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PILOT STUDY INCORPORATING SHAKE TABLE TESTS AND EARTHQUAKE EXPERIENCE DATA TO DEVELOP EQUIPMENT CAPACITIES FOR USE IN FRAGILITY CALCULATIONS

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ABSTRACT

Seismic capacities for use in seismic probabilistic risk assessments (SPRAs) or seismic margin assessments (SMAs) at nuclear power plants (NPPs) are typically evaluated using shake table test (STT) data, earthquake experience, or analysis. Each of these methods have conventionally been treated as mutually exclusive (e.g., a capacity is developed based on STT or earthquake experience data but not both). However, since both STT and earthquake experience data are based on empirical equipment performance, it may be feasible to develop capacities based on the combined experience to achieve a more complete understanding of the equipment capacity. Recent advances in earthquake experience-based methods (e.g., Electric Power Research Institute (EPRI) 3002011627 (2017a)) provide a convenient framework for incorporating test data with earthquake experience data. In 2014, EPRI initiated a multi-phase project to review the available earthquake experience data (eSQUG v2.7, EPRI (2017b)) and apply improved Bayesian statistical methods to update the function-after seismic capacities of sixteen equipment classes. Updated best-estimate median capacities increased by up to 37% over the previous median in-structure spectral acceleration capacity of 4.8g. Phase III of the project (EPRI 3002015996 (2019)) evaluated the use of STT data to further improve the capacity from experience data for a sample class (Control Panels). This paper summarizes the main findings of that pilot study, including addressing several important differences between the STT and earthquake experience data types, and identifying potential challenges in the collection and use of different STT data sets.

BACKGROUND

Phase I of this project (EPRI 3002011627 (2017a)) reviewed previous earthquake experience methods (e.g., EPRI NP-6041-SLR1 (1991a), EPRI 3002012994 (2018a)), improves the *frequentist* approach used in past EPRI studies, and introduces a new *Bayesian* inference statistical framework. The two statistical techniques (frequentist and Bayesian) are examined by developing and comparing capacities for eight classes: Control Panels, Engine Generators, Fans, Horizontal Pumps, Inverters and Battery Chargers, Motor Control Centers, Motor-operated Valves, and Medium Voltage Switchgear. The study concludes that the Bayesian capacities are more realistic, data driven, and capable of incorporating expert experience, and therefore recommends they be treated as best-estimates for fragility evaluation in SPRAs. Phase II of the project (EPRI 3002013017 (2018b)) uses the same Bayesian approach to develop capacities of eight additional classes: Air Compressors, Air-operated Valves, Batteries on Racks, Distribution Panels, Instruments on Racks, Low Voltage Switchgear, Transformers, and Vertical Pumps. Updated best-estimate median capacities for these sixteen classes increase by up to 37% over the previous median in-structure spectral acceleration capacity of 4.8g. Updated high confidence of low probability of failure (HCLPF) capacities increased by up to 47% for these same sixteen classes. To support augmenting the earthquake experience with STT data, the Phase III pilot study addresses several important differences between the two data types, including:

- STTs are performed on discrete test specimens of a particular manufacturer and model number. Multiple tests can address multiple manufactures and/or model numbers but typically the number of STT specimens is more limited than earthquake experience data. At the same time, the information about the test specimens and test performance may be better defined. In this study, the equipment class descriptions, inclusion rules, and caveats are reviewed to assess whether they would require updates if STT data were included.
- Compared to earthquake experience, STT data are typically associated with greater mounting-point accelerations. As such, STT data offer the benefit of additional data at higher acceleration levels, where the earthquake experience data is relatively sparse.
- Test response spectra (TRS) are recorded at the equipment mounting point, whereas earthquake experience data typically include only ground motions. The methodology developed in EPRI 3002011627 (2017a) includes structural amplification factors to estimate mounting-point accelerations for earthquake experience data.
- STT inputs may be defined by single-axis or biaxial target spectra with a range of damping ratios. Seismic input in the experience database is represented by 5% damped response spectra, and the natural earthquakes had three directional components of random motion. The TRS must therefore be adjusted to account for the different seismic input conditions and damping ratios.
- STTs include two distinct test approaches: qualification tests and fragility tests. Qualification tests generally involve a test performed at a target spectral acceleration level, while fragility tests subject the equipment to incrementally increasing excitation levels until the equipment fails. Qualification tests are analogous to actual earthquake performance data since both involve shaking at one defined level, and the result is binary – either a failure or a survival. Fragility tests, however, provide different statistical insights and should be treated differently in the Bayesian inference framework used to develop experience-based capacities.

