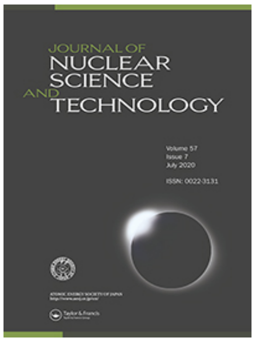

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ARTICLE

Seismic capacity evaluation of NPP electrical cabinet facility considering grouping effects

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ABSTRACT

This study investigates the fragility assessment of the electrical cabinet facility, a steel structural form that exhibits behavior and response patterns distinct from the normal structure. To evaluate this cause, a set of 40 ground motions was spectrally matched to the design response spectra (RG 1.60) and incremental dynamic analysis was considered. The two design guidelines including earthquake loss estimation methodology (HAZUS) and Nuclear Regulatory Commission (NUREG) were followed. Using the response statistics with the consideration of different damage states, the corresponding fragility curves were developed. For validation, the developed fragility functions were found to be consistent with the fragilities available in the HAZUS and NUREG. Subsequently, the seismic capacity for the group of cabinets was evaluated, which manifests a great influence on the probabilistic seismic risk assessment of the facility. The main thrust of this study was the significant alteration in the seismic capacity due to the grouping effects that account for 28% and 50% reduction in the probability of failure for two and three cabinets together. This effect can be considered as one of the important aspects that can induce a considerable impact on the seismic capacity evaluation and performance of the NPP electrical components.

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Seismic response; fragility losses; electrical cabinet; grouping effects; seismic risk analysis

Introduction

The seismic analysis of the important facilities in NPP requires sophisticated analysis and a sound understanding of the safety measures. The classical way of exciting a structure under the sets of ground motions and based on its response analysis deciding the structure performance and design is debated by many researchers. This paper studies the fragility loss estimation of the nuclear power plant electrical components with an emphasis on the safety-related nuclear structures. The electrical cabinet facility is on the priority to qualify its performance and seismic capacity during seismic events. One of the important aspects to be considered for these facilities is the grouping effect that is not highlighted in the present literature. The grouping effect refers to the combination of the electrical cabinet facility [1]. Consideration of this effect reflects the real scenario of these important facilities in the NPP industry. The seismic capacity analysis of the structure depends upon the seismic excitation and the selected scenario (damage state) that regards the structure behavior and needs to be addressed more explicitly.

In the case of NPP structure, the equipment failure due to seismic loads and fire is an alarming issue. A study is conducted on the NPP equipment based on the probabilistic safety assessment (PSA) with an emphasis to reduce the plant risk due to equipment failure [2]. To elaborate on the facility failure, a fragility analysis was performed by [3] that represents the probability of structural damage due to various ground shakings. The sensitivity of the electrical cabinet to the seismic excitation was investigated, and it was found that the electrical cabinet can even get excitation on very low amplitude of vibration [4]. Cordova et al. [5] suggest that the PGA is a good index of peak acceleration in the time history, but the correlation between the input excitation with the fragility function for a frequency sensitive component is still under the debate. An exception was considered for some functional performance of the vibration-sensitive components such as relays and switchboards. The challenge was how to reflect this reality in seismic analysis for a NPP and its components [6].

Many researchers have studied the collapse risk assessment, design check and sorting out the functional loss of the structures using the fragility analysis [7–10]. The fragility function can be generated based on various methods mainly followed by the hybrid, empirical, and analytical methods. The pros and cons due to different methods were investigated by the Muntasir Billah and Shahria Alma [11]. Tran et al. [12] defined the total collapse of the electrical

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cabinet facility in the nuclear power plant structure under a set of ground motion.

This study follows the lognormal cumulative distribution function, which is considered as one of the typical ways for the seismic fragility analysis of the structures [13,14]. The fragility function defines two parameters, median and the standard deviation represented by θ and β. These parameters can be determined by the two well-known methods, maximum likelihood estimation and linear regression analysis [15,16]. In addition, defining a threshold value for the seismic risk assessment of the cabinet varies significantly based on the scenario that includes the intensity measure (IM), damage state (DM), and properties of the structure with the ground motion. The selection of a ground motion intensity measure is one of the challenges considered for developing a seismic fragility. As in performance-based earthquake engineering (PBEE), the peak ground acceleration (PGA) [17] and the spectral acceleration at the first period $(S_a(T_1))$ [18] or the spectral displacement (S_d) are selected as IMs.

The acceleration sensitive electrical cabinet and the device installed within the cabinet are required to be seismically qualified and for this qualification, many methods are in practice in the nuclear power plant industry. The current method that is followed to investigate the dynamic characteristic of the facilities includes the evaluation of a single cabinet and then integrating its dynamic properties to the group of cabinets. This consideration of assigning the dynamic characteristic to the number of cabinets is needed to be described more explicitly. However, the present literature shows no specific information regarding the grouping effect of the cabinet facilities although an extensive work is available that covers the dynamic characteristic of a single cabinet.

The experimental and numerical analysis covers significant research for the electrical cabinet facility considering the time history analysis, linear and nonlinear analysis, fragility assessment, connection nonlinearity, sliding, rocking and overturning. An extensive literature is available on the quantitative and qualitative research on the cabinet to assess its real behavior in seismic activities but there is no particular study in the present literature considering the grouping effect of the electrical cabinet facility. To investigate this cause, this work emphasizes the fragility assessment of the acceleration sensitive cabinet structure considering the grouping effect and its profound impact on the dynamic characteristics that leads to a significant alteration in the seismic capacity.

Methodology

The alteration in the seismic capacity and performance of the electrical cabinet due to the grouping effect are explained using the dynamic characteristic of the cabinets. Figure1. presents the schematic procedure for the analysis. The proposed analysis will address the effect of combing the cabinets and its dynamic response to seismic excitation. To elaborate and make the effect more concrete, the five-step methodology is explained in the following sections.

Selection and scaling ground motion

The dynamic response analysis of cabinet structure was carried out using the collapse risk assessment based on the damage states provided by the HAZUS and NUREG guidelines that are explained in section 2.4. A set of 40 ground motions were selected from the PEER NGA database. The details of the input motions with the important parameters are listed in Table 1. The shear wave velocity (V_{s30}) ranges from 360m/s to 760 m/s with the corresponding magnitude of 6.0 to 7.5 and the rupture distance considering the near to the far distance of 2.86 to 207.14 km was selected, as shown in Figure 2(a).

The selected ground motions were scaled to the design response spectrum (DRS) that is used for the seismic design of nuclear power plants. The DRS obtained from the regulatory guide (RG 1.60) [19] was used. The RG 1.60 spectrum having PGA of 0.3g in the horizontal direction was generated for matching purpose. Details of DRS and spectrally matched motions are shown in Figure 2(b).

Grouping effect and time history analysis

The seismic response of the structure can be evaluated by the consideration of its dynamic parameters. Any change in these parameters can alter the overall response of the structure. Among these parameters, consistent mass, stiffness, and damping are prominent and can be directly related to the dynamic response of the structure. The electrical cabinet facility is a small but more complex structure as its structural configuration carries several elements that include mainframe, plates on the side and top, base tube frame, column frame with bars, the base subframe and most importantly their support conditions. Referring to its complexity it requires sophisticated analysis and consideration to have a clear idea about its dynamic behavior.

