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A COMPUTATIONAL APPROACH TO STREAMLINE DETERMINISTIC SAFETY ANALYSIS AND FRAGILITY ANALYSIS OF STRUCTURES, SYSTEMS AND COMPONENTS (SSCs) FOR NUCLEAR POWER PLANT (NPP)

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ABSTRACT

This paper describes an approach to streamline the calculations to perform deterministic safety analysis (DSA) and fragility analysis (FA) of structures, systems and components (SSCs) of a nuclear power plant (NPP). The DSA and FA calculations are performed for the components in the plant safe shutdown paths and in the seismic equipment list (SEL) associated with the seismic probabilistic risk assessment (SPRA). The objective is to develop tools for standardization and maintenance of fragility information for future plant uses (e.g., PSA updates). The calculations use seismic ground motions corresponding to the seismic hazard definitions. Traditionally, these calculations are performed using Mathcad or similar calculation platforms. This typically engages a fair amount of staff resources, cost and time particularly if the SEL contain many components. Also, the manual calculations are prone to inconsistencies which can adversely affect the results and overall risk insights. Nevertheless, it is recognized that similar steps are repeated for deterministic seismic verification and fragility analysis. In addition, the DSA and FA may need to be periodically repeated (e.g., when seismic hazard is updated).

Modern tools and technologies can be used to streamline and automate both the repetitive steps within the calculations and to repeat the calculations for new seismic hazards. The approach to streamline and automate can help in efficient use of resources and maintain the consistency within the calculations and between the calculations. This paper presents an approach used to automate the seismic evaluation for electrical components, mechanical components and structures using plant specific information. This paper illustrates by means of an example the automation approach.

INTRODUCTION

This paper presents an approach to streamline and automate the calculations in support of deterministic safety analysis (DSA) and fragility analysis (FA) of structures, systems and components (SSCs) of nuclear power plants (NPPs). The objectives of the automation to address the seismic evaluation electrical and mechanical components calculations is presented in Korlapati et al. (2021). The present paper extends the work to structural calculations. The automation methodology helps in optimizing the resources in periodic safety reviews and in the assessment of plant modifications.

The approach is implemented in and is supported by several MATLAB (MATLAB (2020)) scripts to perform various calculation specific tasks and by developing databases to store the component specific information. Most of the NPPs have in house plant databases with various component specific information such as walkdown pictures, design test report information. These plant databases can be directly linked and can be used to support periodic plant seismic safety assessment. The approach to streamline the automation of the calculations is presented in detail in the following sections. The template of a sample calculation generated by applying the approach is presented in this paper to illustrate the effectiveness of the proposed methodology.

GENERAL METHODOLOGY FOR DSA AND FA

The automation process has been recently used for a NPP to perform deterministic verification and fragility analysis of plant SSCs. In accordance with industry practice and regulatory guidelines in ENSI-AN-8567 (ENSI-AN-8567 (2014)), both the DSA as well as the FA of SSCs evaluate three (3) failure modes namely, functional failure, structural integrity and anchorage failure. The intent is to develop seismic margins to failure, where, in general, failure of a component is defined broadly as the loss of component function. The evaluation of each failure mode examines the component design basis capacity and failure level capacity for the DSA and FA, respectively. Similarly, the seismic demand is based on the 84th percentile and 50th percentile response quantities (seismic loads on structural components and floor response spectra (FRS)) for the DSA and FA, respectively. The corresponding seismic margins are defined as follows:

$$F_C = \frac{C - P_N}{P_{RLE}} \tag{1}$$

Where F_C is seismic margin; C is code capacity; P_N is the response quantity due to normal operating loads; and P_{RLE} is the response quantity due to review level earthquake.

The seismic margins from the DSA and the fragility parameters from the FA are expressed in terms of the horizontal peak ground acceleration (PGA) of the review level ground motion typically defined by the uniform hazard spectrum (UHS) with an annual exceedance frequency (AFE) of 10^{-4}.

The seismic evaluations are preferably based on plant specific information such as the design basis qualification documents, test response spectra and anchorage details. These are reviewed and pertinent information is compiled into plant specific databases and accessed by the calculation scripts. The databases also include the applicable generic and experience-based capacities to supplement plant specific information, if necessary.

