

For each damage state, provide the median (θ) and logarithmic standard deviation (β) value of demand at which the component type reaches the damage state. Perform the calculations specified in Appendix C of *Guidelines for Seismic Performance Assessment of Buildings* (ATC 2007), showing all work including a sample calculation. Alternatively, use the fragility function calculator provided at www.risk-agora.org and provide the resulting θ and β values. For methods A and B, report β_r (dispersion implied by the data), β_u (uncertainty associated with differences between tests and actual field behavior of the larger population), and total β. If a different β_u is used than recommended in Appendix C, explain. Report β values to 2 significant figures.

6 SUPPORTING INFORMATION

6.1 SUMMARY SUPPORTING INFORMATION

Provide the following supporting information.

- Relevant literature. Summarize past testing or other observations of damage to similar components. Indicate number of specimens observed, their configurations, loading protocols or other excitation, damage states observed, fragility functions produced (form and parameters), and features identified as relevant to seismic performance.

- Number of specimens tested.

- Construction quality of tested specimens: whether exceeding, meeting, and not meeting manufacturer or code requirements.

- Design, installation, and (if appropriate) maintenance conditions of tested specimens. These should relate to the conditions deemed most relevant to the seismic performance of the general category of component.

- Identify loading protocol. For drift-sensitive components, use FEMA 461 (2007) protocol 1, or comply with the requirements for non-FEMA-461 racking protocol listed below. For acceleration-sensitive components, FEMA 461 (2007) protocol 2, or comply with the requirements for non-FEMA-461 acceleration protocol listed below. For racking or acceleration protocols other than FEMA 461, provide a peer-reviewed reference supporting the use of the alternative protocol, along with plots of the imposed loading history with clearly labeled axes.

- Describe how demand was observed.

- Describe how specimen damage was observed. Indicate how damage states for specimens were determined from these observations. Indicate whether damage states were observed *during* loading or *after* loading. By "during loading" is meant that the approximate value of DP at which each damage state was reached is known. By "after loading" is meant that the maximum value of DP is known for each specimen, and whether or not each damage state was reached at some time during loading.

6.2 TABLE OF TEST RESULTS

Provide a table of test results. In the table, include one row for each specimen. The first column contains the specimen number. The second column contains the value of DP for each specimen for damage state 1. The third column contains the failure indicator *f* for the specimen. The failure indicator is a number between 0 and 1 indicating whether the specimen reached the damage state of interest, as detailed below. For each additional damage state, add pairs of columns containing demand and the failure indicator *f*, as described below. Comments about individual specimens can be included in the right-hand column. Note in the "comments" column any design, installation or maintenance conditions or features of the specimen that varied from other specimens. Record the specimen number, demand, and *f* values as follows.

Test data can come in various forms: with or without damaged specimens, failure at observed or unobserved demand levels, and with or without previous fragility information to incorporate. The required test data varies depending on the type of data available; five types are distinguished here. If all specimens failed at observed values of demand, follow the instructions for Type-A (actual failure demand) data. If some but not all specimens failed and the maximum demand for each is known, follow the instructions for Type-B (bounding) data. If no specimens failed and the maximum demand for each is known, then follow the instructions for Type-C (capable) data.

Type-A data. For each specimen, record the value of demand at which the damage state was reached, and record the failure indicator as $f = 1$. For type-A data where specimens were subjected to increments of demand, and the damage state was observed in the first cycle of the next demand increment, record the demand at the midpoint of the demand increment that caused the specimen to fail. For example, if a specimen was observed not to have failed at demand level D_0, and was observed to have failed when exposed to the first cycle of the next-larger demand level $D_0 + \Delta$, then record the failure demand as $D_0 + 1/2\Delta$.

Type-B data. Tabulate the maximum value of demand to which each specimen was subjected. Record $f = 0$ for specimens that did not reach the damage state, and record $f = 1$ for specimens that did reach or exceed the damage state.