Grouping effect is the inclusion of the structural modification to the idea and it was considered in the form of two entities mainly the mass and stiffness provided by the cabinets. These two parameters are responsible for altering the resonance of a dynamic system directly. As [20] investigates that the dynamic modification of a structure is improved by predicting the modification induced by adding modification like lumped mass, dampers, and rigid links, etc.

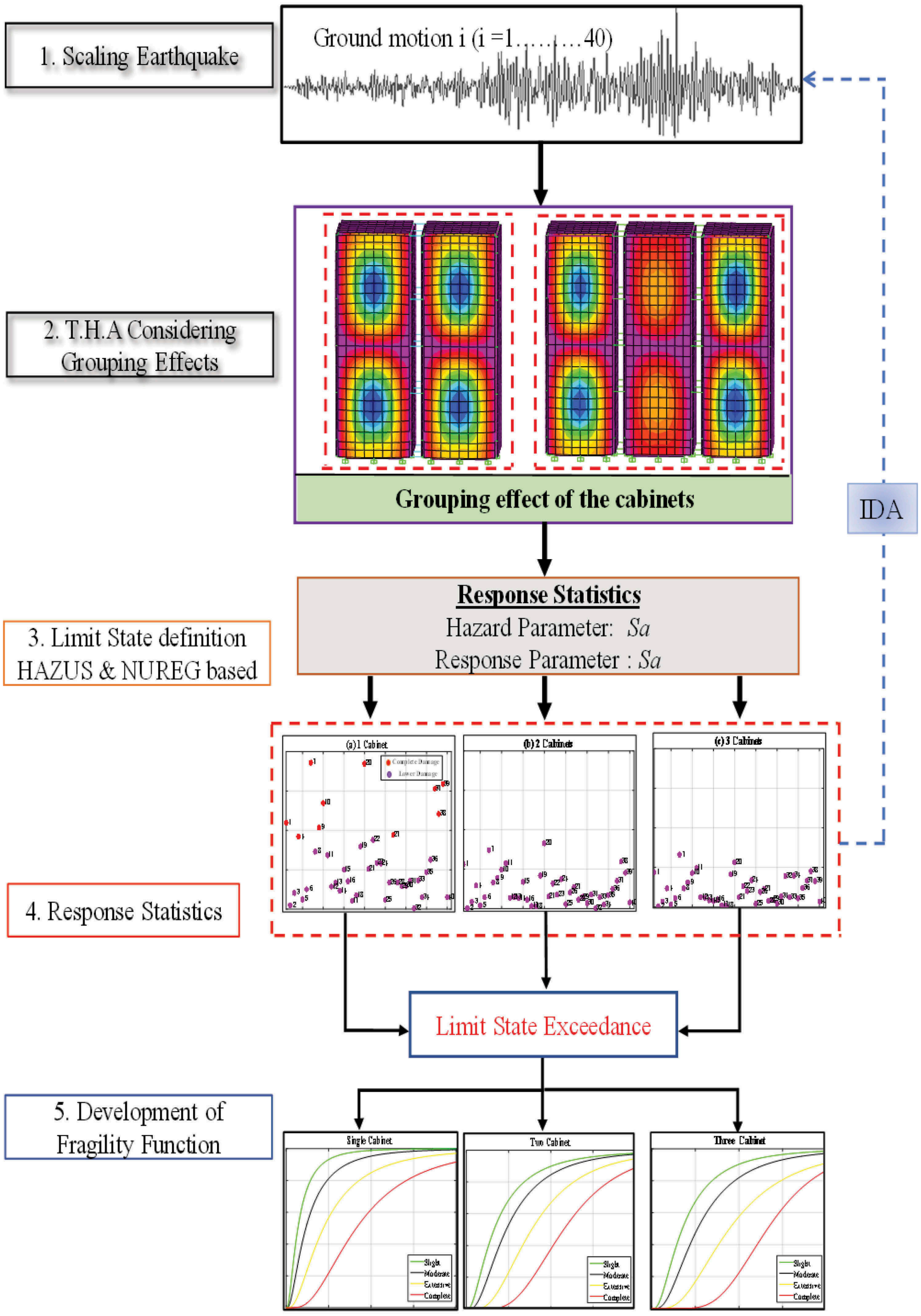

Figure 1. Schematic procedure for the proposed framework.

To induce the grouping effect of the cabinet structure, the following point will describe briefly the procedure of grouping the cabinet together.

- The experimental (impact hammer) test on the prototype model was investigated for the extraction of primary parameters like stiffness and damping properties using the modal analysis.
- The primary parameters like mass, stiffness, and damping with the complete specification of the cabinet structure were used to develop a finite element model in SAP2000 environment.
- All the degrees of the rotation and displacement are restrained for the cabinets and the doors and plates are connected to the main-frame accordingly.
- Validation and verification of the FEM model were achieved with the reference to the experimental modal analysis by using the frequency domain decomposition method.
- For the grouping effect of the cabinet structure, it was considered that the connection between the cabinets is fixed and due to this consideration, the rigid links were assigned. It was assured that the assigned rigid link will group the cabinet together and is not inducing any change in the dynamic characteristic of the structure. Figure 3. represents the typical cabinet's model for the grouping effect.

Table 1. Description of the input earthquakes.

No	Earthquake Name	Year	Magnitude	R_{RUP}(km)*	$V_{s,30}$(m/sec)*
1	Helena_ Montana-01	1935	6	2.86	593.35
2	Kern County	1952	7.36	125.59	415.13
3	Southern Calif	1952	6	73.41	493.5
4	Parkfield	1966	6.19	17.64	408.93
5	Borrego Mtn	1968	6.63	207.14	415.13
6	San Fernando	1971	6.61	173.16	360.45
7	Friuli_ Italy-01	1976	6.5	49.38	496.46
8	Tabas_ Iran	1978	7.35	120.81	377.56
9	Imperial Valley-06	1979	6.53	15.19	471.53
10	Mammoth Lakes-01	1980	6.06	6.63	382.12
11	Victoria_ Mexico	1980	6.33	14.37	471.53
12	Irpinia_ Italy-01	1980	6.9	52.94	612.78
13	Irpinia_ Italy-02	1980	6.2	29.86	476.62
14	Corinth_ Greece	1981	6.6	10.27	361.4
15	Coalinga-01	1983	6.36	42.92	522.74
16	Ierissos_ Greece	1983	6.7	65.67	463.92
17	Taiwan SMART1(25)	1983	6.5	92.04	671.52
18	Borah Peak_ ID-01	1983	6.88	100.22	445.66
19	Morgan Hill	1984	6.19	3.26	488.77
20	Nahanni_ Canada	1985	6.76	9.6	605.04
21	San Fernando	1971	6.61	109.73	443.85
22	Imperial Valley-06	1979	6.53	24.61	362.38
23	New Zealand-02	1987	6.6	16.09	551.3
24	Superstition Hills-02	1987	6.54	5.61	362.38
25	Loma Prieta	1989	6.93	41.88	391.91
26	Loma Prieta	1989	6.93	52.53	517.06
27	Cape Mendocino	1992	7.01	6.96	567.78
28	Landers	1992	7.28	69.21	382.93
29	Northridge-01	1994	6.69	36.77	549.75
30	Northridge-01	1994	6.69	68.93	501.75
31	Northridge-01	1994	6.69	47.98	544.68
32	Duzce_ Turkey	1999	7.14	168.26	399.61
33	Caldiran_ Turkey	1976	7.21	50.82	432.58
34	Hector Mine	1999	7.13	166.11	375.16
35	Hector Mine	1999	7.13	43.05	382.93
36	Hector Mine	1999	7.13	74.92	436.14
37	Montenegro_ Yugoslavia	1979	7.1	66.67	585.04
38	El Mayor-Cucapah_Mexico	2010	7.2	45.47	523.99
39	Darfield_ New Zealand"	2010	7	124.96	586.28
40	Darfield_ New Zealand	2010	7	102.33	586.28