The deterministic verification uses the Conservative Deterministic Failure Margin (CDFM) method (EPRI NP-6041-M (1991)) with the exception that that it uses code based permissible response rather than conservative estimates of failure level response. The seismic demand for the DSA is preferably based on the 84th percentile response quantities developed from probabilistic soil structure interaction analysis (PSSI). When code-based acceptance criteria for stresses and displacements are used, the resulting seismic margins are interpreted to be aligned with the performance goals targeted in the codes. The DSA seismic margins and High Confidence Low Probability of Failure (HCLPF) are developed in the same manner as for the CDFM method:

$$HCLPF = F_C \times PGA \tag{2}$$

Where *HCLPF* is high confidence low probability of failure; F_C is seismic margin; *PGA* is the peak ground acceleration of review level ground motion.

Based on the Separation of Variables (SoV) method described in EPRI 3002012994 (EPRI 3002012994 (2018)), the FA develops the median failure capacity (Am) and associated log standard deviations (β_U and β_R) for use in the seismic probabilistic safety assessment (PSA). The SoV method explicitly characterizes a probability distribution (median value and log standard deviations associated with randomness (β_R) and uncertainty (β_U)) for each parameter affecting the SSCs' response and capacity. In general, failure of a component is defined broadly as the loss of component function and FA focuses on the controlling failure modes identified in the DSA. The plant specific information is used to estimate median capacity of the component, and the 50th percentile response quantities are used to represent the median seismic demand. The SoV approach minimizes unintentional conservatism in the process.

SEISMIC SAFETY EVALUATION METHODOLOGY

Electrical Equipment

The following failure modes are typically considered for the seismic evaluation for electrical equipment:

- Malfunction of mounted devices during the seismic event;
- Structural integrity of housing; and
- Anchorage

The EPRI 3002012994 (EPRI 3002012994 (2018)) methodology is implemented in the automation methodology to present the DSA and FA results for both "function during" and for "function after" failure modes. Since some of the cabinets and panels house devices that are required to function (i.e., no spurious actions) as designed during the seismic event (function during). Along with the devices that need to function during the seismic event some of cabinets and panels may house devices that are required only to maintain integrity during the seismic event and are available for service following the seismic event (function after). Thus, both function during and function after results are presented so that both failure modes are available to the PSA quantification.

The electrical equipment and devices are qualified using shake table tests. The test spectra from the design test reports are used as the capacity spectra for the component functionality and structural integrity. In some cases, such as: i.) no availability of exact design test report; ii.) reported test spectra is not adequate, the generic equipment ruggedness spectra (GERS) (EPRI NP-5223-SL (1991)) and experience-based capacities (EPRI 3002012994 (2018), EPRI 3002010668 (2017)) are used. The component capacity spectra are digitized and is stored in the database along with the other component specific information extracted from the design test report.

Component specific anchorage drawings, checklist documents (documents with anchorage information during the plant construction) along with the walkdown observations are used to obtain the component anchorage information such as anchorage size, anchorage type, anchorage material, anchorage configuration. The anchorage information is stored in the database and is used for the anchorage evaluation.

Mechanical Equipment

Most of mechanical components are evaluated based on the stress analysis presented in the design basis documents. The design basis documents provide the basis and address the following failure modes:

- Elastic functional failures;
- Brittle failures; and
- Ductile failures.

The failure modes presented in the design documents typically address the structural integrity due to bending, buckling of supports, failure of anchorage, as well as or functional failures (binding of valve, excessive deflection in rotating equipment). The qualification analysis and the reported stresses are utilized as basis for the seismic capacity. Design basis seismic stresses and deformations are scaled to the updated spectral accelerations at the component dominant frequency. The design basis documents are reviewed and relevant design basis information such as seismic stresses, normal operating load stresses and allowable stresses for each failure mode are stored in the database.

Most of the design basis documents also presents the basis and qualify the component anchorage. The equipment anchorages are evaluated for the normal operating tension and shear forces combined with the review level earthquake response quantities. The combined anchor forces (tension and shear) are compared with the anchorage capacities based on industry standards such as Eurocode (CEN Eurocode 1992-4:2013 (2013)) and/or ACI-349 (ACI 349-06 (2006)). The anchorage relevant information from the design reports, component specific drawings and room layout drawings are also stored in the database which is used for the subsequent component anchorage calculation.

