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QUANTIFYING PARTIAL FRAGILITY CORRELATIONS IN SEISMIC PROBABILISTIC RISK ASSESSMENTS

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ABSTRACT

Conventional treatment of fragility correlations in seismic probabilistic risk assessments (SPRAs) of nuclear power plants (NPPs) in the United States and worldwide has been binary – either perfect correlation, or no correlation is assumed depending on which of the two is judged to be closer to reality. For a group of partially correlated structures, systems, and components (SSCs) whose concurrent failures result in system failure, the idealization of perfect fragility correlation can be quite conservative. Conversely, if the failure of any one SSC in the group results in system failure, the perfect fragility correlation idealization can be quite unconservative. Depending on the objectives of the SPRA (e.g., safety assessment vs. risk-informed application, or single-unit vs. multi-unit SPRA) and the risk importance of the subject SSCs, it may be desirable to capture fragility correlations in a more realistic manner than the current state of practice.

This paper outlines a practical approach to quantify the degree of partial correlation ("fragility correlation coefficient") between the fragilities of similar SSCs. The approach captures the advantages of both rigorous and judgement-based approaches while minimizing their disadvantages. The proposed approach is relatively straightforward to implement with minimal engineering effort and tries to reduce the impact of variability typical of judgement-based approaches. This is demonstrated through an example implementation presented in this paper. It is expected that the practical nature of the proposed approach will encourage a more realistic treatment of seismic fragility correlations in SPRAs, thus advancing the state of practice and enhancing the quality of risk insights gained from the SPRAs.

SEISMIC FRAGILITY CORRELATION

Seismic fragility for a given SSC is typically described using a lognormal distribution in current practice, characterized by a median ground acceleration capacity and associated variability (EPRI, 2018). The median ground acceleration capacity is the product of several random variables that influence the SSC demand and capacity, e.g., structure response, equipment response, and equipment strength. The variance in the ground acceleration capacity is then the sum of variances of these random variables. Therefore, partial correlation in any of these fragility variables entails partial correlation in the ground acceleration capacity proportional to each variable's share of the total variance.

The determination of the degree of fragility correlation between related SSCs is the first step in incorporating the effect of partial fragility correlations in an SPRA. Once the degree of partial fragility correlation has been established, a partially correlated fragility for the related SSCs can be developed following the Separation of Independent and Common Variables (SICV) approach in NUREG/CR-7237

(Budnitz et. al, 2017). Conceptually, the determination of the degree of partial fragility correlation can be performed rigorously using techniques such as simulation and testing. For example, correlation coefficients for structure response variables can be statistically derived from a properly randomized probabilistic seismic response analysis of a structure or multiple structures (e.g., Talaat and Kennedy, 2019). Some of these rigorous methods were benchmarked in past research work, the most significant being the Seismic Safety Margins Research Program (SSMRP) sponsored by the U.S. Nuclear Regulatory Commission (NRC) at the Lawrence Livermore National Laboratory in the late 1970s (e.g., Cummings, 1986; Wells et. al, 1981). Application of these methods to actual NPP SPRAs in the current state of practice has been very limited (a recent example can be found in Talaat and Kennedy, 2019) because of the high computational costs and engineering effort associated with these methods. Instead, either perfect correlation or no correlation is typically assumed, and at most, a sensitivity analysis is performed to assess the influence of this binary assumption. However, a meaningful estimate of the seismic risk may require a more realistic characterization of fragility correlation between SSCs required for safe shutdown than the usual assumptions of either perfect correlation or uncorrelation. This is even more critical in multi-unit SPRA studies, which have been gaining interest in recent years. It is expected that a major factor driving the seismic risk in a multi-unit SPRA could be the degree of correlated failures between the individual units. Consequently, proper treatment of partial fragility correlations is necessary for a realistic estimate of multi-unit risk.

A relatively simplified and practical approach is presented in this paper to establish the appropriate degree of partial fragility correlation for related SSCs. The group of related SSCs can be within a single unit in the case of traditional single-unit SPRAs or across multiple units in the case of multi-unit SPRAs.

