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MULTI-HAZARD PROBABILISTIC RISK ANALYSIS OF OFF-SITE OVERHEAD TRANSMISSION SYSTEMS

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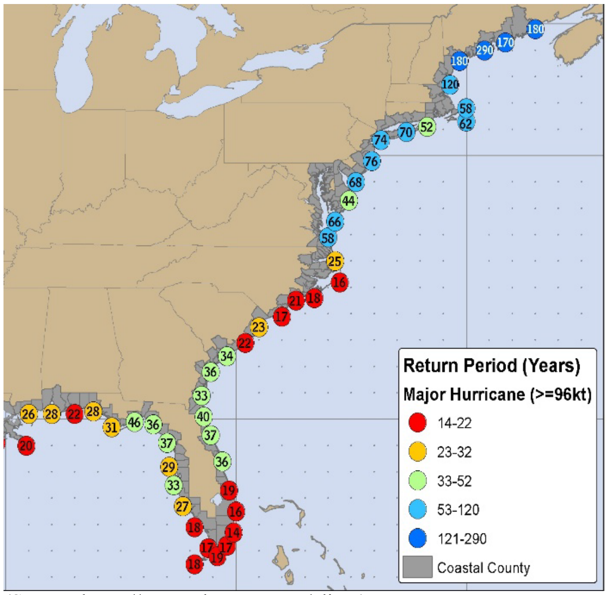
ABSTRACT

Many nuclear power plants (NPPs) in the world are located in areas prone to multiple hazards, and the structures, systems, and components (SSCs) of these NPPs are subject to the complex impacts of these hazards. This study presents a probabilistic framework for multi-hazard risk analysis of SSCs in NPPs. In this framework, hazard models are convolved with state-dependent fragility models of SSCs in order to account for damage accumulation under a sequence of hazards and evaluate multi-hazard risks. Among SSCs, an essential component is offsite transmission towers, which are considered here for demonstration purposes. Following the presentation of the framework and its components, the hurricane fragility analysis of a typical lattice transmission tower is investigated. For this purpose, a physics-based high-fidelity computational model of the tower is developed to capture its various modes of failure. Using this detailed 3D model, the linear to nonlinear performance of the transmission tower is analyzed under a large range of hurricane intensities, and parametric fragility functions are studied using an advanced reliability analysis method based on Kriging surrogate model. The proposed risk assessment procedure based on parameterized fragilities enables a comparative assessment of the contributions of different hazards and the significance of damage accumulation for the total risk of failure of SSCs.