This pilot study evaluates the above aspects by investigating the use of STT data to augment earthquake experience-based capacities for a sample class (Control Panels).

SHAKE TABLE TESTS

Several sources of STT data for use in enhancing earthquake experience-based seismic capacities were initially identified and reviewed:

- STT data used to develop the Generic Equipment Ruggedness Spectra (GERS) in EPRI NP-5223-SLR1 (1991b).
- U.S. Nuclear Regulatory Commission (USNRC) seismic test programs, published by Brookhaven National Laboratory (BNL) in NUREG/CR-4659 Volumes 1 to 4 (BNL (1986, 1987, 1990, 1991)).
- Seismic Qualification Reporting and Testing Standardization (SQURTS) test results as summarized in EPRI 3002010668 (2017c).
- Japan Nuclear Energy Safety Organization (JNES) equipment fragility testing program, reviewed in NUREG/CR-7040 (USNR, 2011).
- California Department of Health Care Access and Information (HCAI) database of seismic certification testing for healthcare facilities (2018).
- Other testing programs (e.g., research groups, testing companies, NPP utilities).

Each STT program has unique objectives and investigates a particular set of equipment and testing configurations. EPRI 3002015996 (2019) provides details on their specific setup and results. Among these sources, the GERS and BNL STT data were most useful for the following reasons:

- These programs tested several specimens for multiple equipment classes, providing an opportunity to incorporate population diversity.
- Tested equipment is similar to typical NPP installations and to earthquake experience data equipment.
- Equipment was generally tested at relatively high spectral accelerations.

SELECTION OF PILOT EQUIPMENT CLASS

Phases I and II (EPRI (2017a, 2018b)) developed experience-based capacities for sixteen equipment classes, which were a mix of mechanical and electrical equipment. The Control Panels class was ultimately selected as the pilot class for the following reasons:

- The Control Panels class had the greatest number of combined GERS and BNL data.
- The GERS and BNL Control Panel data contains both qualification and fragility tests and a variety of failures and anomalies, which were judged valuable to include in the pilot effort to fully assess the capacity evaluation methodology.
- Control panels are often important risk contributors to seismic core damage frequency (SCDF).

CAPACITY CALCULATION INPUTS

The Control Panel experience capacity is augmented with GERS and BNL STT data using the Bayesian approach documented in EPRI 3002011627 (2017a). To this end, three key inputs must be defined for the Bayesian updating calculation:

- *Prior distribution* representing the current state of knowledge of the seismic capacity.
- *Likelihood function* to incorporate new failure and survival data with the current knowledge.
- *Equipment performance data*, which includes the number of independent samples, their outcome (e.g., failure or survival), and corresponding mounting-point spectral demand.

Prior Distribution

EPRI 3002011627 (2017a) defines the prior as a joint lognormal distribution with logarithmic standard deviations β_{Cm} and $\beta_{\beta m}$ representing uncertainty in the best-estimate values of C_m and β_{Cm}, respectively, where C_m is the best-estimate prior median 5% damped in-structure spectral acceleration capacity and β_C is the best-estimate logarithmic standard deviation on C_m:

C_m = 4.80g
β_C = 0.42
β_{Cm} = 0.42
$\beta_{\beta C}$ = 0.20

EPRI 3002011627 (2017a) updates this prior using 186 independent control panel survival records from the eSQUG v2.7 database (EPRI (2017b)) and computes the following posterior experience capacity:

C'_m = 6.37g
β'_C = 0.40

EPRI 3002011627 (2017a) indicates that the analytical form of the posterior distribution is nontrivial because its shape is not necessarily the same as the prior (i.e., not joint lognormal). This study therefore uses the same prior as EPRI 3002011627 (2017a) and performs a single update with the combined earthquake and test experience data, instead of augmenting the posterior with just STT data. Additional discussion on the topic is included in EPRI 3002011627 (2017a).