APPROACH

The degree of fragility correlation between two SSCs can be represented by a "fragility correlation coefficient" ρ, defined as (Reed et. al., 1985):

$$\rho = \frac{(\beta^*)^2}{\beta_1 \beta_2} \tag{1}$$

Where β_1 and β_2 are fragility variabilities (logarithmic standard deviations) associated with SSCs 1 and 2, and β^* is the common or "correlated" portion of β_1 and β_2. Note that ρ, β_1 and β_2 can correspond to the total fragility variabilities or to a particular fragility variable, e.g., equipment response. The value of ρ in Eqn. (1) varies from zero to one, zero implying no fragility correlation, and one implying perfect fragility correlation. A simple, qualitative sliding scale of the degree of fragility correlation may be defined as suggested in Table 1.

Table 1: Qualitative Scale for Degree of Fragility Correlation.

Degree of Fragility Correlation	ρ
None	0
Weak	0.2
Moderate	0.5
Strong	0.8
Perfect	1

Eqn. (1) splits a given variability into a common (perfectly correlated) portion and an independent portion. The independent portion represents variability that is specific to individual SSCs and not reduced by demonstrating similarity to one or more other components within the group. For example, if ten nominally "identical" steel specimens are tested in a universal testing machine under the same conditions, some variation in the test capacities will still be observed. Assuming that the tests are properly controlled such that variations in all other variables (e.g., execution of the test procedure) are negligible, the observed variation in test capacities represents variability that is independent in nature.

For a given pair of SSCs, two types of fragility correlation coefficients can be defined: ρ_R and ρ_U. The former relates the logarithmic standard deviations for randomness (β_R) between the SSCs, while ρ_U relates the logarithmic standard deviations for uncertainty (β_U). In general, ρ_R may not be identical to ρ_U. However, if either one of the randomness and uncertainty contributions to the variability is small compared to the other for a given variable, differentiating between ρ_R and ρ_U has no significant effect on the mean fragility representing the partially correlated failures of the SSCs.

By judging the degree of correlation for the individual fragility variables, the fragility analyst can compute the associated common/perfectly correlated portions (β^*) using Eqn. (1). These correlated portions can be combined using the square root of the sum of squares (SRSS) to yield the total β^*, which can be then used to compute the total fragility correlation coefficient ρ using Eqn. (1). This approach is practical since making fragility correlation judgements on individual fragility variables is typically easier than directly judging an overall fragility correlation coefficient. This is illustrated by the following example.

EXAMPLE

Table 2 illustrates how a fragility correlation coefficient can be computed following the above approach for a fragility group of two distribution panels. The two panels are located in the same building, at the same elevation, but in different rooms. The panels have similar design, similar installation and anchoring, and similar orientation (i.e., along the same direction). A bounding seismic fragility governed by functional failure was developed for the fragility group, described by a median seismic capacity (A_m) of 1.16g, β_R of 0.24, and β_U of 0.45. The contributions to the β_R and β_R values from the main fragility variables are shown in the first three columns on Table 2.

In Table 2, a fragility correlation coefficient is judged for each of the three high-level fragility variables from Eqn. 3-16 of EPRI (2018). The associated common correlated portion (β^*) is computed following Eqn. (1). In the table, $\rho = \rho_R = \rho_U$ is implicitly judged for each variable for the sake of simplicity in this example illustration. The β^* values are combined using SRSS to yield the total β^* for randomness and uncertainty, from which the overall fragility correlation coefficients ρ_R and ρ_U can be computed as:

$$\rho_R = \frac{0.18^2}{(0.24)(0.24)} = 0.6$$

$$\rho_U = \frac{0.36^2}{(0.45)(0.45)} = 0.6$$

The high-level fragility variables analysed in Table 2 can be decomposed into sub-variables per Eqns. 3-17 through 3-19 of EPRI (2018). A similar fragility correlation analysis can be performed at the more refined level of the sub-variables for risk-significant SSCs, if warranted.

Table 2: Example Fragility Correlation Analysis.