R_{RUP} and $V_{s,30}$means radius of rupture and share wave velocity

According to the structural dynamic modification [17], a cantilever beam linked with the ground by its free end and the stiffness modification was studied and it was found that the used rigid link is not inducing any change in the frequency response function of the cantilever beam, according to the equation.

$$\alpha_{ij}(\omega) = \sum\nolimits_{r=1}^{N} \frac{\phi_{ir}\phi_{jr}}{\omega_r^2 - \omega^2} \tag{1}$$

where $\alpha_{ij(\omega)}$ is the anti-resonance of a receptance FRF, which defines the frequency characteristic of a structure between two coordinates i and j; ω_r and $\omega$are the resonance frequencies; ϕ_{ir} and ϕ_{jr} are the mass-normalized modal displacements. The concept of structural dynamic modification was studied for the two main parameters of the cabinet structure that include the mass and stiffness provided by the number of cabinets.

Intensity measure (IM) definition

The peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), spectral acceleration (S_a) and spectral displacement (S_d) are usually selected as intensity measures for seismic fragility analysis in engineering applications. These IMs have the pros and cons when being applied to components in the nuclear power industry. Since the cabinet facility is sensitive to acceleration this study proposes the use of $S_a$as the intensity measure. As mentioned in the NUREG [21], the response of the acceleration-sensitive component in the electric cabinet is an important factor, which should be considered carefully for evaluating the dynamic characteristics. The PGA is a good index of peak acceleration in the time history, but it is not clear how to make the correlation between the input data with the fragility function for a frequency-sensitive component. The $S_{\bar{a}}$ was first introduced by Cordova [4]which is defined as the geometric mean of two S_a components at a range of the period of interest. Therefore, the $S_{\bar{a}}$ becomes the proposed IM to overcome the drawbacks.

$$S_{\bar{a}}(T_i) = \left[\prod\nolimits_{i=1}^{n} Sa(T_i)\right]^{1/n} \tag{2}$$

where n is the number of periods of interest used for determining the $S_{\bar{a}}$ in the frequency range of interest

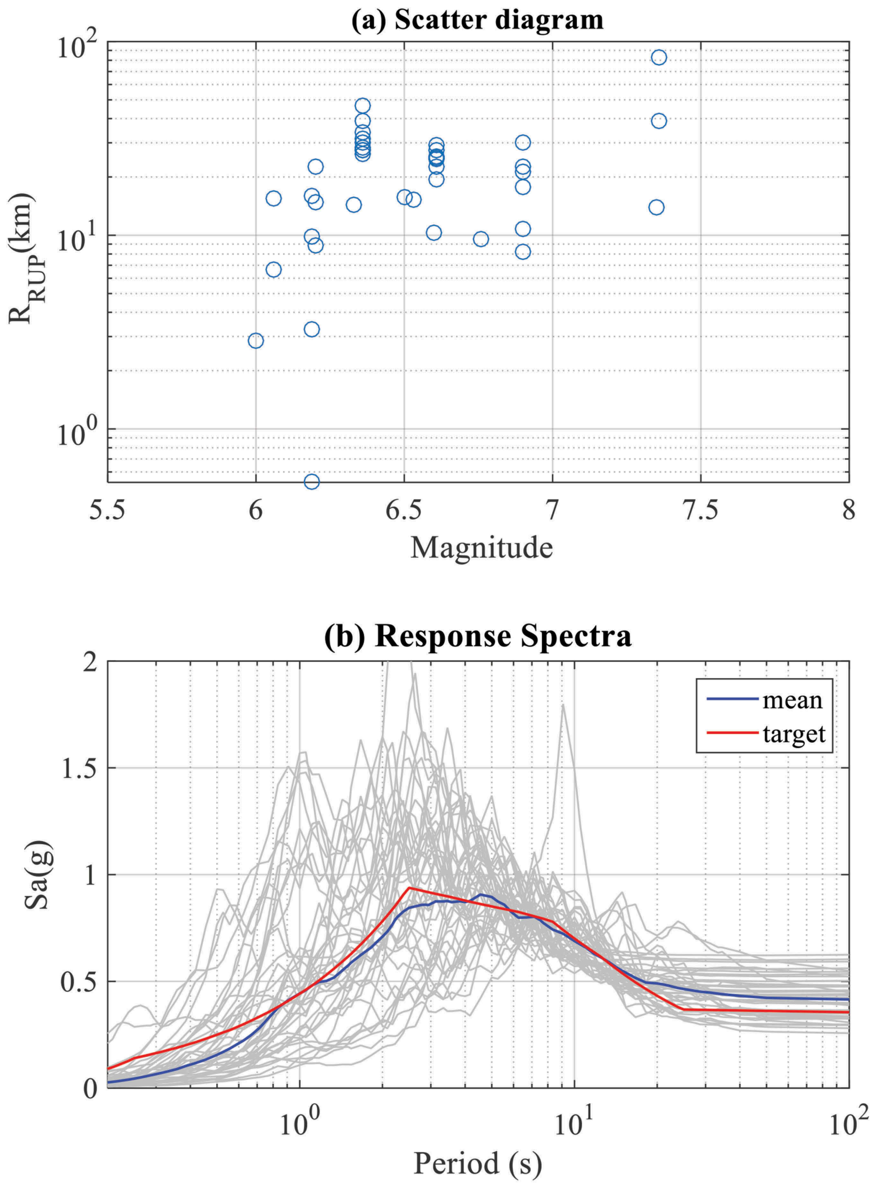

Figure 2. (a) Scatter diagram and (b) spectral matching to design response spectra.