Likelihood Function

The likelihood function used in this pilot study is from EPRI 3002011627 (2017a). It quantifies the likelihood of observing the test outcomes given a set of fragility parameters. The function is formulated to account for data that are neither clearly survivals nor failures (i.e., some confidence (Q) of representing a failure, $0\% < Q < 100\%$), which facilitates the incorporation of fragility test data, as discussed later in this paper. The likelihood function operates on the following input parameters for each dataset:

- n = number of independent components tested at a given acceleration level.
- f = number of failures ($f \leq n$).
- amb = number of ambiguous observations (i.e., data that are not clearly a survival or failure), which are assigned a $0\% < Q < 100\%$ confidence of representing a failure ($amb \leq n$).
- Sa_{bl} = local broad-banded spectral acceleration level (i.e., the equipment mounting-point demand); for earthquake experience data, EPRI 3002011627 (2017a) uses the 2.5 to 7.5 Hz average spectral demand scaled to account for structural amplifications; structural amplifications are not needed for STT data if the equipment is mounted directly on the shake table.
- P_F = probability of an independent component failing at acceleration level Sa_{bl}, given a pair of capacity distribution parameters C_m and β_C.

EPRI 3002011627 (2017a) provides details of the likelihood function development and interpretation.

Equipment Performance Data

The equipment performance data used to update the prior distribution were assembled from the 186 control panel earthquake experience records documented in EPRI 3002011627 (2017a) and the applicable GERS and BNL STT data. Table 1 shows forty-four samples available from the GERS and BNL programs. A variety of technical challenges exist when interpreting and incorporating older STT data such as GERS and BNL tests into the Bayesian updating process. This section summarizes the “base case” technical criteria developed by the authors of this study, which represent a reasonable approach given the limited documentation available. Capacity results developed using the “base case” criteria are documented in the following section, after which several sensitivity studies are presented using alternative criteria.

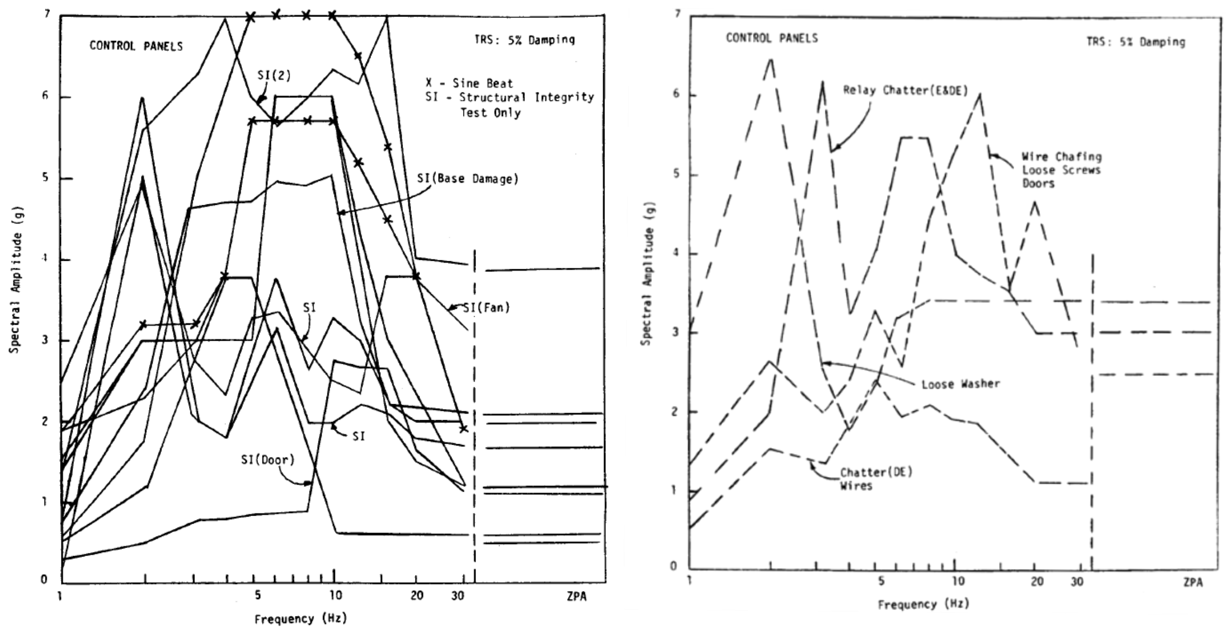
Table 1: Control Panel Data from GERS and BNL STT Programs.

