Evaluation of an Expert Opinion Survey to Determine Component Seismic Fragility

V.N. Vagliente, M. Voutyras, A. Curtis
Nutech Engineers, Inc., 6835 Via Del Oro, San Jose, California 95119, U.S.A.

ABSTRACT

Probabilistic risk assessment of nuclear power plants is assuming a more important role with regulatory authorities. This is part of an effort to quantify the risks to people and the environment in the vicinity of the nuclear plant.

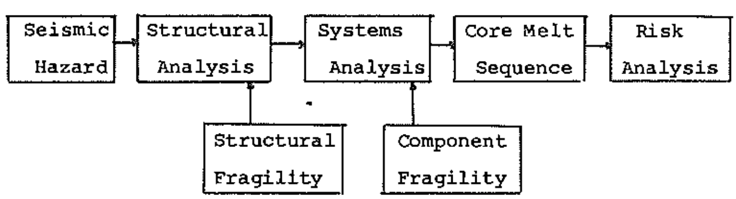
Seismic occurrences are considered as external initiating events in a risk analysis. An important part of a seismic risk analysis is to determine the probabilities of failure of the safety-related components in a nuclear power plant. Unlike random failure analysis, there is no significant data base to establish component fragility during an earthquake. This situation led to the consideration of an expert opinion solicitation for seismic fragility of nuclear components. The results of the survey are presented in the form of the parameters of a lognormal distribution. The distributions represent the weakest mode of failure.

The distributions are generic. They can be used with other data in a Bayesian analysis to construct site specific distributions.

1. INTRODUCTION

The use of probabilistic methods in the risk analysis of nuclear power plants is gaining widespread attention. A major use for these methods in the future will be to evaluate the effect of installing new systems or upgrading old systems. The relative risk of the plant, with and without the system, or a comparision of the risk before and after the system is upgraded. The decision of whether or not to add a system or upgrade a system in the plant will take into account not only risk mitigation, but the cost associated with the action. Criteria for making the decision are diverse and generally associated with a function of the change in risk to the cost of the modification.

The risk associated with earthquakes comes under the heading of external events. Uncertainty exists in every task composing the seismic risk calculation chain. Evaluating the seismic hazard is extremely difficult due to the infrequent occurrence of earthquakes. Consequently, the definition of the seismic hazard relies heavily on subjective judgement. Methods of structural analysis generally employed are reliable for small displacements only. Extrapolation of the analysis to the point of failure requires engineering judgement with its associated uncertainties. The seismic risk analyst has to be content with structural fragilities resulting from this method since there is no recourse.



Block Diagram: Seismic Risk Calculation Chain

Testing of specially constructed nuclear structures would be prohibitively expensive because of their size and complexity. Component fragility is the third major task of seismic risk analysis. This task is a major contributor to the uncertainty in the risk analysis. Similar to the seismic hazard analysis and the structural fragility analysis, the component fragility incorporates a great deal of subjective opinion.

With component fragility, one distinguishes between pressure boundary failure and functional failure. Stress analysis of pressure retaining components can provide a reasonable foundation upon which to base a fragility estimate. The stress analysis is especially pertinent if it is non-linear for components made of ductile material and for such systems as piping. Functional failure is more difficult to quantify. The basic tool of the engineer-stress-analysis is not very useful in this situation. Tests-to-failure of components are performed infrequently. Seismic qualification tests are normally performed at a level significantly below failure. Extrapolation of seismic qualification tests to failure lack credibility. Near failure, the component is likely to be responding non-linearly, making extrapolation extremely difficult. There have been attempts to extrapolate from military shock data on components very similar to those used in nuclear power plants. The military tests were performed at a frequency spectrum representative of a bomb blast. These tests need to be extrapolated into the frequency range characteristic of earthquakes. Since the military tests are response spectra, a mathematical extrapolation is not enough. The response of the component at low frequencies could be quite different from its high frequency response. Once component fragility curves have been constructed, by whatever means, the system analysis can be performed . The probabilities of core melt follow from the system analysis and hence, the degree of risk can be evaluated to the utility (e.g., the cost of having the plant shutdown following a core melt) and also to the public in the vicinity of the plant.

2. PREDICTING COMPONENT FRAGILITY

Component fragility is inherently a random phenomena. This situation comes about because of the variation in material properties, component geometry, support conditions, and tolerances in moving parts between members of a given population of supposedly identical components. Consequently, component fragility must be described by a probability distribution.