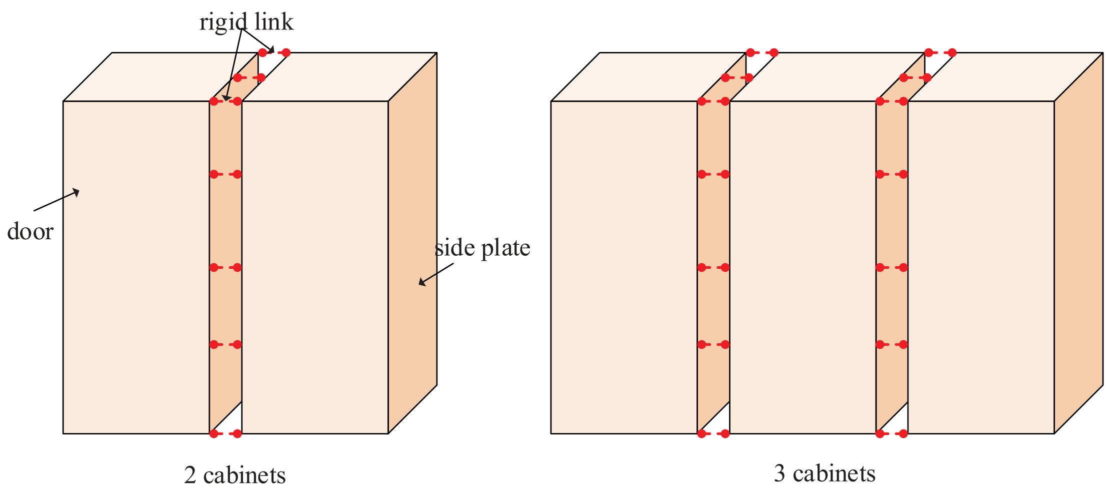

Figure 3. Typical cabinets model.

for electric cabinet range from 4 ~ 16Hz. Likewise, the HAZUS earthquake loss estimation methodology considers the spectral displacement for the drift sensitive non-structural components and spectral acceleration for the acceleration sensitive non-structural components [22].

Damage states

Generally, the response of a structure can be evaluated by the engineering demand parameters (EDPs), which are useful to predict the damage to the structural and non-structural components [23]. Previous studies have defined various damage levels/states (DS) and corresponding quantities to specify them. The damage limit states in seismic fragility analysis can be employed as maximum displacement/acceleration at the peak of the structure (θ_{max}) [24]the inter-story drift ratio (θ) [25], or the stress (σ) for evaluating the EDPs. Determining these limits for the damage measures vary for different structures such as bridges, wind turbine or nuclear power plant and its components. In this study, two design guidelines are followed to define the damage states by considering the spectral acceleration as an EDPs for the acceleration sensitive electrical cabinets that are listed below.

Fragility levels based on NUREG

The U.S. Nuclear Regulatory Commission (NUREG) document entitled 'Seismic Fragility of Nuclear Power Plant Components' (NUREG/CR-4659 BNL-NUREG -52,007 Vol.4) provides the probabilistic fragility levels for 18 electrical equipment's (non-structural components) in nuclear power plants. This guideline summarizes several failure modes of electrical equipment and suggested effective engineering demands (response demands) for the fragility functions such as acceleration response for the cabinet. Based on this guideline, the acceleration response is chosen to be a critical engineering demand parameter for the fragility analysis since it can be determined analytically with reasonable accuracy. The DS related to the zero-period acceleration at 2% damping is selected and this value is defined when the zero-period acceleration (ZPA) comes to 1.8g.

Fragility levels based on HAZUS

Based on the HAZUS earthquake loss estimation methodology, this section describes building fragility curves for slight, moderate, extensive and complete non-structural components damage states. Each fragility curve is characterized by median θ and lognormal standard deviation (β) values of potential earth science hazard (PESH) demand. Spectral displacement is the PESH parameter used for structural damage which is drift-sensitive while spectral acceleration is the parameter used for calculating non-structural damage to acceleration-sensitive components.

The peak acceleration values are listed in Table 2 for different seismic design level that summarizes the methodology used for defining the median values of the fragility function for the acceleration sensitive non-structural components. The moderate seismic design code is followed for the damage state definition, as Korea belongs to a low to moderate seismicity region. Historic documents such as the Annals of the Choson Dynasty contain many entries on the earthquake events that claimed many human casualties and serious property damages in the past 2000 years [26].

Table 2. HAZUS-based damage threshold for non-structural acceleration sensitive components.

	Acceleration at the threshold of non-structural damage (g)			
Seismic Design	Slight	Moderate	Extensive	Complete
High-Code	0.30	0.60	1.20	2.40
Moderate-Code	0.25	0.50	1.00	2.00
Low-Code	0.20	0.40	0.80	1.60

Development of fragility function

This study considers the linear time history analysis of the cabinet structure and its effect on the fragility function with the consideration of the grouping effect. The cabinet facility is excited under the 40 ground motions for the comparative analysis between the single cabinet and group of cabinets.

The output of fragility estimation is an estimate of the cumulative probability of being in or exceeding each damage state for the given ground shaking. Time history analysis for the cabinet structure corresponds to the intensity measure define by the Cordova et al. [4] and the HAZUS estimation for the acceleration sensitive electrical components. It is noteworthy that both the methods account for the same intensity measure (S_a) that is proved to be a good index of measuring the fragility function of the acceleration sensitive cabinet structure. The fragility functions are obtained using the maximum likelihood estimation (MLE). The probability of being in or exceeding a given damage state is modeled as a cumulative lognormal distribution. For structural damage, given the spectral displacement,S_d, the probability of being in or exceeding a damaged state,$d_s$ds is modelled as:

$$P(d_s|S_{\bar{a}}) = \Phi\left[\frac{1}{\beta_d} ln\left(\frac{\bar{S}_d}{\bar{S}_{d,ds}}\right)\right] \quad (3)$$

where $\bar{S}_{d,\ ds}$ is the median value of the spectral acceleration at which the acceleration sensitive component reaches the threshold of the damage state, β_d is the standard deviation of the natural logarithm of spectral acceleration of the damage state ds and $\Phi$is the standard normal cumulative distribution function (CDF) The CDF of a lognormal distribution was used to define a fragility function. In the present study, the fragility curves were generated by a damage state (DS) given the average spectral acceleration, $S_{\bar{a}}$. Thus, the fragility function can be written as follows:

$$P(DS|IM) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{IM}{\theta}\right)\right] \quad (4)$$

In which P is the probability that a ground motion with $S_{\bar{a}} = x$ will cause the structure to collapse, θ, and β are the median and the standard deviation of the intensity measures; $\Phi$is the standard normal cumulative distribution function (CDF). The maximum likelihood estimation is proposed by Shinozuka et al [11]. The assumption that the $Sa_{avg} = x_j$ for each ground motion is independent, the likelihood function of the entire data set was taken from the Bernoulli distribution as follows:

$$Likelihood = \prod_{i=1}^{m} \left[P(DS|S_{\bar{a},i})\right]^{p_i}\left[1 - P(DS|S_{\bar{a},i})\right]^{1-p_i} \quad (5)$$

where m is the number of $S_{\bar{a}}$ levels and Π denotes the product overall levels; p depending on whether the limit state exceeds or not, and takes the value 1 or 0, respectively. The fragility function parameters, θ andβ, were obtained by maximizing the likelihood function [27].

$$\left\{\hat{\theta},\ \hat{\beta}\right\} = \underset{\theta, \beta}{\arg\max}\ \ln(Likelihood) \quad (6)$$

Numerical modelling considering grouping effects

Prototype of cabinet

The cabinet specimen has a dimension of 800 × 800 × 2100 mm (width×height×depth) as shown in Figure 4. The electrical cabinet models were developed in SAP2000 environment according to the specified design drawings and technical specifications for the material properties. The material and element properties and cross-sections are given in Table 3. Inclusion of support conditions was considered by restraining all the degrees of freedom for displacement and rotation. The cabinet model consists of frames and panels which are connected by welded or screw fasteners. The rigid link was used to connect the panels and doors to the mainframe. The door is attached to the mainframe by shim and hinge connection, while the plates are connected to the frame using rigid links. The transformation of the prototype to the finite element model with the complete details of the support condition is presented in Figure 5.