Program	Samples
GERS	16
BNL NSSS[1] I&C[2] (Volume 3)	13
BNL BOP[3] I&C (Volume 4)	15
Total STT Data	44

[1] NSSS = nuclear steam supply system
[2] I&C = instrument and control panels
[3] BOP = balance of plant

Figure 1 shows the GERS TRS data available for Control Panels: 12 survival data and 4 anomalies. These TRS were standardized in EPRI NP 5223-SLR1 (1991b) to 5% damped multi-axis random input motions using frequency-independent scaling factors. This standardization process is consistent with the testing procedure in IEEE 344 (1975) and the experience-based capacities developed in EPRI 3002011627 (2017a). As such, no correction was applied to the GERS TRS for this pilot study. A review of the equipment characteristics, design vintage (1974 or later), mounting configurations, and fundamental frequency (8 to 16 Hz) suggests that all the tested panels comply with the SQUG class caveats and criteria

(SQUG (2001)). The GERS panels are therefore judged substantively similar to the panels in the experience database. Three of the four anomalies did not affect the equipment function after testing, and therefore are treated as survivals. One anomaly record was discarded because it was caused by a loose washer, which would be prevented in normal nuclear quality installation and maintenance programs. Each GERS TRS represents a separate qualification test and can therefore be considered an independent sample. Being qualification tests, the TRS 2.5-75 Hz average spectral acceleration is equivalent to the local broad-banded demand (Sa_{bl}) computed for earthquake experience in EPRI 3002011627 (2017a). EPRI 3002015996 (2019) provides further details on the GERS standardization procedure and equipment performance interpretation process.



(a) Survivals (b) Anomalies

Figure 1. GERS Survivals and Anomalies Test Response Spectra for Control Panels.

BNL control panel data are available from Volume 3 (NSSS I&C panels) and Volume 4 (BOP I&C panels) (BNL (1990, 1991)). TRS are typically not provided. Results in Volumes 3 to 4 are reported in terms of average spectral acceleration (ASA) capacities in the 4-16 Hz frequency range. For this feasibility study, the 4 to 16 Hz average test capacity is judged a reasonable analog to the 2.5 to 7.5 Hz average spectral demand used for earthquake experience data and GERS. In one sense, treating the 4 to 16 Hz capacity as equivalent to the 2.5 to 7.5 Hz capacity is conservative, since the former has a broader bandwidth, which is generally considered to be more damaging. In another sense, it may be somewhat unconservative since the higher frequency input is generally considered to be less damaging than lower frequencies. It is not obvious whether the net effect is slightly conservative or slightly unconservative, but for the purposes of this study, treating the two as equivalent is convenient and does not affect the overall conclusions, as discussed later.

The NSSS I&C units were tested between 1971 and 1981 and had characteristics compatible with the class caveats and criteria in GIP-3A (SQUG (2001)). The BOP I&C panels are self-standing enclosures fabricated between 1978 and 1985. Equipment frequencies and dimensions are not provided. The tested panels likely comply with the caveats and criteria in GIP-3A (SQUG (2001)) since the BNL programs were intended to develop NPP equipment capacities. The NSSS STTs were either qualification, fragility, or structural integrity tests. For the purpose of this study, BNL qualification and structural integrity tests are considered survivals similar to the TRS provided in the GERS report. In contrast, fragility tests are incorporated into the Bayesian update by treating the ASA at which an anomaly was induced as having

50% confidence of representing a failure (i.e., Q = 50%). The justification for such treatment is discussed in detail in EPRI 3002015996 (2019). This data treatment may be conservative because some fragility tests were terminated and ASA capacities reported upon observing an anomaly that would not have caused a loss of function after shaking.