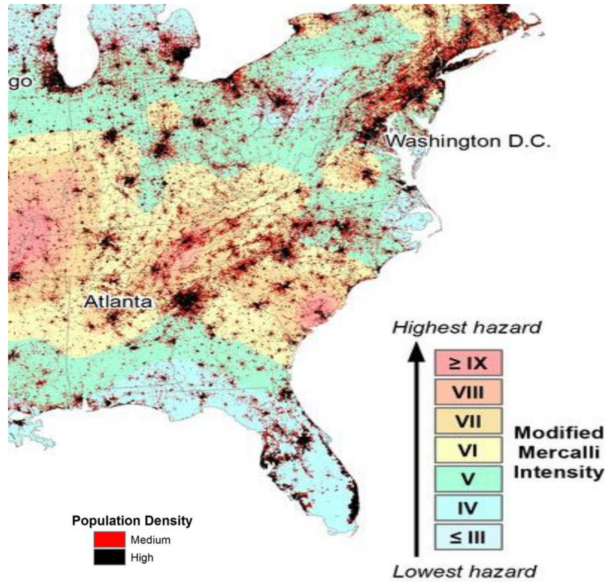
INTRODUCTION

Against extreme hazards, probabilistic and risk-based approaches for analysis and design have been developed and implemented for nuclear power plants (NPPs). However, analysing multi-hazard impacts on NPPs and associated risks are still a challenge. Considering the service life of the NPPs, there is potential for these systems to face multiple occurrences of extreme hazards, although their likelihood of occurrence may be very small. In summer 2018, Japan was shaken by the 6.7 M earthquake just two days after one of the strongest hurricanes landed with high wind and heavy rain. As expected, the damage from these consecutive events was significant. Another example occurred in 2017 in Puerto Rico, which was hit by a series of strong hurricanes in a month; the island have not yet fully recovered from induced damages. These multi-hazard scenarios have been considered as extremely rare events, but recent multi-hazard events have shown the extensive societal consequences including physical and operational failures in critical infrastructure systems. These consecutive hazards triggered the blackout of millions of households, led to casualties, and induced severe economic losses and business disruptions. Despite the fact that multi-hazard scenarios have low probability of occurrence, given the high consequences of failures and the highly strict safety requirements for NPPs, such hazards need to be considered in risk assessment of NPPs. Moreover, many of nuclear power plants in the world are located in areas prone to multi-hazards, and the structures, systems, and components (SSCs) of NPPs can be vulnerable to compounding effects of these events. As shown in Figure 1, states of South and North Carolina and Virginia are both hurricane and earthquake prone regions in the U.S. Although these hazard types are independent, it is possible that a sequence of these two natural hazards occurs in a short period.



(Source: https://www.nhc.noaa.gov/climo)

(a) Estimated return period in years for major hurricanes passing within 50 nautical miles of various locations on the U.S. Coast

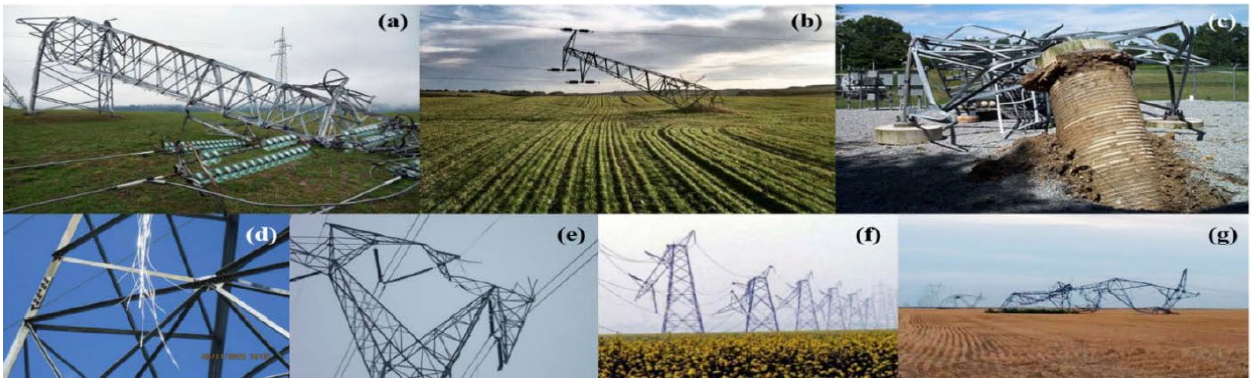


(Source: https://www.usgs.gov/media/images/potential-earthquake-map-shaking)

(b) USGS map showing 1) the locations of major populations and 2) the intensity of potential earthquake ground shaking that has a 2% chance of occurrence in 50 years

Figure 1. Multi-hazards Regions in the U.S.

This paper first introduces a framework for the probabilistic risk assessment of SSCs in NPPs subject to multiple hazard types and occurrences. This framework includes hazard models that are convolved with state-dependent multi-hazard fragility models of SSCs. The fragility models here should consider the accumulation of damage in SCCs under a sequence of hazards. Following the presentation of the framework, the study presents the preliminary results for the hurricane fragility analysis of a typical steel lattice transmission tower. These structures are an essential electrical component that can be vulnerable to multi-hazards. We have developed a physics-based high-fidelity computational model of the tower to capture various modes of the failure of this structural system. Some of the observed failure modes of transmission lines and towers from past hurricane and other extreme events are presented in Figure 2. Using this detailed 3D model, the linear to nonlinear performance of the transmission tower is analyzed under various levels of hurricane intensities, and a fragility function is derived. The presented risk assessment method based on parameterized fragilities enables a comparative assessment of the contributions of different hazards and the significance of damage accumulation for the total risk of failure of the tower.



(a) http://www.nmgroup.com/en/new-project-tower-verticality-checks-to-prevent-catastrophic-failure/. [Accessed: 07-Jan-2016].
(b) http://www.thetimes.co.uk/tto/multimedia/archive/00522/147453653__522161b.jpg. [Accessed: 07-Jan-2016].
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(g) http://www.ect.coop/weather-effects/power-restoration/fire-hail-winds-and-floods-hit-coops/82815. [Accessed: 07-Jan-2016].