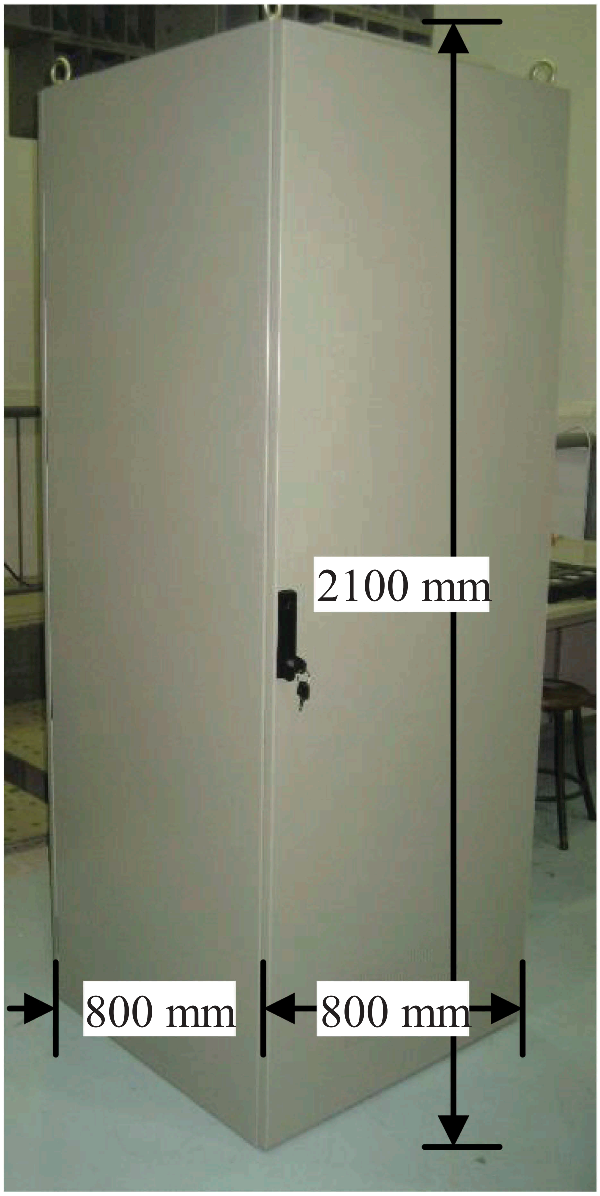

Figure 4. Details of prototype.

Table 3. Material and elements cross section specification.

Material properties	Element cross section
Type: SS400	Main frame: 50 × 50 x 3.2 mm
Modulus 2.14 x 10^6 kgf/cm^2	Sub-frame 1: 14 × 60 x 3.2 mm
Poisson's ratio: 0.3	Sub-frame 2: 2.3 × 60 x 3.2 mm
Unit weight: 7.85 $tonf/m^3$	Panel thickness: 2.3 mm

Validation and verification

The output response due to the impact hammer test was recorded by the accelerometer installed on the cabinet. The experimental data were analyzed for the extraction of the primary parameters using the frequency domain decomposition method (FDD). The experimental analysis reveals the fundamental frequencies with the corresponding damping ratio of the cabinet. The higher damping ratio with the frequency of 15.10 Hz for the side-side direction was selected because the model mass was more active in this mode which was further investigated through the FDD method. The validation of the numerical model was achieved with the dynamic properties of the experimental modal analysis. Figure 6 represents the natural frequencies of the cabinet due to the impact hammer test in both X (front-back) and Y(side-side) directions. The natural frequencies obtained from the

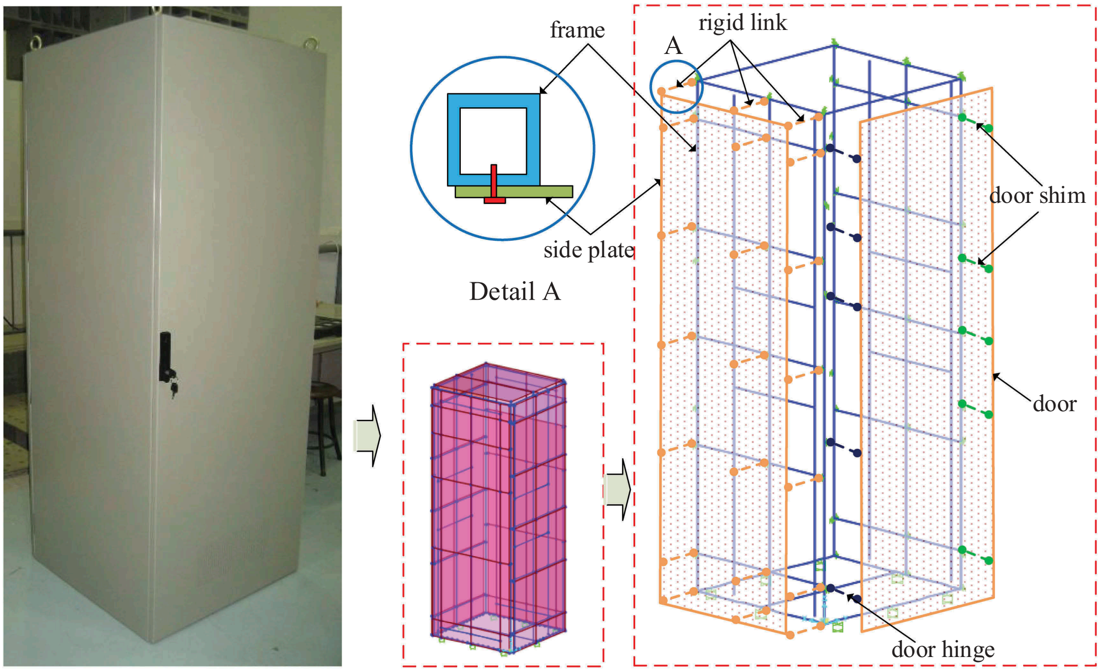

Figure 5. Numerical detailing of the cabinet structure.