The BOP I&C data include qualification and fragility tests. The ASA results are provided, but the testing procedure (qualification or fragility test) is not explicitly identified. Volume 4 suggests that the ASA capacities were initially determined (denoted "test data") and then subsequently revised to estimate the "fragility level input data." The revision process involved judgement to incorporate information from test reports and interviews. For example, the ASA capacities for qualification tests were increased by 10 to 30% to estimate the corresponding fragility levels and decreased by 10 to 20% if the cabinets were modified from their original manufactured condition before testing. This revision process information was used to postulate whether a test was a fragility or qualification test. Consistent with NSSS data, BOP fragility tests are assigned a confidence of failure Q = 50%. A 20% capacity reduction is conservatively applied to panels with modifications. EPRI 3002015996 (2019) discusses the revision process in detail. The BNL capacities are provided at 2% damping and must be converted to 5% damping. EPRI 3002015996 (2019) provides the frequency-dependent scale factors used for such conversion. No conversion was needed for input vibration conditions since the ASA capacities were computed from converted spectra that are analogous to ground motion records in the experience database in terms of input directions and frequency content (multi-axial random vibration). Table 2 lists a subset of the GERS and BNL data included in the calculations and the associated confidence of failure, Q. The full list of forty-four STT data evaluated in this pilot study is included in EPRI 3002015996 (2019).

Table 2: Pilot Study Equipment Performance Data (subset of data in EPRI 3002015996 (2019)).

Test Group	Test No.	ASA (g)[a]	Sa_{bl} (g)[b]	Confidence of Representing a Failure Q (%)[c]	Test Configuration
GERS	1	-	3.02	0	Qualification
	2	-	4.81	0	Qualification
	4	-	6.08	0	Qualification
BNL Vol. 3	1	7.5	5.56	50	Fragility
	2	7.4	5.48	50	Fragility with anchorage modifications
	3	4.7	3.48	0	Qualification
	4	5.0	2.96	0	Qualification with modifications
	5	6.3	4.67	0	Structural Integrity
BNL Vol. 4	1	6.0	4.44	50	Fragility
	2	9.0	6.67	50	Fragility
	3	5.0	3.70	0	Qualification
	4	4.0	2.96	0	Qualification

a) 2% damping
b) 5% damping
c) 0% confidence of representing a failure is equivalent to a survival

BASE CASE CAPACITY

The likelihood function and the prior distribution are used to update the Control Panels capacity by incorporating the earthquake and test experience data presented in the previous section. This case is referred to as "Base Case" in Table 3 (Case 1). The best-estimate prior capacity (Case 2) and the posterior experience-based capacity from EPRI 3002011627 (2017a) (Case 3) are also included in Table 3 for comparison. The median (C_m) and 1% probability of failure ($C_{1\%} \approx$ HCLPF) capacities including test and earthquake experience data are increased by 13% and 5%, respectively, over that including only experience data. The composite variability is slightly increased.

Table 3: Control Panel Capacities Including Test and Earthquake Experience Data vs Past Studies.

Case	Data	Samples	C_m (g)	β_C	$C_{1\%}$ (g)
1	Base Case in Current Pilot Study (including 186 Earthquake Experience Data + 43 Test Data)	229	7.21	0.43	2.66
2	Best-Estimate Posterior Capacity in EPRI 3002011627 (2017a) (including 186 Earthquake Experience Data)	186	6.37	0.40	2.53
3	Best-Estimate Prior Capacity	-	4.80	0.42	1.80

SENSITIVITY STUDIES

EPRI 3002015996 (2019) includes five sensitivity studies to investigate the importance of various judgments and technical criteria used in the base case analysis:

(a) Exclude BNL data from the Bayesian update (assumes GERS are higher quality data)
(b) Include BNL and GERS data and exclude experience data (checks contribution of STT data)
(c) Exclude structural integrity data (assumes function-after of subcomponents was not verified)
(d) Omit 20% reduction for BNL ASA capacities for panels with modifications
(e) Conservatively decrease the BNL fragility test ASA capacities by 10%

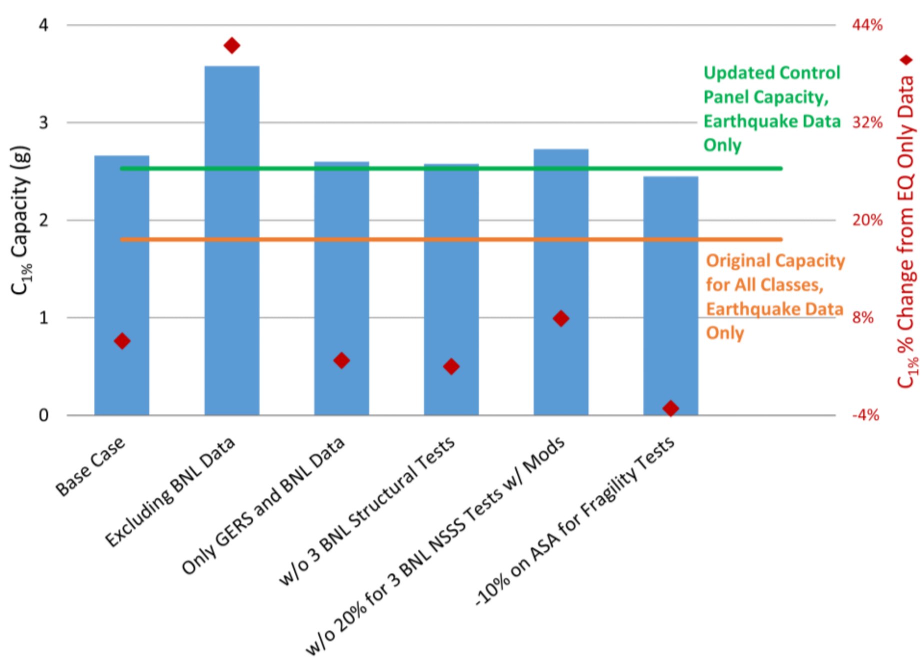


Figure 2. Summary of the Sensitivity Study Results.

Figure 2 provides a summary of the $C_{1\%}$ capacities for each case shown in vertical bars. The horizontal lines represent the capacities from EPRI 3002011627 (2017a) before and after Bayesian updating with earthquake experience data only. The percent difference of each case from the EPRI 3002011627 (2017a) updated earthquake-experience based capacity (green line; Case 2 in Table 3 above) is shown as red diamonds. These sensitivity studies demonstrate that the Control Panels seismic capacity is relatively stable using different sets of technical criteria. EPRI 3002015996 (2019) provides additional details of the five sensitivity studies setup and interpretation.

REVIEW OF POTENTIAL RESTRICTIONS

Both GERS and BNL reports recognize the limited sample of tested equipment and configurations may not be representative of all the cabinets installed in nuclear plants. Therefore, they recommended that a series of criteria be satisfied before the STT results are applied to a nuclear installation. These include restrictions on equipment vintage, diversity, modifications, installation and maintenance requirements, and anchorage and relay reviews. EPRI 3002015996 (2019) reviews these restrictions and recommends the following caveats applicable to the Control Panels capacity developed in the pilot study:

- The panel must be manufactured in 1971 or after, or its design demonstrated to be structurally/functionally similar to that of post-1971 equipment.
- All wiring must be properly insulated to prevent contact shorts.
- Wiring and cabling inside of the control panel must be visually inspected, and a restraint provided if large deformation can be induced based on the determination of the two Seismic Capability Engineers performing the walkdown review.

These criteria should be combined with the SQUG caveats for Control Panels included in GIP-3A (SQUG (2001)). Similar reviews should be completed when combining STT data with earthquake experience data to develop updated capacities.