Fragility Variable	β_R	β_U	Correlation Coefficient ρ		β_R*	β_U*
			Judged Value	Qualitative Basis		
Equipment Capacity	0.09	0.32	0.8	Both panels are seismically qualified by the same test data, and variability in the capacity is for the range of panels configurations that can be represented by this seismic qualification test. The construction of the individual panels, though not identical, is very similar. The boundary conditions provided by the field anchorage configuration are nominally identical. The capacity variables are therefore judged to be strongly correlated.	0.08	0.29
Equipment Response	0	0.12	0.2	The associated variability is governed by the spectral clipping variability. Due to the difference in the bandwidth of the input spectra at the locations of the individual cabinets, the associated correlation is judged to be weak.	0	0.05
Structural Response	0.22	0.30	0.5	The panels are in the same building and at the same elevation, with the same orientation. However, they are in different rooms with significant independence in the governing input spectra such that a strong correlation cannot be justified. The structural response variables are judged to be only moderately correlated.	0.16	0.36
Total (SRSS)	0.24	0.45			0.18	0.36

Following the quantification of the total correlated variabilities β_R* and β_U* using Eqn. (1), the desired partially correlated fragility can be computed using the SICV approach in NUREG/CR-7237 (Budnitz et. al, 2017). Alternative methods for computing the correlated fragility include Monte Carlo simulation and the Tail-Oriented Multi-Normal Model method described in Talaat and Anup (2022). Figure 1 shows the partially correlated union and joint fragilities for the distribution panel pair. The union fragility corresponds to failure of any one of the two distribution panels (i.e., the union of two failure events), while the joint fragility corresponds to the concurrent failures of the two panels (i.e., the "intersection" of two failure events). The fragilities shown in the figure are mean fragilities, i.e., based on composite variability and not associated with a particular confidence level (e.g., the 95% confidence curve). The figure also compares union and joint fragility solutions under partial correlation to those under perfectly correlated and uncorrelated fragility idealizations. When perfectly correlated, the union and joint fragilities are the same and as such, only a single curve is shown in the figure.

Figure 1 highlights the importance of proper treatment of fragility correlations in an SPRA. Idealization of the correlation as perfectly correlated would have resulted in unconservative characterization of the failure probabilities for concurrent failures, while the perfectly uncorrelated idealization would have resulted in an unconservative union fragility. At the same time, a perfectly uncorrelated idealization for the joint fragility can result in considerable conservatism, and likewise for a perfectly correlated idealization for a union fragility. If the example distribution panels are risk-significant, then a binary idealization of their fragility correlation can have a potentially significant impact on the single- or multi-unit seismic risk.