Structures

In accordance §5.1 of ENSI-AN-8567 (ENSI-AN-8567 (2014)), the potential failure of structures is associated with two limit states namely 1) structural strength and 2) usability or function. In addition, the following failure modes, as identified in ENSI-AN-8567 (ENSI-AN-8567 (2014)) are also investigated:

- Seismic interaction (pounding) with adjacent structures; and
- Other geological effects as identified in §2.2.1 of ENSI-AN-8567 (ENSI-AN-8567 (2014))

Typically, the lateral load resisting elements of Category I structures consist of reinforced concrete floor diaphragms and the supporting shear walls. The floor diaphragms are typically seismically rugged because the in-plane seismic shear is due only to the vertical dead load and the imposed live load for which it is designed. Thus, the design basis and the median seismic strength capacities of the structures are determined by the seismic capacity of critical shear walls.

Consistent with the requirements of §5.1.3 of ENSI-AN-8567 (ENSI-AN-8567 (2014)), the seismic strength evaluation considers the following failure modes of shear walls:

- Diagonal tension;
- Axial capacity of the wall edge regions;
- Out-of-plane flexure and shear; and
- Shear friction at pre-existing horizontal and vertical construction joints

The shear walls of NPP structures are typically rectangular and are characterized by relatively low aspect ratio (< 2.0). Typically calculated in-plane and out-of-plane bending moments are not significant. Also, no pre-existing horizontal or vertical construction joints are identified. Therefore, of the above failure modes, shear failure in diagonal tension is the controlling, and is evaluated to assess strength limits for the DSA and FA. In accordance with §5.1.7 of ENSI-AN-8567 (ENSI-AN-8567 (2014)) and SIA 260 (SIA 260 (2004)), the deterministic verification for usability reflects successful function of mounted equipment and limiting the deformations for leak tightness. The subsequent FA for functional capacity uses the median values of acceptable seismic deformations as recommended in EPRI 3002012994 (EPRI 3002012994 (2018)).

The seismic induced structural displacements could result in the closure of the gap and consequently pounding with the adjacent structures. These interactions are specifically evaluated using the displacement response of buildings. Potential pounding, particularly at ground motions associated with the strength limits, is addressed specifically with respect to the possible local damage and the global effects on the building contents.

As required in §2.2.1 of ENSI-AN-8567 (ENSI-AN-8567 (2014)), "other geologic effects" include slope stability failure, liquefaction, compaction and settlement, and ground subsidence due to seismic events. According to reference to §4.2.1 of ENSI-AN-8567 (ENSI-AN-8567 (2014)), the following associated impacts are addressed:

- Settlements and tilting as well as the corresponding load on the building structures;
- Overall stability (sliding and overturning) and bearing capacity of the structures or their parts and the useability (e.g., integrity of the building envelope).

All the required parameters for the structural calculations for each building are obtained by review of various plant specific documents and are saved into the database.

Uncertainty Evaluation

In accordance with EPRI 3002012994 (EPRI 3002012994 (2018)), the SOV approach evaluates median seismic margins and corresponding logarithmic standard deviations β_R and β_U for each variable affecting the response and capacity. Of the primary capacity and response variables the more significant are the floor response spectra and equipment failure modes. This calculation can get extensive particularly when the PSA examines more than a single failure mode.

With increasing computational capabilities, probabilistic methods can be easily accommodated in the calculation of seismic response using PSSI. This provides a more stable method to obtain uncertainty parameters associated with seismic response using the 84th percentile and 50th percentile response quantities. The scripted approach facilitates the implementation of the full SoV methodology incorporating equipment information from well-designed plant databases including selected information from qualification analysis. Additionally, the script-based approach is able to also address other sources of uncertainties such as equipment amplification for mounted components and post-installed anchor capacity in potentially cracked concrete. The plant specific as well as generic test data are embedded into the database/scripts.

COMPUTATIONAL APPROACH OF SEISMIC SAFETY EVALUATION

Figure 1 shows the automation methodology implemented in the current study. The methodology is implemented in MATLAB scripts and relational database. MATLAB scripts are used to generate the LaTeX files, which are used to generate the pdf version of the calculation. The methodology can be broadly divided into the following 3 steps:

- Read component specific information from database (Step 1 in Figure 1);
- Perform design basis evaluation for proof of safety and perform fragility analysis for controlling failure mode (Step 2 in Figure 1); and
- Generate LaTeX files to generate the calculation pdf version (Step 3 in Figure 1)

The detailed function of each step is presented in the following sections of the paper. Figure 2 presents the detailed approach of the automation methodology.