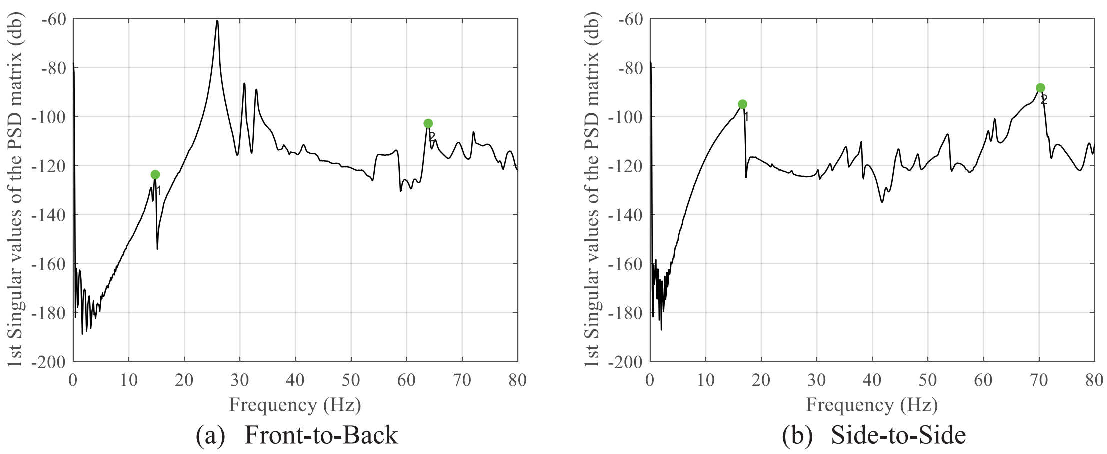

Figure 6. Fundamental frequencies for the cabinet prototype.

experimental analysis are used to investigate the global and local mode behavior of the cabinet. The global modes refer to the cantilever action of the cabinet that occurs at a lower frequency while the local modes correspond to the panel excitation that usually occurs at a higher frequency. The green marks in Figure 6 represent the global and local mode frequencies of the cabinet in both directions.

Following the experimental analysis, the natural frequencies of the cabinet are obtained using the numerical models. Table 4 compares the natural frequencies obtained from the experimental and numerical modal analysis for both sides of the cabinet. The dynamic properties from both the analysis were found in good agreement that validates the considered analysis.

Table 4. Natural frequencies of the cabinet (Hz).

Directions	Mode	Experiment	FEM
Front-Back	1	14.75	14.55
	2	61.85	61.05
Side-Side	1	15.10	15.12
	2	70.74	71.40

Numerical modelling considering grouping effects

Considering the grouping effect of the cabinet is one of the important aspects of this study and it was explained in Section 2.2 in detail. Numerically the grouping effect of the cabinets was considered by linking the cabinets together. The cabinets will effectively respond when they are group together as one unit to the seismic excitation and this scenario reflect the behavior of the cabinets more practically in NPP. Figure 7 represents the numerical model considering the grouping effect of the cabinets. The connections between the cabinets are fixed and rigid links were

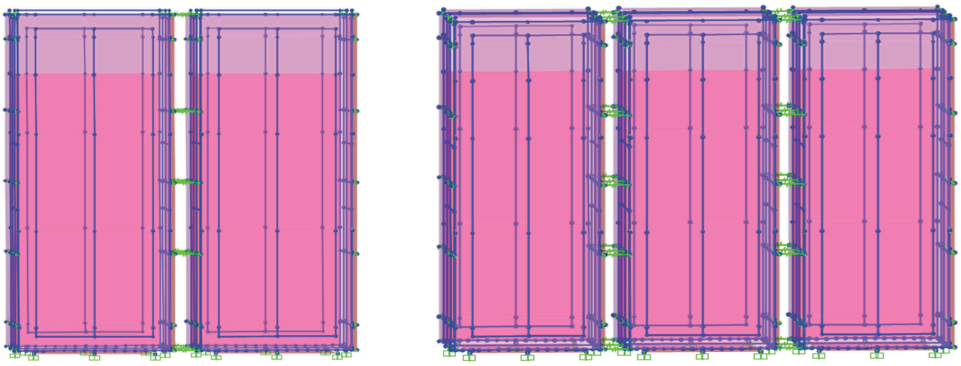

Figure 7. FE models considering the grouping effect of the cabinets.

assigned for this cause. It is understood from the structural dynamic modification that these rigid links are not inducing any change in the dynamic properties of the cabinet system. All the boundary conditions remain the same as used for the one cabinet structure.

Results and discussions

Response statistics based on two design guidelines

The time history analysis of the validated numerical model was carried out under the excitation of 40 earthquakes. Firstly, these earthquakes are scaled to 1g of ground motion and then incremental dynamic analysis (IDA) was used to scale the set of earthquakes in the range (0.1–4g). The scaled set of ground motion was applied to the three cabinet models for the fragility analysis of the cabinets. Three cases are considered (1) single cabinet (2) two cabinets (3) three cabinets, and the peak spectral acceleration is recorded at the top of the cabinet. According to the HAZUS guideline, different colors are used to represent the threshold spectral acceleration at the top of the cabinets for the different levels of damage states. The purple, green, blue, and red colors in Figure 8 represent the slight, moderate, extensive and complete damage (correspond to LS1, LS2, LS3 and LS4, respectively) to the cabinet structure. The grouping effect of the cabinet and its consideration in the seismic analysis are significant, as shown in the right column Figure 8. Similarly, the corresponding peak acceleration responses for the three cases are illustrated in left column Figure 8 for the NUREG guideline. The red colors manifest the complete damage to the cabinet and the purple one corresponds to the lower damage.

Based on the four damage states, under the same input excitation a single cabinet is found to be more vulnerable causing a complete failure with the corresponding peak (*Sa*) of 32 m/sec^2 ($\approx$ 3.2g) that is the exceeding of limit state LS4 (complete damage). In contrast, the two and three cabinets show the damage state LS3 (extensive damage) with the corresponding peak (*Sa*) of 17m/sec^2 ($\approx$ 1.7g) and 13 m/sec^2 ($\approx$ 1.3g), respectively. The significance of considering the grouping effect of the cabinet structure on the dynamic response is an important aspect to be considered. The acceleration response manifests that for a given seismic activity the structural response using the three scenarios produces a significant change. This change is further highlighted in the fragilities function for the given damage states.

Fragility function verification

Fragility analysis considers the structural strength and its vulnerability under seismic excitation and it does provide a decision-based outcome that is followed for the risk assessment of the structures. Electrical cabinet facility is one of the important facilities in the nuclear power plant structure and its seismic response analysis is highly important due to its sensitivity to the excitation. In this study fragility estimation of the cabinet and the corresponding significant change due to the grouping effect of the cabinet is studied. The concluded fragility analysis is found in good agreement with the fragilities function available in the HAZUS earthquake loss estimation methodology and NUREG design guideline as given in Tables 5 and 6.

The seismic intensity and the hazard parameters are defined as stated in section 2.3 and 2.4. The peak acceleration used for defining the mean threshold value θ_m for the slight, moderate, extensive and complete failure of the acceleration sensitive non-structural components by HAZUS methodology and this study is listed in Table 5 for the selected DM of 2g. The consistency in the θ_m value for two methods, and for different damage states (slight, moderate, extensive and complete) failure can be referred to the same intensity measure (S_a). It is noteworthy that the difference in the median values between the HAZUS and NUREG is due to the difference in the damage state (2g is used by HAZUS and 1.8g by NUREG respectively). Likewise, the fragility functions are given in Table 6 between this study and NUREG guideline as NUREG defines the median value $S_a$for the total collapse of the cabinet structure.