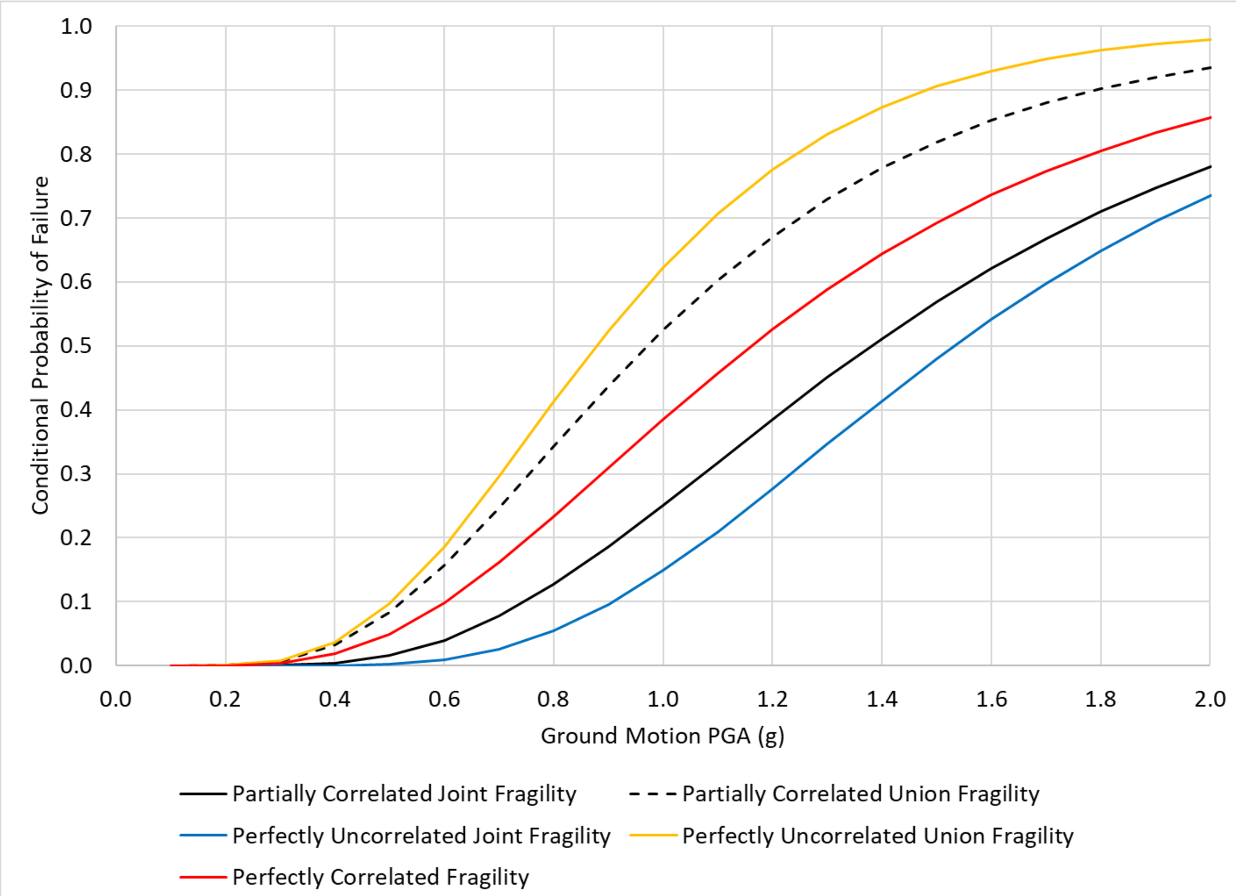

Figure 1. Mean Partially Correlated, Fully Correlated, and Uncorrelated Fragilities for Example Distribution Panels.

APPLICATION GUIDANCE

When performing a fragility correlation analysis like the example illustrated in Table 2, the fragility analyst's judgement on the degree of correlation (ρ) for the underlying fragility variables should be influenced by several component- and plant-specific factors, and will require familiarity with the SSCs (e.g., understanding of walkdown observations), details of the fragility analysis (e.g., structure response and SSC failure mechanism), and ground motion input to structures (e.g., SSI effects). Insofar as the correlation estimates are based partially on judgement, as opposed to rigorous computation, the process will also require that the analyst have in-depth experience performing fragility analyses in general. Previous research led by Sandia National Laboratory (SNL) developed qualitative guidance for assigning correlation coefficients to structure and equipment response variables for typical nuclear power plant configurations. These so-called "rules of thumb" were compiled in Table 3.1 of NUREG/CR-4840 (SNL, 1990) and adopted in a U.S. NRC-sponsored report on severe accident risks, which included SPRA studies of two pilot NPPs in NUREG-1150 (U.S. NRC, 1990). They offer simple guidelines to judge an appropriate correlation coefficient. Further detailed guidance and discussion is provided in EPRI (2021).

While the proposed approach relies on engineering judgement of the fragility analyst, the overall results (the partially correlated fragility) are typically only moderately sensitive to the precision in the judged correlation coefficients for individual fragility variables. The impact of variation in the judgements of different fragility analysts using the approach is thus reduced. Furthermore, the variation in judgements between different fragility analysts for the individual fragility variables is expected to be smaller than the variation if the overall ρ_R and ρ_U values were to be judged directly, more so when the detailed guidance provided in EPRI (2021) is followed. The proposed bottom-up approach is therefore expected to give reasonably consistent results when used by experienced fragility analysts.

LIMITATIONS

The simplified approach presented in this paper is applicable to positive partial fragility correlations only. Negative correlation is not common for seismic fragilities and typically will not be a high priority in single- or multi-unit SPRAs except in special cases (e.g., where one failure mechanism tends to preclude another).

CONCLUSION

This paper outlines a practical approach to estimate the fragility correlation coefficient to quantify the degree of partial correlation between the fragilities of similar SSCs. The proposed approach is relatively easy to implement, and while involving engineering judgement, is expected to give reasonably consistent results when used by experienced fragility analysts. The authors hope that the practical nature of the proposed approach will encourage a more realistic treatment of seismic fragility correlations in SPRAs, thus advancing the state of practice and enhancing the quality of risk insights gained from the SPRAs.

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