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Original Article

# Grouping effect on the seismic response of cabinet facility considering primary-secondary structure interaction

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ABSTRACT

Structural modification in the electrical cabinet is investigated by a proposed procedure that comprises of an experimental, analytical and numerical solution. This research emphasizes the linear dynamic analysis of the cabinet that is studied under the seismic excitation to demonstrate the real behavior of the cabinets in NPP. To this end, an actual electric cabinet is experimentally tested using an impact hammer test which reveals the fundamental parameters of the cabinet. The Frequency-domain decomposition (FDD) method is used to extract the dynamic properties of the cabinet from the experiment which is then used for numerical modeling. To validate the dynamic properties of the cabinet an analytical solution is suggested. The calibrated model is analyzed under the floor response obtained from the Connecticut nuclear power plant structure excited by Tabas 1978 (Mw 7.4) earthquake. Eventually, the grouping effect of the cabinets is proposed which represents the influence on the dynamic modification. This grouping of the cabinets is described more sophisticatedly by the theoretical understating, which results in a significant change in the seismic response. Considering the grouping effects will be helpful in the assessment of the real seismic behavior, design, and performance of cabinets.


## 1. Introduction

The seismic response analysis of structure based on its performance level is the crucial aspect of structural and earthquake engineering. The role of seismic evaluation is more challenging in case of sensitive structures like a nuclear power plant (NPP) and its components. For nonstructural components (NSC), the seismic evaluation is studied by many researchers using the structure-structure interaction which is generally known as Primary-Secondary Structure Interaction (PSSI). In the case of a nuclear power plant, the electrical cabinet is the facility that is considered to study the interaction effect [1]. Many researchers have investigated the linear and nonlinear behavior of the cabinet under different seismic excitations and field tests which mainly include an impact hammer test, shaking table test, etc.

Following the seismic analysis of the cabinet, it was found that the dominant failure mode faced by the electrical cabinet is an inadequate anchorage, and the percentage of the observed damage to the number cabinets is 30% [2]. To understand the dynamic characteristic of the cabinet using the deterministic and probabilistic analysis, significant studies have been done in the numerical modeling of the cabinets. The recent advancement in the cabinet model is from a stick model to a 2D frame and finally to a 3D frame model. The significance of these modeling is to achieve more close interpretation for the real behavior of the cabinet. Using the stick model approach, it was found that the response of the cabinet is non-linear even when the input motion is not very high [3].

Based on the dynamic characteristic of the cabinet, the evaluation of its seismic response is considered using the primary-secondary structure interaction. In PSSI, the primary structure provides resistance to all the loads applied to it. It is the supporting structure for the equipment (non-structural component). Secondary structures are the members that are not part of the primary load-bearing components in a structural system. A secondary structure may include the following components: stairways, parapets, ceilings, piping systems, mechanical and electrical components, emergency power systems, computers, data acquisition systems, and communication equipment.

Floor response method or in-structure response method is the

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type of time history analysis used for the equipment that is located within the structure, as the equipment doesn't have direct interaction with the ground, so the floor excitation is used to qualify the performance of the equipment. The floor response spectra method was firstly used for generating the maximum response of the secondary structure by Penzien and Chopra [4], Kanpur and Shao [5]. The amplification effect of the cabinets was considered in the lower floors when the natural period of the non-structural components is equal to the second or third period of the building with the consideration of the non-linearity and narrowband excitation of the primary structure [6]. In the work by Segal and Hall [7], the interaction effect of the cabinet to the primary structure was studied; it was found that mounting of cabinets on the primary structure will not reduce the peak response and it will not act as a damper for the primary structure. Using the structure interaction, an accurate prediction for the top displacement of the secondary structure was concluded by considering the relationship between the interacting force and the response under dynamic loading [8]. As the secondary structures are not subjected to the external excitation but in case of seismic activities, they are excited by the force induced in the primary structure, which can be considered in the form of floor response [9].