The term "probability" as used in an expert opinion survey is defined as the expert's degree of belief in the survey probabilistic statements. It is not appropriate to use the empirical frequency definition of classical statistics. The expert whose opinion is solicited has in his possession a block of evidence which consists of analytical methods, prior analysis, and test data on identical or similar components. Using this evidence, the engineering expert will have to make adjustments in order to produce a fragility probability distribution. The inaccuracies associated with adjusting prior evidence to determine these probabilities are documented in Reference 1. Typically, estimates are biased toward the initial evidence. This phenomenon is called anchoring. Because of anchoring, estimates of failure of complex components will generally be underestimated. The phenomenon of adjustment and anchoring appear to be the two most important factors in estimating component fragility using engineering expert opinion. The significant factor is that the resulting mean of the fragility distribution will be conservative. However, the spread of the distribution (i.e., the variance) will generally be too small.

The probability distribution must be selected and fitted to the expert opinion information. The lognormal distribution is in common use. However, the probability of failure is sensitive to the precise area of overlap between the probability distribution of load ($f_s(s)$) and the fagility distribution ($f_\delta(\delta)$). This area represents the probability that load exceeds the strength of the component. This problem is illustrated in Figure 1 and is commonly referred to as the "tails problem." The relative shapes of the tails of common probability functions are shown in Figure 2 which is taken from Reference 2. The available information indicates that the reliability calculation is very sensitive to the shape of the tails of the selected distributions. For large probabilities of failure (e.g., $P_f > 10^{-3}$) the choice of distribution is immaterial while for small values (e.g., $P_f < 10^{-5}$) the failure probability could be quite sensitive to the distribution's shape in the tails region (Reference 3). Choice of the lognormal distribution can be unconservative for coefficients of variation between 0.10 and 0.25 (Figure 2).

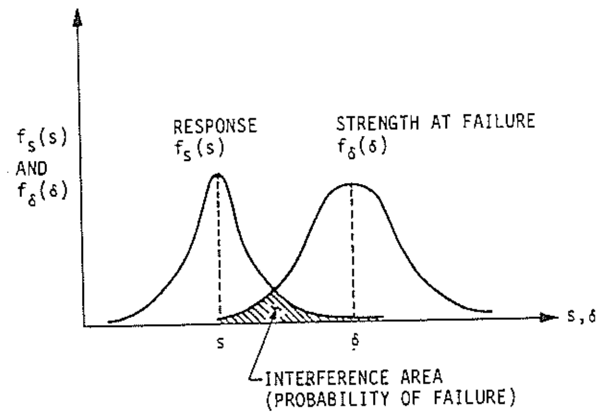
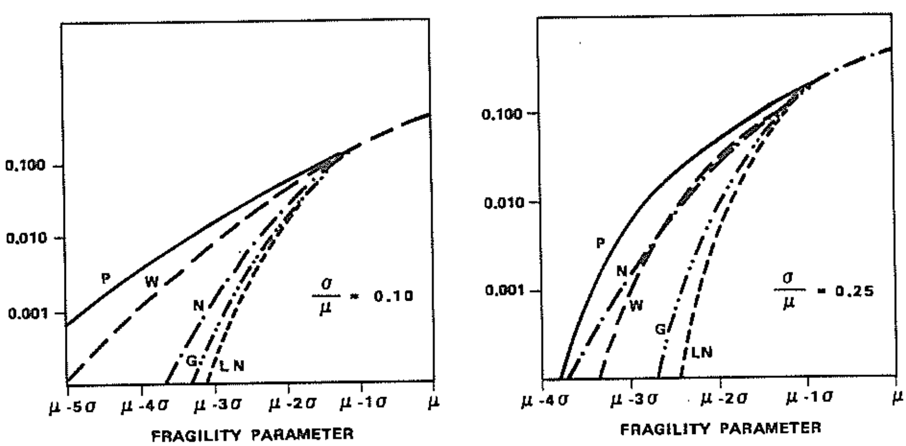


Figure 1
RESPONSE – STRENGTH AT FAILURE INTERFERENCE ANALYSIS



LEGEND:

PROBABILITY DENSITY FUNCTION, F(X):

N	NORMAL	P	POWER
LN	LOGNORMAL	W	WEIBULL
G	GAMMA		
μ	MEAN	σ	STANDARD DEVIATION

Figure 2
LOWER TAIL PROBABILITIES FOR COMMON STATISTICAL MODELS

3. RESULTS OF AN EXPERT OPINION POLL

A discussion of an expert opinion survey on component fragility is presented in Reference 4. The selection of experts and construction of the questionaire to solicit the expert opinion on fragility is discussed in this reference, but the results were never presented. The results presented here represent a generic fragility function and strength at failure in the weakest mode.

These generic fragility distributions could be used in a Bayesian Analysis if additional fragility data is available for specific components used in a particular plant to produce plant specific fragility descriptions. The procedure would be similar to the calculations illustrated for random failure in Reference 5.