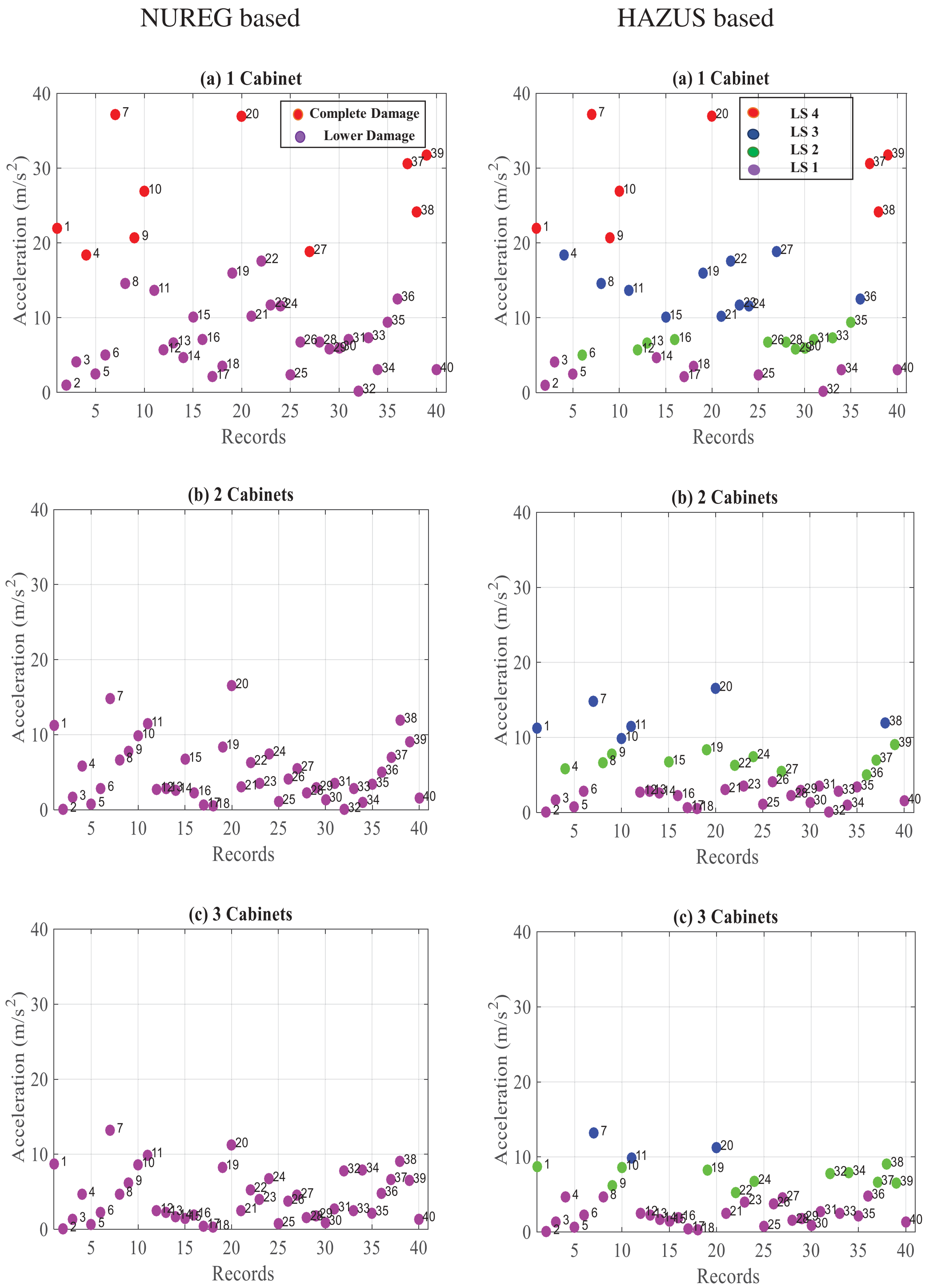

Figure 8. Responses statistics of cabinets based on HAZUS and NUREG damage states.

Table 5. Peak acceleration threshold (g) for single cabinet damage by HAUZS and this study.

Seismic Design	Slight	Moderate	Extensive	Complete
Acc.	0.25	0.50	1.00	2.00
This Study	0.23	0.48	0.91	1.9

Table 6. Peak acceleration threshold for single cabinet damage by NUREG and this study.

Approach	θ	β
NUREG	1.8g	0.66
This study	1.81g	0.64

Grouping effects and seismic capacity of cabinets

The fragility assessment is one of the good and practical approaches that can predict the risk associated with the structure. However, underestimating any scenario can cause a profound impact on loss estimation analysis. For this cause, the cabinet structures considering the grouping effect are investigated. The fragility functions are derived for the grouping effect of the cabinets following the two design guidelines as mention. It is noteworthy that the damage state for the single and group of the cabinet is the same.

The fragility curves are developed corresponds to the HAZUS and NUREG guidelines. Figure 9 represents the curves for the three cases of acceleration sensitive cabinet based on HAZUS methodology. The median value of spectral acceleration for the different damage states considering the grouping effects are enlisted in Table 7. The four damage states for the three different configurations of cabinets illustrate the significant effect of the grouping of the cabinet.