Figure 2. Damaged Transmission Towers under Natural Hazards

MULTI-HAZARD RISK ANALYSIS

The Framework

In order to capture multi-hazard effects on the risks of failure of SSCs in NPPs, this study proposes the probabilistic framework shown in Figure 3. It includes a module for generation of multi-hazard scenarios considering the stochastic characteristics of hazard sequences, their time of occurrence along with the uncertainties in their intensities. Another key module is high-fidelity computational models of SSCs that can reliably predict the structural and functional state of SSCs in response to extreme hazards. As often a large number of random variables are involved in such computational models, reliability analysis to determine the probabilities of failure becomes very challenging. To overcome this, sensitivity analyses are needed to identify statistically most significant variables. Integration of computational models with probabilistic procedures will provide an spectrum of failure modes of the system from small to large failure probabilities. These information can be used to generate state dependent fragility models of SSCs. The convolution of these models with multi-hazard models will produce estimates of the risk of failure of SSCs. Consequently, the proposed framework offers new understandings of damage to SSCs under multi-hazard scenarios. The proposed procedure will serve as an aid to risk-based approaches for analysis and design of NPPs considering low probability-high consequence events.

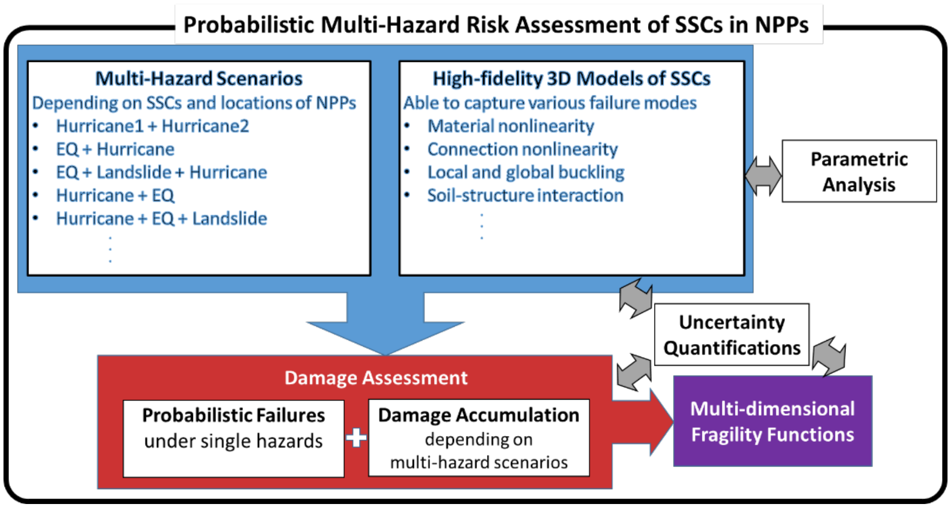


Figure 3. Framework of Probabilistic Multi-Hazard Risk Assessment

Fragility Functions

In the past decades, significant research efforts have been devoted to assessing the reliability and performance of nuclear power plants under a single external event and dependent secondary effects. However, there have been limited research comparatively on multi-hazard scenarios. As shown in Figure 3, there can be various combinations of multi-hazard scenarios in NPPs. Some of the scenarios can be dependent on each other such as earthquake (EQ) and landslide or hurricane and flood, or independent from each other. Here, we consider the case where there are no dependencies among characteristics of hazards with respect to time and order of occurrence. Using the theorem of total probability, the conditional probability that the damage in an SSC reaches the limit state (LS) at *j*th hazard is derived and presented in Equation (1) (Fereshtehnejad and Shafieezadeh, 2018). This probability, $P\left(LS^{j}_{[n_1,\dots,n_M]}|i\right)$, is expressed as the likelihood of exceeding limit-state $[n_1,\dots,n_M]$ at *j*th incident given the damage-state of the system in terms of $DS^{j-1}_{[n_1^{'},\dots,n_M^{'}]}$, the occurrence of hazard type *h*, intensity of the hazard type *h*, and *i* hazards taking place during time period [0 *t*].