To reduce the problem of determining these functions to a manageable size, it is necessary to group the components appearing in the Fault Trees into categories for a reactor system. This is not unreasonable in view of the fact that many components serving similiar functions in systems differ only slightly in size and design and thus, can be described adequately by a single generic fragility function. If categorization of components is not done, individual fragility functions would be required for more than two thousand components appearing in the Fault Tree model of a nuclear reactor system.

Table 1 presents the fragility functions for significant components appearing in a typical Fault Tree Model of a nuclear reactor. No partial failures were considered for this table since partial failure does not appear normally in Fault Tree Models of complex systems.

The fragility functions in Table 1 are based on test information, analysis, and subjective opinion. A weighting scheme is used to emphasize that test information is the most reliable, and subjective opinion is least reliable. Most of the responses to the questionaire are based on test information and analysis. Also, the majority of returned questionaires represent the combined judgement of a number of engineers within a given organization. For example, the questionaire was generally mailed to an individual. However, the response in the returned questionaire was normally the collective judgement of selected engineers within a particular organization. Their evaluations imply an attempt to arrive at a consensus within their organization based on the information available.

Uncertainties within the fragility functions in Table 1 are qualitatively outlined, since accessible data for a quantitative statistical analysis is insufficient. Note that perhaps a significant contributor to uncertainty is a difference among equipment supplied by different manufacturers within an individual category.

The accuracy of fragility functions presented should not be underestimated. Test information and analysis provide a firm foundation for the results. These results provide a best-estimate of what would constitute a distribution for a random sample.

Table 1

Fragility Functions

Category	Fragility Parameter	Notes on the Fragility Parameter	Lognormal Distribution $\mu_{\ell nx}$	$\sigma_{\ell nx}$	m_c	β_c	Coe. of Var.
1 Reactor Internals (PWR)	Spec Accel G'S	Spectral Accel at frequencies of 4 Hz	.72	.40	2.05	.40	.41
2 Reactor Vessel (PWR)	Spec Accel G's	Frequency: 15 Hz	1.31	.18	3.72	.18	.19
2 Pressurizers	Spec Accel G's	Predominant Frequency: 7 Hz	.69	.39	1.99	.39	.41
2 Reactor Vessel	Moment	Frequency: 15 Hz	18.97	.35	1.73×10^8	.35	.36
2 Steam Generators	Spec Moments & Forces	Predominant Frequency: 12 Hz	.64	.21	1.89	.21	.21
"	Forces(SSE)	Frequency: 20 Hz	1.55	.34	4.71	.34	.35
"	Spec Accel G's	Frequecny: 8 Hz	.76	.40	2.14	.40	.41
3 Primary Coolant	ASME Eq #9 Sm (in percentages)	Frequency: 15 Hz	5.96	.20	387.91	.20	.20
"	Spec Accel G's	Frequency: 5 Hz	.72	.25	2.06	.25	.25
4 Large Piping	Yield Moment	Frequency: 6 Hz	.35	.25	1.43	.25	.25
"	Spec Accel G's	Frequency: 6 Hz	1.18	.27	3.27	.27	.28
5 Intermediate Piping	Yield Moment	Frequency: 6 Hz	.47	.26	1.60	.26	.26
"	Spec Accel G's	Frequency: 7 Hz	1.02	.25	2.78	.25	.25
6 Small Pipes	Spec Accel G's	Frequency: 7 Hz	1.02	.25	2.78	.25	.25
"	Yield Moment	Frequency: 6 Hz	.70	.43	2.01	.43	.45
7 Large Vert. Storage Vessels	Spec Accel Moment	Frequency: 7 Hz	.38	.40	1.47	.40	.41
"	Yield	Frequency: 6 Hz	1.26	.94	3.52	.94	1.18

Table 1

Fragility Functions
(Continued)