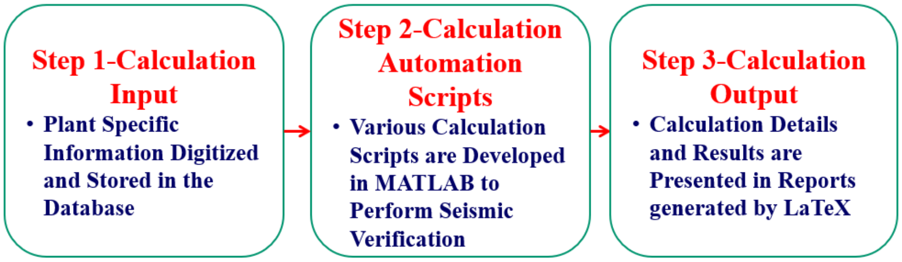

Figure 1: Main steps in the proposed automation approach

Step 1: Calculation Input

A relational database is built and is used to store all the input information for the DSA and FA calculations. As discussed in the previous sections, various plant specific information such as the design basis qualification documents, test report documents and anchorage details, which are compiled and the relevant information for the calculations are saved into the database. The information stored in the databases can be broadly categorized as follows:

- Equipment physical characteristics such as description, location and function;
- Walkdown photographs, notes and walkdown findings;
- Component relevant information from design reports;
- Anchorage information from both design reports and drawings;
- Qualification data such as test spectra from test reports and stress quantities from design reports;
- Applicable floor response spectra (FRS) from PSSI analysis; and
- GERS and experience-based response spectra
- Critical shear wall locations and dimension
- Applicable in-plane shear forces at critical wall sections
- Possible building to building pounding locations

Some of the information such as test spectra, GERS and experience-based response spectra are digitized and are saved in the form of excel sheets and are linked to the relevant components in the database. Similarly, the component relevant pictures or drawings are saved separately and are linked in the database with the components. Structures query language (SQL) scripts are developed in MATLAB and are used to access the component specific information from the database.

Step 2: Calculation Automation Scripts

As mentioned in the previous sections, the automation scripts are developed in MATLAB. Figure 2 presents the complete overall layout of the automation scheme along with the interactions between various steps. The “MATLAB Master Script” is the main MATLAB function script that interacts with different SQL scripts and MATLAB functions to extract the information from the database and generate the final LaTeX input files for the calculation pdf. Following are 3 major sub-components of the MATLAB master script:

- Interact with the database to extract the component specific information;
- Perform the DSA and FA calculations using the component specific information; and
- Generate the LaTeX input files using the calculation results

The detailed function of each sub-component of the MATLAB master file are as follows:

➢ MATLAB-Database Query Scripts:

The function of these MATLAB scripts is to i) interact with the database, ii) save the relevant component specific information into MATLAB workspace and iii) create a log file. Some of the tasks performed by these scripts are presented below:

- Generate test spectra using the input test motions used for the shake table tests (e.g., sine sweep signal, sine dwell signal, plane crash simulation signal etc.)
- The FRS data from the PSSI study are obtained at different damping ratios (1%, 2%, 4%, 5%, 7% and 10%). If necessary, the MATLAB files interpolate the FRS data to the TRS damping ratio and save the spectra into the MATLAB workspace
- All the information from the database is read and saved into MATLAB workspace with required initial data processing. The data used for the calculation is saved into log file

➢ MATLAB Scripts to Perform Calculations:

This MATLAB function interacts with various MATLAB sub-functions to perform calculations. The primary function of these set of scripts are to use the data saved from the MATLAB-Database scripts and perform the required DSA and FA calculations for the component and save the results in the MATLAB workspace. Some of the important aspects of this step are as follows:

- The functional evaluation for DSA is performed by clipping the TRS and FRS spectra in accordance with ASCE 4-16 (ASCE 4-16 (2017)) guidelines. Calculate the minimum clipped TRS to clipped FRS ratio.
- The functional evaluation for FA is performed by clipping the median TRS and FRS spectra in accordance with SoV guidelines and obtain the minimum clipped TRS to clipped FRS ratio. Subsequently, the log standard deviations associated with the SoV methodology are calculated and fragility plots are developed using the fragility parameters.
- The design basis anchorage evaluation is performed by calculating design basis anchorage capacity and seismic forces on the anchor bolts. Factor of safety is calculated by taking the ratio of the seismic demand and capacity.
- Anchorage evaluation for fragility analysis is performed for the governing failure mode from the DSA. The anchorage median capacity and demands are estimated, and the fragility parameters are calculated. Fragility plots are generated using the fragility parameters.
- Similarly, various other MATLAB sub-functions are generated to perform functional and structural integrity of mechanical components and structures as well as to assess uncertainty variables for the SoV analysis.