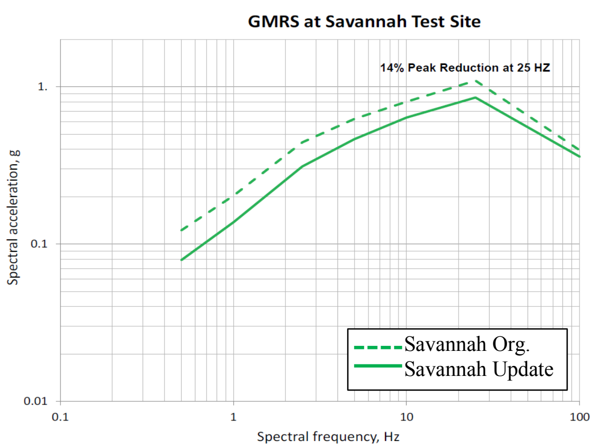
$$P\left(LS^{j}_{[n_1,\dots,n_M]}|i\right) = \sum_{n_1^{'}=1}^{N_1^{'}} \dots \sum_{n_M^{'}=1}^{N_M^{'}} \sum_{h=1}^{N_H} \sum_{IM_h} P(LS^{j}_{[n_1,\dots,n_M]}\left|DS^{j-1}_{[n_1^{'},\dots,n_M^{'}]}, HT_h, IM_h, i\right) \times P(DS^{j-1}_{[n_1^{'},\dots,n_M^{'}]}|i) \times P(HT_h) \times P(IM_h) \quad (1)$$

In the above equation, $N_M^{'}$ is the total number of damage-states for damage type *M* that the structure may sustain right after *j*-1th hazard, N_H is the total number of hazard types that may hit the system, HT_h is hazard type *h*, and IM_h is the intensity measure of hazard type *h*. Noticeably, $[n_1^{'},\dots,n_M^{'}]$ and $[n_1,\dots,n_M]$ are the vector of damage-state sustained by the system after *j*-1th hazard, and the vector of the limit-state that is exceeded after *j*th hazard, respectively. In Equation (1), $DS^{j-1}_{[n_1^{'},\dots,n_M^{'}]}$ represents the damage-state of the system at *j*th hazard incident given the damage-state after *j*-1th hazard event. The term $P(HT_h)$ is the probability that the structure is impacted by hazard type *h* at *j*th hazard occurrence.

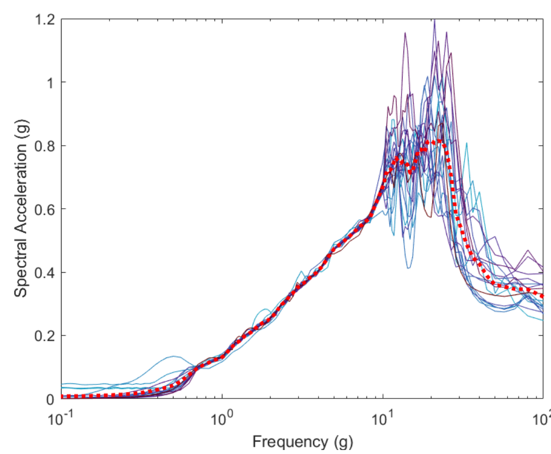
Based on the above formulation, multi-hazard fragility functions can be generated. The damage-state at the time of *j*th hazard can be different from the intact damage-state, and therefore the fragility curves need to be available for all damage-state possibilities. Such models are called damage-state dependent fragility functions, which are able to reliably capture the accumulation of damage against a series of hazards.

Earthquake Hazard

For seismic hazard, ground motion response spectra (GMRS) of Savannah, GA can be considered as an example. It is one of the representative locations of NPPs in the CEUS region. Figure 4 (a) and (b) show the GMRS generated by the ground motion modification (GMM) program of EPRI, and selected ground motions, respectively. As shown in Figure 4(b), this spectrum includes relatively high frequency contents compared to ground motion histories in the Western region of the U.S. (Hur and Shafieezadeh, 2019). Eighteen sets of ground motion histories are selected and matched to the GMRS of Savannah Update. The spectral acceleration of these ground motions are shown in Figure 4(b).



(a) Ground Motion Response Spectra (GMRS) at Savannah Test Site by EPRI (DOE NPH Meeting, 2014)



(b) Spectral Accelerations of 18 sets of ground motions in the CEUS (Damping 5%)

Figure 4. Earthquake Load Model

Hurricane/Typhoon Hazard

For hurricane or typhoon models, wind speeds can be determined from ASCE 7 Minimum Design Loads for Buildings and Other Structures. The wind speeds associated with different mean recurrence intervals (MRIs) for Savannah, GA are shown in Table 1. The wind speed varies depending on the MRIs. Based on the historical data, the wind speed of MRI 100-year for Savannah is 104 mph. Using the information presented in this table, a probabilistic model for wind velocities can be generated for the location of interest.