Primary-secondary structure interaction was considered using the decoupling method for the generation of maximum floor response spectrum [5]. The structural modelling of an auxiliary building using 3D and 2D stick models with the consideration of non-structural components was investigated by Hur et al. [10] and it was found that the non-structural components are directly influenced by the dynamic characteristic of the primary structure. These interactions are important to be considered for the dynamic analysis of both structural and non-structural components. The location effect of the nonstructural components within the primary structure has been investigated with a significant impact on its seismic response [11].

The dynamic characteristic of a cabinet is mainly examined by its global and local mode considerations. The global mode corresponds to the cantilever action of the cabinet frame, while the corresponding high frequency modes are the local modes. Local modes are used to study the stiffness effects of the plates and their diaphragm action under the lateral loads. Local panel's deformation occurs at higher vibration modes that are important to be considered for the electrical devices that are attached to the panels [12]. In the field of structural engineering, the global behavior of the structure must be considered, as it is directly affected by the support boundary condition in the model analysis [13]. The non-linear behavior of the supporting structure can amplify the acceleration response of the tuned secondary structure [14].

In general, three methods are used to assess the performance of electrical cabinets such as: (1) experimental test (i.e., shake table test or impact hammer test), (2) analytical method related to the development of finite element model (FEM), and (3) expert opinion [15]. Moreover the in-cabinet response spectrum (ICRS) should be estimated prior to the qualification of devices mounted in electrical cabinets [16]. In Electric Power Research Institute (EPRI) report, each device attached to the cabinets is analyzed using three different floor response spectra including different amplitude with dominant frequency range to get the amplified response spectra [17,18]. The primary concern of this research focuses on the cabinet as a secondary structure while considering its grouping behavior under the seismic excitation. Many researchers have analyzed the cabinet by using numerical solutions [3, 10, 12] and modeled the cabinet as a stick model, 2D frame and 3D frames; and its seismic response analysis has been carried out. However, to the best knowledge of the authors, no extensive studies on the grouping effect of the electrical cabinets and its structural modification on the modal characteristics have been reported in the published literature. This paper emphasizes on the dynamic response analysis due to the grouping effect of the electrical cabinets based on the primary-secondary structure interaction.

## 2. Methodology

Electrical cabinets are important equipment, they require an accurate and practical approach to evaluate their performance due to their seismic sensitivity. These evaluations are the essential requirements for the safety of NPP industry. Based on the seismic evaluation of these cabinets the following concerns are presented that are not addressed specifically in the present literature.

- How rational is the approach to consider the seismic response of a single electrical cabinet and its integration to the multi-cabinets?
- What will be the seismic behavior to consider the grouping effect of the cabinet system rather using the integration of the dynamic behavior of a single cabinet?
- The grouping effect with a change in the boundary condition can induce any significant impact which can be considered for the seismic analysis?

The schematic procedure as shown in Fig. 1 is used to investigate the structural dynamic modification and response analysis due to the grouping effect of the cabinet. The structural modification is implemented using experimental, analytical and numerical solutions that are explained in detail in the next sub-sections. The seismic response analysis is considered to elaborate the effect induced by the grouping of the cabinets. For a better understanding of the proposed problem and its solution, the theoretical explanation is presented in Section 3 that comprises of frequency response function (FRF), response analysis based on Rayleigh damping and structural modification.

### 2.1. Experimental model analysis

An experimental vibration test was conducted on the prototype of the electric cabinet in INNOSE Tech Company in Korea (http://innosetech.com). The cabinet specimen has a dimension of 800 $\times$ 800 $\times$ 2100 mm (width, height, depth) as shown in Fig. 2a and weighing approximately 290 kg. The impact hammer test was conducted in two directions and six accelerometers were installed on the panels to get the dynamic response of the cabinet as shown in Fig. 2b. The recorded responses from the accelerometers are analyzed to get the preliminary dynamic properties that are explained in Section 4.1.

### 2.2. Finite element modelling

The finite element model (FEM) of the cabinet was created in the SAP2000 environment according to the design drawings and technical specifications for the material properties. The material properties and element cross-sections are given in Table 1. The cabinet model consists of frames and panels which are connected by welded connections. In the case of FEM modelling, the rigid links were used to connect the panels to the main-frame. The boundary condition was included by restraining all the degrees of freedom for displacement and rotation.