Type-C data. Record the maximum value of demand to which each specimen was subjected. Record:

$f_i = 0$ for specimens with no apparent damage

$f_i = 0.1$ for specimens that experienced some damage but where the damage was not suggestive of imminent failure (i.e., imminently reaching the damage state of interest), in the judgment of the investigators.

$f_i = 0.5$ for specimens that experienced damage suggestive of imminent failure in the judgment of the investigators.

Type-UA data. Record the median θ and logarithmic standard deviation β from the prior work along with a citation to the prior work. Tabulate test results as described under "Type-A data," above.

Type-UB data. Record the median θ and logarithmic standard deviation β from the prior work along with a citation to the prior work. Tabulate test results as described under "Type-B data," above.

6.3 FRAGILITY FUNCTION PLOTS

Provide a single plot of test results and fragility functions. The plot shall have as its vertical axis the probability of reaching or exceeding the specified damage state, with limits 0 and 1. Its horizontal axis shall indicate demand, labeled with the demand parameter and units, if appropriate. For ordered damage states, show fragility functions for each damage state. The fragility function should be of the form

$$P\left[DM \geq dm \middle| DP = x\right] = \Phi\left(\frac{\ln\left(x/\theta\right)}{\beta}\right) \quad (1)$$

where x denotes a particular value of demand, Φ denotes the cumulative standard normal (Gaussian) distribution, θ denotes the value of demand at which there is a 50% probability that a component will reach or exceed damage state *dm*, and β denotes the logarithmic standard deviation of the value of demand at which a component reaches damage state *dm*. For types A and B data, also include the observed damage data as (x, y) points, as follows.

x_i = demand to which specimen i was exposed. For type-B data, this is the maximum demand to which the specimen was subjected. For type-A data where specimens were subjected to increments of demand and damage was observed at the end of each increment, x_i is the midpoint of the demand increment that caused the damage to occur. For type-A data where specimens were subjected to slowly increasing demand and the demand was observed at the moment when the damage state was reached, x_i is that level of demand.

y_i = fraction of specimens that failed when subjected to demand x_i or less, i.e.,

$$y_i = \frac{n\left(x_i\right)}{N+1} \quad (2)$$

where $n(x_i)$ refers to the number of specimens that failed at a demand x_i or less, and N is the total number of specimens observed.

For types A or B data, show both the smooth fragility function that best fits the data (i.e., using θ and β_r, before including β_u), and the final smooth fragility function (i.e., using θ and β, after including β_u). For types A or B data with multiple ordered damage states, show both curves for each damage state. For types A or B data with multiple mutually exclusive or simultaneous damage states, provide both curves for the probability of entering any of the damage states and provide another plot showing on the vertical axis the probability that, given that the component is damaged, a given damage state is experienced. The horizontal axis shall indicate demand, labeled with the demand parameter and units, if appropriate. Each curve on this plot shall be clearly labeled to indicate which damage state it refers to.

6.4 QUALITY TESTS

For Type-A data, indicate whether each fragility function passes the Lilliefors goodness-of-fit test at the 5% significance level.

For Type-A or Type-B data, justify ≥20% difference in θ or β versus past estimates.

For Type-A or Type-B data, examine and justify any case of $\beta < 0.2$ or $\beta > 0.6$

It is particularly important that the fragility function be accurate at lower percentiles, i.e., that the fragility function indicates approximately the correct value of demand associated with 5-10% failure probability. State whether you believe the demand with 10% failure probability appears to be approximately correct, and briefly discuss why.

6.5 EXTRAPOLATE TO OTHER CONDITIONS

List the specific construction, installation, maintenance, and safety practice details that in practice are most likely to affect median capacity (θ) and dispersion (β). List any factors that might make as-built θ and β differ from tested conditions, such as representativeness of test setup versus as-installed conditions; size effects; variability in installation detail; and quality of workmanship. Other details that are likely to affect median capacities of acceleration- or force-sensitive components are those that transfer forces between the component boundaries (especially anchorage points) to the masses within the component. Those that are likely to affect median capacities of drift- or deformation-sensitive components are those that constrain deformation, such as gaps between the component and adjacent building elements. Details that are likely to affect dispersion in capacity are variability in anchorage strength, internal masses, internal member strengths and stiffnesses, dimensions, internal connection strengths, orientation, and installation quality and construction supervision.