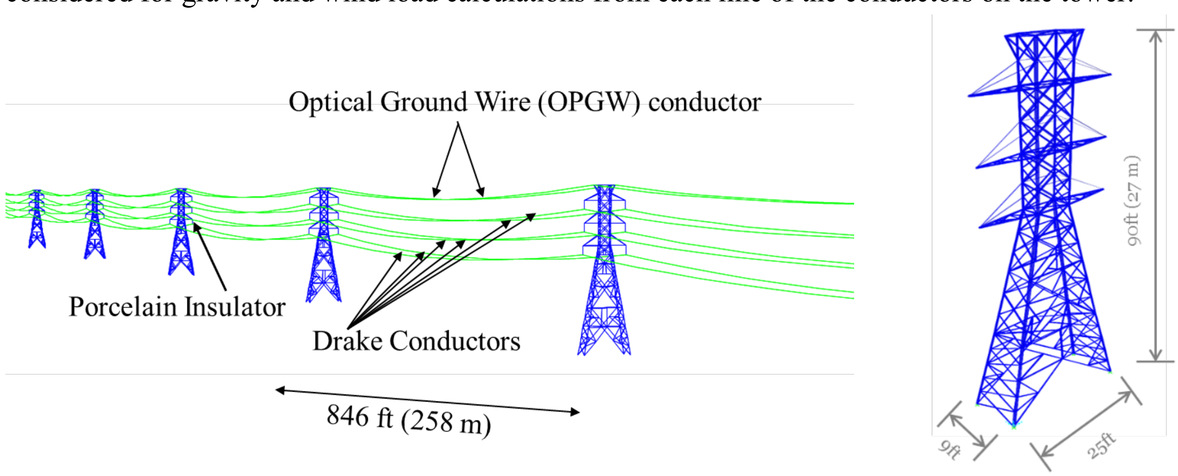
Table 1. Wind Load Model for Savannah, GA, USA

Mean Recurrence Interval 10-Year	75 mph
Mean Recurrence Interval 25-Year	86 mph
Mean Recurrence Interval 50-Year	94 mph
Mean Recurrence Interval 100-Year	104 mph

HIGH FIDELITY 3D MODEL OF THE TOWER

Description of the Model

This study considers a double circuit vertical steel transmission tower as shown in Figure 5. This type of tower is representative of a large percentage of lattice towers which are commonly used in hurricane prone coastal areas in southeast of the U.S. Its height is approximately 27 m (90 ft), and its transverse and longitudinal width dimensions are 3 m (10 ft) and 7.5 m (25 ft), respectively. The tower carries two lines of three phase conductors at three cross arm levels and two lines of neutrals at the top. Therefore, a total number of eight conductors are carried by the tower. The three phase conductors are Drake based on US naming system for ACSR conductors, and have a diameter of 28.1 mm with a 1627 kg/km mass. In addition, the neutrals are Optical Ground Wires (OPGW) with a diameter of 13.4 mm. The span length of conductors is 258 m. It is assumed that multiple spans with identical towers, conductors and span lengths exist in the transmission line system of interest. According to Darestani et al. (2016a and 2016b), if the properties of adjacent spans in a line are identical, the structural couplings between the adjacent spans are not significant and can be neglected. Subsequently, in this study, transmission towers are modeled individually without any conductors attached to them. However, the gravity and wind-induced loadings from the conductors attached to the towers are applied at the intersection of cross arms and insulators as point loads. The gravity and wind-induced loadings are distributed equally between adjacent towers. Therefore, in order to calculate the point loads of the conductors on the towers, an effective span length of 258/2=129 m is considered for the conductors at each side of the tower. Subsequently, an overall effective span length of 258 m is considered for gravity and wind load calculations from each line of the conductors on the tower.



(a) Double Circuit Vertical Steel Transmission Towers in a line

(b) Dimensions of a Single Tower

Figure 5. Transmission Tower Models for this Study

Finite Element Modeling of the Transmission Tower

In order to evaluate the complex performance of the transmission tower against extreme hazards, Finite Element (FE) models are generated. A transmission tower is composed of a large number of components, and the complexity of the performance stems from material and geometric nonlinearities in individual components especially under strong wind loadings or strong shakings. Therefore, various failure mechanisms can emerge in a transmission tower when several components have experienced their post yield state, reached buckling stress, or when the tower experienced differential settlements. The FE analysis method is capable of handling this structural system with a large number of components considering the geometric and material nonlinearity of individual components. In this study, complex FE models are generated to capture material nonlinearity, p-delta effects, buckling due to imperfection and eccentricities, and nonlinear semi-rigid behavior of connections. Some of the modelling approaches followed for this structure in OpenSEES FE platform are explained next.