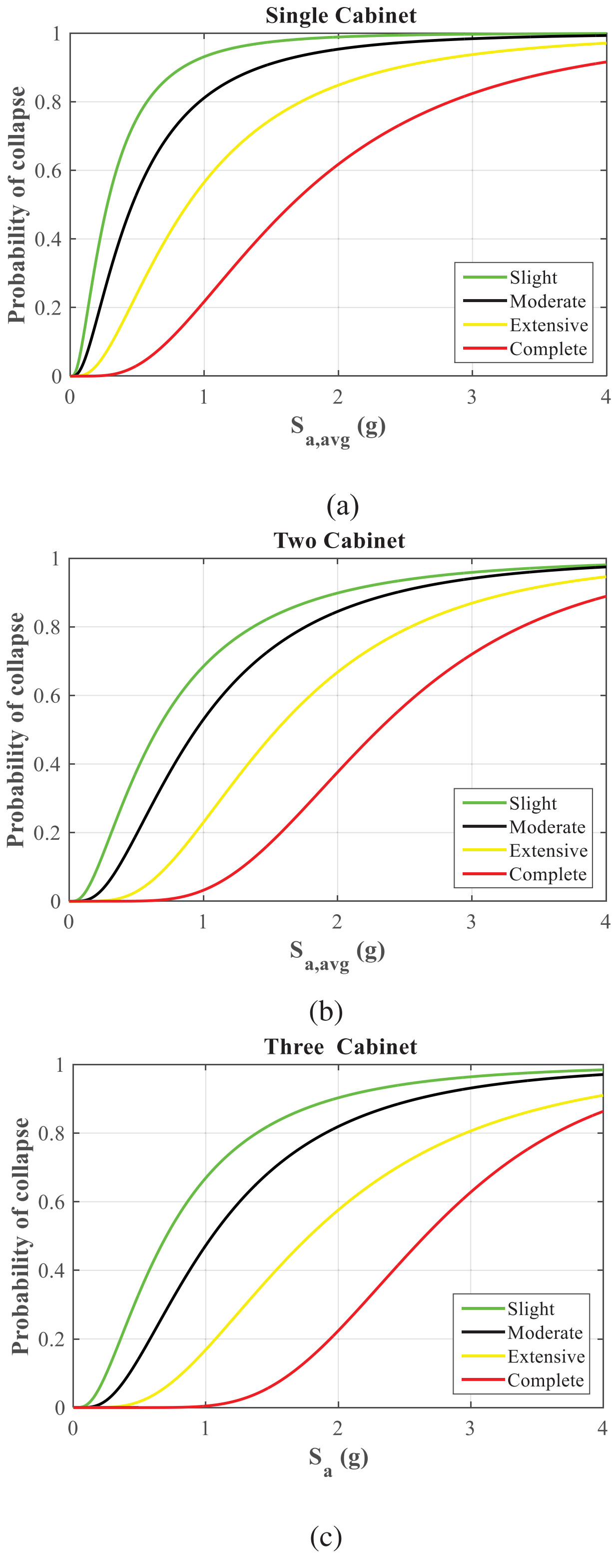

Figure 9. Fragility curve for three cases with different damage states based on HAZUS estimation.

Likewise, Figure 10 represents the total collapse of one, two and three cabinets, which shows a profound impact on the seismic capacity of the cabinet due to the grouping effect. Table 8 shows the median spectral acceleration values for the different damages of the cabinet following the NUREG guidelines. This dramatic change in the fragility function can correspond to the structural dynamic modification, the inertia of the system and support boundary condition. Grouping the cabinets together turn to increase the integral stiffness of the system more effectively which results in the decrement in the acceleration response of the cabinet system.

Levels of seismic intensity and difference in the probability of sustaining damage for a group of cabinets and a single cabinet vary about 28% and this extends up to 50% for three cabinets. These changes are more prominent as the intensity of the input excitation increased. It is noteworthy that the difference in the median value for the group of cabinets varies significantly compared to the one cabinet structure. This summarizes the effect of the grouping of the cabinet facility on the seismic capacity that varies about 30% for two and increases with the number of cabinets.

Conclusions

The seismic capacity evaluation of cabinet structure is investigated using the linear time history analysis. The structure is excited using the set of 40 ground motions that are spectrally matched to the DRS (RG 1.60). Using the IDA method, the structure is examined with the varying amplitude of PGA ranging (0.1–4g) with different cases. The input excitation and the corresponding damage state are the two parameters that are considered to highlight its effect on the seismic capacity of the electrical cabinet when a single cabinet and a group of cabinets are subjected to the same seismic excitation. Fragility analysis is conducted that manifests the significance of considering the grouping effect for the cabinets. The seismic evaluation reveals that the cabinet structure is a sensitive component of NPP and thus the grouping effect induces a very profound impact on the dynamic characteristic and seismic response of the cabinet system. This dramatic alteration in the dynamic characteristic of the structures is mainly induced by the structural dynamic modification and support boundary conditions of the cabinets.

For the real-time assessment of the cabinet facility, the two design guidelines HAZUS and NUREG are followed. The effect of the grouping on the seismic damage levels and capacity of the cabinets is discovered by the fragility functions that are developed for different

Table 7. Difference in the seismic capacity of electrical cabinets (HAZUS-based).

Case	One-Cabinet				Two-Cabinets				Three-Cabinets			
Damage	S	M	E	C	S	M	E	C	S	M	E	C
Acc. (g)	0.23	0.48	0.91	1.9	0.50	1.09	1.84	2.42	0.70	1.18	1.91	2.83

*S, M, E, C represents slight, moderate, extensive and complete damage.

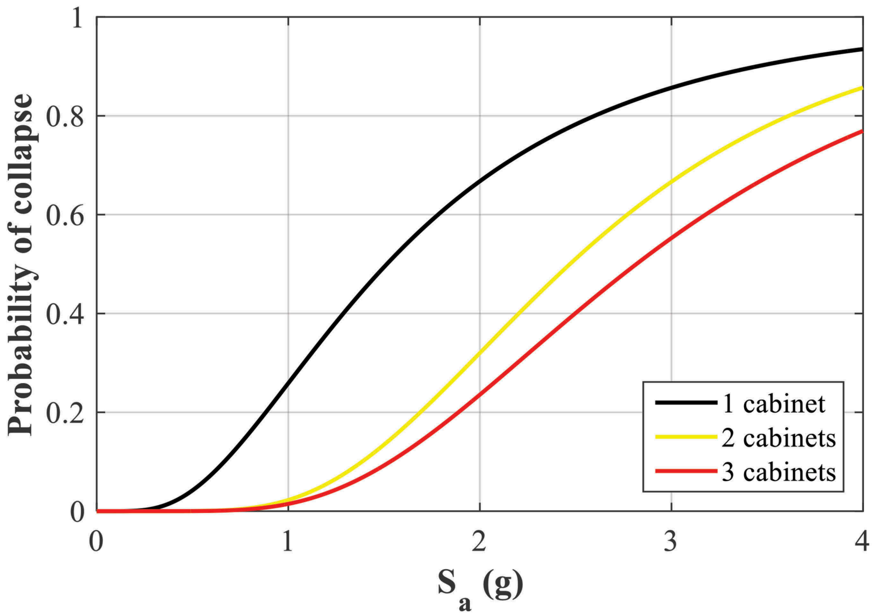

Figure 10. Fragility curve for complete damage state based on NUREG guideline.

Table 8. Difference in the seismic capacity of electrical cabinets (NUREG-based).

	One-Cabinet		Two-Cabinets		Three-Cabinets	
Case	θ	β	θ	β	θ	β
Acc. (g)	1.861	0.66	2.4	0.45	2.8	0.41

cases. The fragility assessment of this study is consistent with the fragilities available in the two design guidelines. Levels of seismic intensity and difference in the probability of sustaining damage for a group of cabinet and a single cabinet vary about 28% and this extends up to 50% for three cabinets. These changes are more prominent as the intensity of the input excitation increases.

The probability of failure for the complete damage state varies significantly as compared to a single cabinet. Procedural differences in the development of fragility curves may lead to significant differences in loss assessment results, to bay pass this concern the HAZUS and NUREG guidelines are also considered. Therefore, a close examination of fragilities for different scenarios should be undertaken. The most significant distinction between the methodology used by the authors, HAZUS and NUREG is that the fragility curves are derived based on spectral acceleration. Based on this study, the grouping effect of the cabinet structure is an important parameter to be considered in the seismic capacity evaluation of the cabinet structure in the NPP.

Disclosure statement

No potential conflict of interest was reported by the authors.

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