Describe these details in four groups: one set of conditions that would be reasonably characterized as "best," one set "moderate," one set "worst," and one set "average or unknown." If tested specimens correspond to one or these groups, identify which one. Then if possible, extrapolate from your test results to estimate the fragility parameters (median and dispersion) for the other conditions and state the basis for the extrapolation.

7 RESULTS TEMPLATES

Table 3. Summary results template

Fragility, damage measures, and consequences for			
Component category:			
Basic composition:			
Units:			
Demand parameter:			
Number of damage states:			
If multiple damage states:	☐ ordered; ☐ mutually exclusive; ☐ simultaneous		
Author and date:			
Damage states, fragilities, and consequences			
	DS1	**DS2**	**DS3**
Description:			
Illustration:			
Median demand (θ)(1):			
Data dispersion (β_r)(2)			
Uncertainty (β_u)(2)			
Total dispersion (β)(1):			
Probability(1):			
Correlation:			
Repairs required:			
Possible consequences:			
Repair cost (Y/N/?):			
Death or injury (Y/N/?):			
Inoperative facility (Y/N/?):			
Red tagging (Y/N/?)			
Comments(2):			

(1) If ordered damage states, leave "probability" blank. If mutually exclusive or simultaneous damage states, provide parameters in DS1 column only, and probabilities of each damage state in "probability."

(2) For methods A and B only, provide β_r and β_u and explain in the "comments" row any β_u value that differs from recommendations in Appendix C.

Table 4. Summary supporting information template

Literature summary	
Number of specimens tested:	
Construction quality:	☐ exceeds ☐ meets ☐ does not meet requirements of: ______
Seismic installation conditions:	
Loading protocols applied:	
Method for observing demand:	
Method for observing damage:	

Table 5. Table of test results

Specimen	DS1		DS2		DS3		Comment
	Data type:		**Data type:**		**Data type:**		
	demand	***f***	***demand***	***f***	***demand***	***f***	
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
add as req							

Table 6. Quality tests

Quality test	DS1	DS2	DS3
Passes Lilliefors goodness of fit test? (Type A only)	Y/N/NA	Y/N/NA	Y/N/NA
Are θ and β within 20% of past results? If not discuss.			
Are $0.2 \leq \beta \leq 0.6$? If not discuss.			
Do you believe the demand with 10% failure probability?	Y/N/NA	Y/N/NA	Y/N/NA
Discussion			

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

Condition (describe)	From tests?	DS1		DS2		DS3	
		θ	***β***	**θ**	***β***	**θ**	***β***
Best	Y/N						
Moderate	Y/N						
Worst	Y/N						
Average	Y/N						
Basis for extrapolation. What factors affect θ and β?							

"From tests" means that the tests reported here are believed to represent this condition level

[Place fragility function plots here]

Figure 1. Fragility function(s)

8 REFERENCES CITED

(ATC) Applied Technology Council, 2007. *Guidelines for Seismic Performance Assessment of Buildings 35% Complete Draft*, Prepared for the Department of Homeland Security, Washington, DC.

(FEMA) Federal Emergency Management Agency, 2007 (expected). FEMA 461: Interim Protocols for Determining Seismic Performance Characteristics of Structural and Nonstructural Components Through Laboratory Testing. Washington DC, 110 pp.

(NIST) National Institute of Standards and Technology, 1999. *UNIFORMAT II Elemental Classification for Building Specifications, Cost Estimating, and Cost Analysis,* NISTIR 6389, Washington, D.C., 93 pp., http://www.bfrl.nist.gov/oae/publications/nistirs/6389.pdf [viewed 3 March 2006]