CONCLUSIONS

This pilot study confirms that the Bayesian update process developed in EPRI 3002011627 (2017a) can be used to combine earthquake experience and STT data into a composite equipment class capacity for use in seismic fragility evaluations. The use of older test data presents some complications in determining the appropriate test specimen capacities and in understanding the test anomalies and failures. Sensitivity studies can be used to understand the significance of these issues.

A “base case” assessment is conducted for the Control Panels equipment class. The earthquake experience data include 186 independent survivals from fifty-seven sites and nineteen earthquakes spanning 1971-2010 (EPRI, 2017b). The test data represent fifteen different manufacturers and vintages from 1971 to 1985. The combined experience database includes 229 samples. The addition of STT data increases the number of independent experience data samples by 23%, improves the diversity of the database, incorporates higher acceleration levels where the earthquake experience data is relatively sparse, and accounts for both failure and survival data.

The base case median (C_m) and 1% probability of failure ($C_{1\%} \approx$ HCLPF) capacities are 13% and 5% higher, respectively, than the EPRI 3002011627 (2017a) earthquake experience-based capacities, as shown in Table 3. The results for this equipment class suggest that augmenting the earthquake experience data with test experience only marginally increases the capacity beyond that developed using earthquake experience alone. Nevertheless, for other classes with fewer earthquake experience records, lower database site demands, more test samples, or higher test acceleration levels, augmenting earthquake data with test experience could have a more significant effect.

The focus of this study was to assess the technical challenges associated with using test data to refine earthquake experience-based equipment capacities. While the study achieved the intended goals, there are too many uncertainties in some areas of the older test data interpretation to recommend using the base case updated Control Panels seismic capacity in SPRAs or SMAs. Some of the challenges identified as part of this study include:

- Documentation in older test data is frequently insufficient to objectively discern failures from anomalies or incidental effects in the tests.
- The TRS are not always readily available for each test reported.
- The BNL test capacities are typically referenced to a broader and higher-frequency average spectral acceleration range (4 to 16 Hz) than that used to characterize the earthquake experience-based capacity (2.5 to 7.5 Hz).
- Capacity conversion factors for damping and input direction can lead to some uncertainty in the credited capacities.
- Modifications to the test specimens can lead to some uncertainties in determining the appropriate sample capacity.
- There is some uncertainty as to whether some structural integrity tests were accompanied by separate tests of the cabinet internals to the same acceleration level, and therefore incorporating these tests into the overall equipment class capacity is not always straightforward.
- There is also uncertainty in the confidence of failure assigned to qualification and fragility tests.
- Equipment vintage, diversity, modifications, installation and maintenance requirements, and anchorage and relay review processes should be investigated in detailed to define additional class caveats resulting from the combined use of STT and earthquake experience data.

The challenges identified above are consequences of the limited documentation available for the older test data. If newer test data were available with more complete documentation, the capacities developed could be considered more reliable and potentially recommended for use in SPRAs or SMAs.

Given this proof of concept, the following recommendations are provided to advance this research effort:

- Determine the equipment classes where the potential for increased seismic capacities beyond the results using only earthquake experience data would be the most valuable.
- Explore the available STT data for the applicable classes including, but not limited to, the testing programs reviewed in this report.
- Provided adequate test data is available in the important classes, pursue updated equipment class capacities with combinations of earthquake experience data and STT data using, for example, the methods and sensitivity studies described in this paper.
- Consider improvements in the interpretation of qualification and fragility test data and the method for including them in the Bayesian update. For example, this study considered the database demands as being deterministic (i.e., no variability) as a simplifying approximation. A future improvement could be to reformulate the Bayesian update to explicitly account for uncertainty in database demands (both earthquake and STT data).

A recent Korea Atomic Energy Research Institute (KAERI) project (Choi et al., 2021) applied the lessons learned from this pilot study to re-evaluate the capacity of a 480V MCC using South Korea earthquake experience and STT data. That example showed that significant capacity increases are achievable using the process described in EPRI 3002011627 (2017a) and EPRI 3002015996 (2019). The same Bayesian updating process developed in this multi-phase EPRI project could be considered for other applications, for example, using different demands (e.g., PGA, displacement) or hazards (e.g., wind, wave loads).

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