Modeling Steel Lattice Elements

In order to account for post yield elasticity, Steel01 material model is considered in OpenSEES, which assumes a bilinear relationship for stress-strain behavior. Nonlinear displacement-based beam-column elements are defined with five integration points with 10 fiber sections along the height and three fiber sections along the width of angle elements at each integration point. In addition, p-delta effects and geometric nonlinearities are accounted for through a co-rotational geometric transformation. In order to consider buckling accurately, according to Uriz et al. (2008), each element is divided in half and a camber displacement equal to 1/2000 to 1/1000 of the length of the element is applied to the middle node.

Modeling Connections

Under strong wind loads such as hurricanes, there is a significant level of joint slippage in the connections. Joint slippage considerably increases the lateral displacement of the tower, which can result in additional p-delta effects and structural couplings between adjacent towers. Ungkurapinan (2000) suggested a nonlinear model for joint slippage behavior based on a set of experiments they performed for steel angle members. This study adopts this model to consider joint slippage behavior. The general form of the connection behavior and the proposed approach to capture this complex behavior are presented in Figure 6. As shown in Figure 7, the developed joint slippage models are implemented by assigning zero-length elements in OpenSEES at the connections and applying the joint slippage behavior to the zero-length elements as a material model.

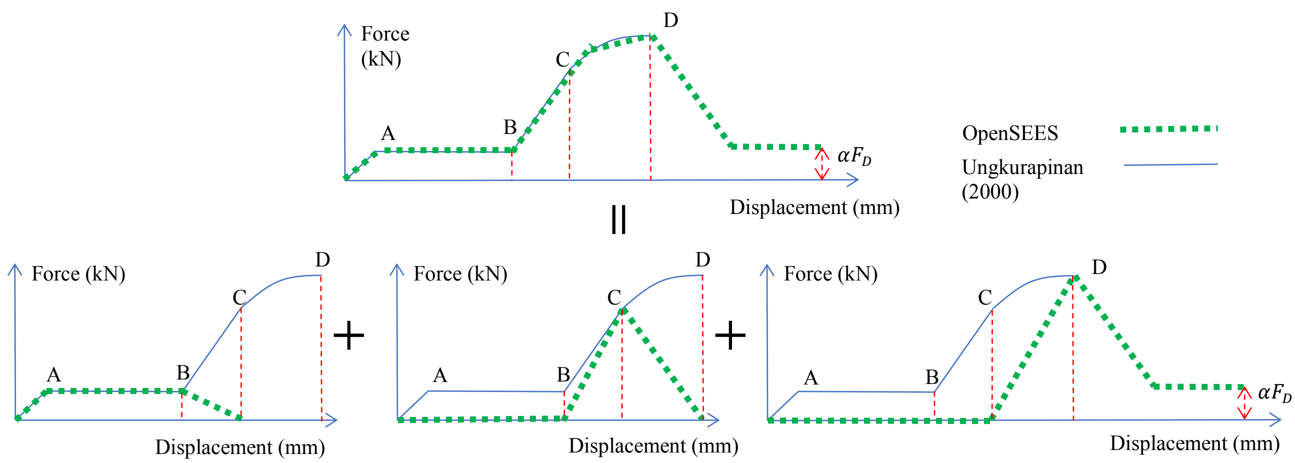


Figure 6. Developing Connection Material Model in OpenSEES

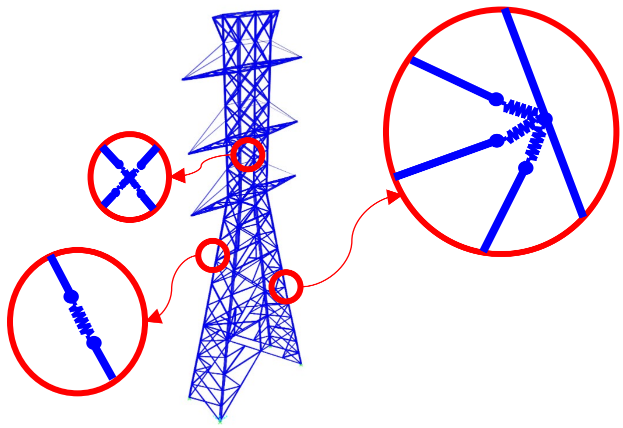


Figure 7. Modeling Joint Slippage Behavior in OpenSEES Using Zero-Length Elements

To estimate the wind-induced load on lattice towers, the static gust wind load suggested by ASCE07 (2016) is employed in this study.