Grouping effect was considered by linking the cabinets together using the rigid links. These connectors are not inducing any change in the dynamic characteristic of the cabinet and that are verified from the theoretical understanding of structural dynamic modification explained in Section 3.1. The natural frequencies of the two and three cabinets were determined based on the calibrated single cabinet. The fixed link was assigned only to connect the cabinet as one unit. Fig. 3 represents the finite element models for the

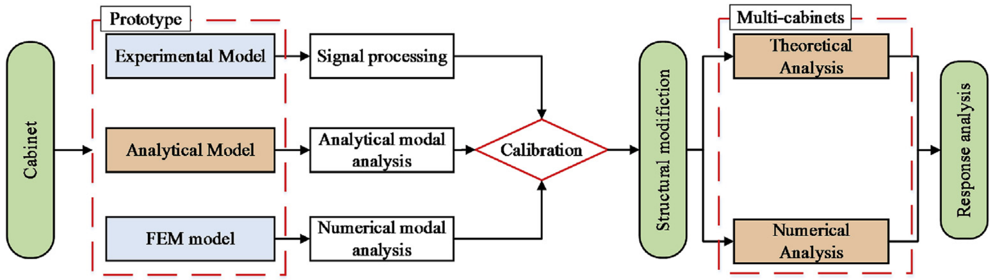


**Fig. 1.** Schematic procedure of the proposed analysis.

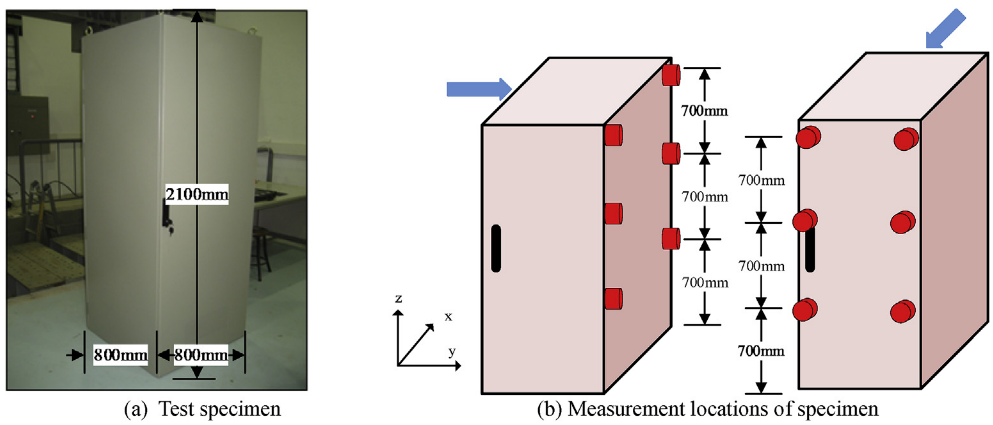


**Fig. 2.** Configuration and measurement locations of the test specimen.

**Table 1**
The material and element properties used in the cabinet.

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

grouping effect of the cabinet structure that were linked together using fixed links.

### 2.3. Simple stick model

The simplification of the cabinet structure was considered, and a stick model was developed that carries the same properties as the cabinet prototype. The primary parameters for the dynamic characteristics are obtained by the experimental test that contains the mass, damping ratio and natural frequency of the cabinet. Considering the cabinet as a single degree of freedom (SDOF) system, the stiffness was calculated for a stick model which was then simulated in the SAP2000 environment. The stiffness of the cabinet as an SDOF is derived from Eq. (1):

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

where $k$ and $m$ are the stiffness and mass of the cabinet structure. Knowing the natural frequency and the mass of the cabinet, the stiffness as an SDOF is calculated. The calculated parameters are shown in Table 2, which were assigned to the stick models. The mentioned parameters are experimentally extracted for one cabinet and it was calculated for the two and three cabinets to consider the grouping effects. Considering the lumped mass of the cabinet, the stick model was analyzed under the floor response obtained from the Connecticut power plant.