Category	Fragility Parameter	Notes on the Fragility Parameter	Lognormal Distribution $\mu_{\ell nx}$	$\sigma_{\ell nx}$	m_c	β_c	Coe. of Var.
8 Large Vert. Storage Vessels Flat Bottom	Spec Accel G's	Frequency: 6 Hz	.70	.25	2.01	.25	.26
9 Large Horiz. Vessels	Floor Accel G's	Frequency: 16 Hz	1.36	.61	3.90	.61	.67
10 Horiz. Tanks, Sm Vessels, Ht. Exch	Accel G's	Frequency: >15 Hz	.61	.27	1.85	.27	.28
11 Buried Pipe	Ground Accel G's	Frequency: Rigid	.24	.51	1.27	.51	.55
12 Reactor Cool Pump	Spec Accel G's	Frequency: 4 Hz	.97	.34	2.64	.34	.34
13 Large Vert. Cntr. Pumps	Spec Accel G's	Frequency: 4 Hz	.96	.25	2.62	.25	.25
14 Large Vert Pumps	Spec Accel G's	Predominant Frequency: 3 Hz	.79	.38	2.21	.38	.40
"	Factor x SSE Accel	Predominant Frequency: >33 Hz	.64	.18	1.91	.18	.18
15 Centrifugal Pumps	Accel G's	Rigid	1.10	.28	2.74	.28	.29
"	Zero Period Accel G's	Ridig	1.46	.34	4.32	.34	.35
"	Factor x SSE Loads	Rigid	.42	.16	1.52	.16	.16
16 LMOV'S	Spec Accel	Frequency: Hz 15	.58	.31	1.78	.31	.31
17 Large Relief & Check Valves	Spec Accel G's	Frequency: Rigid	.40	.13	1.49	.13	.13
18 Misc Sm Valves	Accel G's	Frequency: Rigid	.54	.11	1.72	.11	.11
"	Piping Loads	"	1.75	.28	5.76	.28	.28
18 Misc Sm Valves	Pipe Dis-placement	Frequency: Rigid Damping 5%	.69	.10	1.99	.10	.10

Table 1

Fragility Functions
(Continued)

Category	Fragility Parameter	Notes on the Fragility Parameter	Lognormal Distribution $\mu_{\ell nx}$	$\sigma_{\ell nx}$	m_c	β_c	Coe. of Var.
19 Fans, Electric Motors	Accel G's	Rigid	2.49	.33	12.02	.33	.34
20 Generators	Spec Accel G's	Frequency: 15 Hz	.43	.33	.65	.33.	34
21 Batteries	Accel G's	Frequency: >15 Hz	.77	.38	2.16	.38	.39
22 Switchgear	Accel G;s	Frequency: 4 Hz	.52	.32	1.68	.32	.32
23 Dry Transformers	Spec Accel	Frequency: 8 Hz	.73	.30	2.07	.30	.31
24 Air Handling Units	Floor Accel G's	Frequency: 21 Hz	.80	.34	2.23	.34	.35
25 Instrument Panels	Accel G's	Rigid	.17	.73	1.18	.73	.84
27 Control Panels and Racks	Spec Accel G's	Frequency: >12 Hz	1.30	.83	3.66	.83	.99
30 Local Instruments	Spec Accel G's	Frequency: 12 Hz Damping: 5%	.52	.28	1.69	.28	.28
31 Motor Control Centers	Spec Accel G's	Frequency: >15 Hz Damping: 5%	1.01	1.19	2.74	1.19	1.77
33 Light Fixtures	Factors x SSE	Frequency: 5 Hz Damping 2%	.43	.20	1.53	.20	.20
35 Converters	Spec Accel G's	Rigid	2.75	.44	15.64	.44	.46
36 Cable Trays	Accel Spec SSE in Percentages	Frequency: 5 Hz	5.24	.37	188.09	.37	.39
"	Spec Accel G's	Frequency: 5 Hz	.80	.39	2.23	.39	.40
37 Ducting	Spec Accel G's	Frequency: 8 Hz	1.38	.40	3.98	.40	.42
"	Factor x	Frequency: 18 Hz	.85	.13	2.34	.13	.13
38 Hydraulic Snubbers	Rated Load	Rigid	.38	.15	1.46	.15	.15

Table 1

Fragility Functions
(Concluded)

Category	Fragility Parameter	Notes on the Fragility Parameter	Lognormal Distribution $\mu_{\ell nx}$	$\sigma_{\ell nx}$	m_c	β_c	Coe. of Var.
39 Curcuit Breakers	Spec Accel G's	Frequency: 3 Hz	-.43	.70	.65	.70	.80
40 Combiners	Accel G's	Frequency: 10 Hz	2.11	.14	8.24	.14	.14
41 Ceramic Insulators	Accel G's	Rigid	-1.76	.39	.17	.39	.40
42 Spent Fuel Racks	Spec Accel G's	Frequency: 8 Hz	-1.29	.47	.28	.47	.50

Notes: $\mu_{\ell nx}$ = expected value of the natural logarithm of the fragility parameter

$\sigma_{\ell nx}$ = standard deviation of the natural logarithm of the fragility parameter

m_c = median of the lognormal distribution

β_c = standard deviation

4. CONCLUSION

Participants in the expert opinion survey are familiar with safety-related nuclear power plant components. They are usually specialists on a narrow range of components within any nuclear plant. Generally, their responses to the questionaire are based on analysis and/or test results.

The authors suggest that the fragility table in this paper presents a good beginning. Very little seismic testing of components in the range where failure is likely to occur has been carried out to date. Thus, expert opinion has to be used to develop the needed inputs for seismic risk analysis.

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