FRAGILITY FUNCTIONS OF TRANSMISSION TOWERS

The fragility analysis of lattice towers requires evaluation of the limit state function for a large number of realizations of uncertain variables using Monte Carlo simulations. However, as nonlinear Finite Element analyses are computationally expensive and considerably time consuming, direct evaluation of the limit state function for the entire set of realizations is practically impossible. In order to address this limitation, various reliability analysis methods based on Kriging have been developed in the literature (Echard et al., 2011; Wang and Shafieezadeh, 2018). In Kriging-based reliability analysis, estimation of the limit state function using computationally expensive Finite Element methods is limited to a small number of candidate realizations, in which the limit state function is close to zero. Subsequently, a Kriging model is used to estimate the limit state function for the entire set of realizations of uncertain variables to efficiently perform Monte Carlo simulations. Therefore, using Kriging-based reliability analysis, a large number of Finite Element simulations are avoided and subsequently, the probability of failure of lattice towers are efficiently estimated. Further discussion on limitations of different Kriging-based reliability analyses can be found in Wang and Shafieezadeh (2018). Here we adopt the Error rate-based Adaptive Kriging (REAK) proposed in (Wang and Shafieezadeh, 2019). This method has shown two advantages over the existing adaptive Kriging reliability analysis methods. First, this method introduces an effective adaptive sampling region, in which the points with low joint probability density function are removed from candidate samples. Second, an upper bound for the rate of error is introduced based on the Lindeberg's condition for the Central limit Theorem. Using this upper bound, a faster convergence can be obtained for the reliability analysis and accuracy in failure probability estimates can be ensured with high confidence.

Using REAK, a fragility model is developed for the double circuit vertical lattice tower. The results are presented in Figure 8. For the considered lattice tower, the number of calls to estimate the limit state function through Finite Element analysis is less than 150. Comparing this number with conventional Monte Carlo simulations, which require tens of thousands of simulations, highlights the efficiency of adaptive Kriging reliability analysis methods such as REAK to generate fragility models for complex systems such as lattice towers.

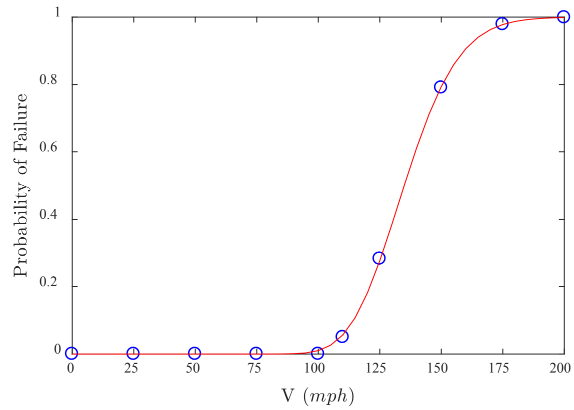


Figure 8. Hurricane Fragility Model for the Double Circuit Vertical Lattice Tower

CONCLUSIONS

This study presented a probabilistic framework for multi-hazard risk analysis of SSCs in nuclear power plants focusing on transmission towers. The framework involves the convolution of state-dependent fragility models of SSCs with hazard models to account for the sequence scenarios and intensities of multi-hazards. The framework requires state-dependent fragility models to capture the accumulation of damage from one event to another. Preliminary results were presented for a lattice transmission tower subject to hurricane loads. A physics-based high-fidelity computational model of the tower was generated in OpenSees Finite Element platform. Using this detailed 3D model, the linear to nonlinear performance of the transmission tower was analyzed under various levels of hurricane intensities, and parametric fragility functions were developed using an adaptive reliability analysis method. Analysis results demonstrated the ability of this surrogate modelling-based method to efficiently and accurately estimate even small probabilities of failure associated with multi-hazard effects on SSCs in NPPs.

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