➢ MATLAB Scripts to Generate LaTeX Input Files:

The results (output variables) from the various sub-functions of "MATLAB Scripts to Perform Calculations" are used as an input for this step. LaTeX input generation scripts (LIGS) are developed in MATLAB, the main function of LIGS is to use the results saved in the MATLAB workspace to generate the LaTeX input files that can be directly used to generate the pdf version of the calculation. Various LIGS sub-functions are developed for each sub-functions in the "MATLAB Scripts to Perform Calculations" so that once the "MATLAB Scripts to Perform

Calculations" sub-functions are executed a relevant LIGS sub-function is executed to generate the sub-LaTeX input file. Once all the sub-LaTeX input files are generated, a master LaTeX file is generated to interact with the sub-LaTeX files and is saved.

Step 3: Calculation Output:

In this final step, the master LaTeX file is executed using LaTeX compilers. The master LaTeX file interacts with all the necessary sub-LaTeX files to generate the final printable pdf version of the calculation. Figure 3 presents the snapshots of an example calculation, after the content is cleared for proprietary purposes.

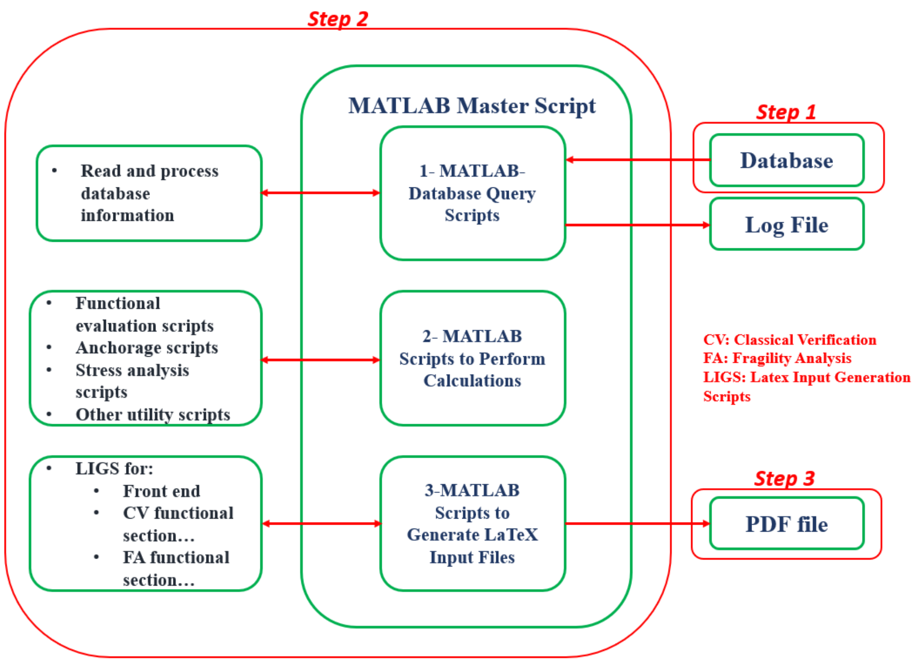

Figure 2: Complete Automation Flowchart

ADVANTAGES OF THE METHODOLOGY

Some of the advantages of the computational methodology can be summarized as follows:

- The current computational approach helps in reducing the time to perform various repetitive steps both within and between the calculations.
  - For example, the seismic margin of an electrical component is calculated by first clipping the TRS and FRS and then calculating the minimum clipped TRS to FRS ratio within the component frequency range of interest along X, Y, and Z directions as part of the functionality evaluation (for both DSA seismic margin and as well as the median seismic margin). In addition, similar spectral peak clipping operations as above are performed to obtain the logarithmic uncertainty parameters in the FA calculation. In fact, the total number of spectral peak clipping operations sums up to 20 within a single calculation. The total effort to perform these repetitive calculations are reduced by means of scripts.
  - Such repetitive steps also exist between different calculations which are streamlined by means of scripts as well (e.g., estimation of anchorage capacity and demand, scaling of response quantities, obtaining TRS to FRS ratio are common between different component calculations)

- A new standalone calculation can be generated quickly under the following example scenarios:
  - If the evaluated component has the same design qualification report and/or anchorage information as a previously evaluated component (i.e., information is readily available in the database).
  - When the seismic input parameters change for a previously evaluated component (e.g., change in seismic hazard, location in the building, etc.).
  - When more plant specific information become available for a previously evaluated component (e.g., shake table testing, fundamental frequency determination, etc.).
  - When a systematic issue is identified and fixed in the overall methodology.
- With the scripts, the manual errors can be eliminated, time to perform a calculation can be reduced significantly, and can help in producing quality and consistent calculations.
- Scripts can be maintained and improved constantly to refine the calculations as needed.


Calculation Title: Seismic Verification and Fragility Analysis
Calculation No.: - Revision: 0 Date: -

SEISMIC VERIFICATION AND FRAGILITY ANALYSIS FOR ELECTRICAL COMPONENT

1 PURPOSE AND BACKGROUND

A brief calculation purpose as well as the calculation background is presented this section.

2 COMPONENT DESCRIPTION

Component specific information such as location, component safety relevance, component safety function, anchorage (if applicable) is presented in this section. Applicable component specific walkdown pictures are also presented in this section.

3 BASES FOR SEISMIC CAPACITY AND SEISMIC DEMAND

3.1 Identification of Failure Modes

Applicable failure modes for this component calculation is presented in this sub-section.

3.2 Basis for Seismic Capacity

3.2.1 Functional and Structural Capacity

Component functional and structural integrity capacity information is presented in this sub-section.

3.3 Anchorage Capacity

If applicable, component anchorage capacity information is presented in this sub-section.

3.4 Seismic Demand

Seismic demand used for the component calculation is presented in this sub-section.

3.5 Seismic Interaction Evaluation

Seismic interaction information is presented in this sub-section.

4 RESULTS OF ANALYSIS

4.1 Preliminary HCLPF Based on CDFM using Experience Based Capacities

Results from preliminary HCLPF based on CDFM using experience based capacities are presented in this sub-section.

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4.2 Seismic Margins Using Classical DSA

Results from classical DSA are presented in this sub-section.

4.3 Fragility Calculation for PSA

Results from PSA along with the fragility curves are presented in this sub-section.

5 CONCLUSIONS

Calculation final conclusions are presented in this section.

6 References

Calculation specific references are presented this section.

Calculation Title: Seismic Verification and Fragility Analysis
Calculation No.: - Revision: 0 Date: -

A PRELIMINARY HCLPF BASED ON CDFM USING EXPERIENCE BASED CAPACITIES

Detailed preliminary HCLPF based on CDFM using experience based capacities calculation is presented in this appendix.

B SEISMIC MARGIN USING CLASSICAL DSA

Detailed classical DSA calculation is presented in this appendix.

C FRAGILITY CALCULATION FOR PSA

Detailed fragility calculation for PSA is presented in this appendix.

Figure 3: Outline of a sample component calculation (Korlapati et al. (2021))

VERIFICATION AND VALIDATION OF THE METHODOLOGY

The log file generated by the "MATLAB Master Script" contains all the input information such as TRS, FRS, anchorage information, etc. As part of the current study, independent reviewers verified the automated calculations by means of independent Mathcad calculations. These Mathcad calculations use the log files as input and perform the same DSA and FA evaluations. The results from both the automated and Mathcad calculations were consistently observed to be same.

CONCLUSIONS

The paper presents a novel approach to streamline and automate the DSA and FA calculations using advanced tools such as MATLAB scripting and plant databases. The plant specific documents are reviewed and are stored in the relational databases, using the component unique ID. MATLAB scripts are developed to retrieve the information from the database, perform the DSA and FA calculations, and generate the final standardized printouts.

The methodology provides the means to directly access information in plant databases as well as to augment calculation scripts and address equipment change-outs entered into database updates. The scripts are useful to perform repetitive steps in the calculations in a cost and time effective manner. Further, the standardization of extensive outputs and printouts facilitates internal and regulatory reviews. Any future changes in the component parameters (e.g., new test report, anchorage modifications) can also be easily incorporated into revised calculation through the updated database.

The overall streamlining approach leads to efficient use of engineering resources while minimizing human errors and maintaining the quality and consistency of results. This approach in general improves the quantification of plant risk and risk insights by re-allocating engineering resource from time consuming calculations to considering alternate failure modes and treatment of uncertainties in cooperation with risk engineers. The ability to perform a greater number of calculations allows examination of additional failure modes and sensitivity studies to understand which variables affect most the final fragility parameters to support that risk-based decisions for plant modifications. Emerging issues and improvements in industry guidelines can be introduced in the scripts in a tractable manner. The calculation methodology and results are readily verifiable by independent reviewers.

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