### 2.4. Analytical procedure for model analysis

The decoupling analysis was considered in which the floor response was used for the interaction effect between the NPP structure and the electrical cabinet. The simplest solution was proposed for the cabinet as an SDOF system. In this procedure, a linear elastic oscillator, shown in Fig. 4, was considered for the excitation under the floor response. This model was developed to consider the cantilever action (global mode) of the cabinet and it was calibrated with the numerical model. This linear elastic oscillator has the same dynamic properties as a simple stick model which is considered in Section 2.3. The SDOF is restrained with the floor and it was excited under the floor excitation.

The equation of motion of linear elastic oscillator during the floor motion is defined as follows:

$$\ddot{u} + 2\zeta\omega_n\dot{u} + \omega_n^2 u = -\ddot{u}_g \tag{2}$$

Where $\ddot{u}_g$ is the horizontal floor motion, $\omega_n$ is the natural frequency of the system that is given in Eq. (1) and $\zeta = c/(2\sqrt{km})$ is the damping factor. The model was analyzed using the available ODE23 function by implementing Runga-Kutta method in MATLAB.

### 2.5. Considering the interaction effect

The interaction of primary with the secondary structures is considered under the following two aspects:

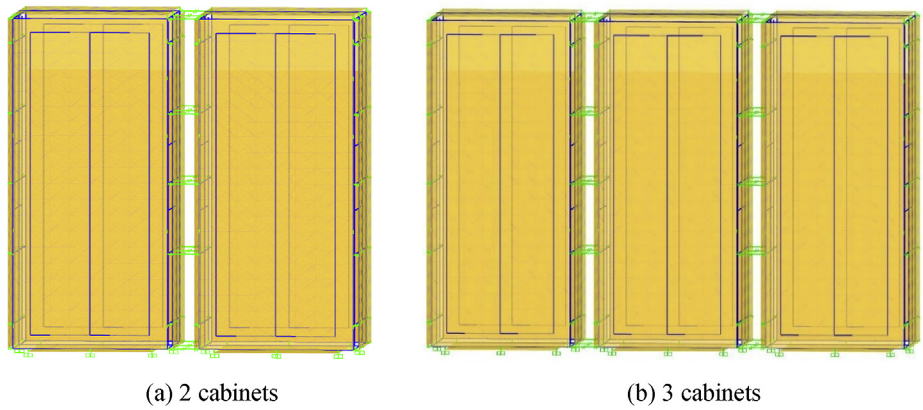


**Fig. 3.** FE models for the grouping effect of the cabinets.

**Table 2**
Model parameter for numerical models.

| Case | Mass (kg) | Frequency (Hz) | Calculated Stiffness ($kN/m$) |
|---|---|---|---|
| 1 cabinet | 287 | 16 | 2897 |
| 2 cabinets | 574 | 20 | 9055 |
| 3 cabinets | 861 | 22 | 16434 |

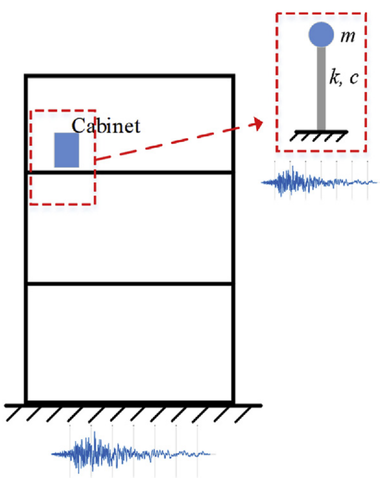


**Fig. 4.** Simplified model of the electrical cabinet.

(a) The interaction effect of the cabinets as a secondary structure on the primary structure was negligible and it is explained as follows:

Based on the equation of motion

$$\boldsymbol{F}(t) = \boldsymbol{M}\ddot{U} + \boldsymbol{C}\dot{U} + \boldsymbol{K}U \tag{3}$$

The generalized equation of motion for the combined structures are given as below

$$\boldsymbol{M} = \begin{bmatrix} m_p & 0 \\ 0 & m_s \end{bmatrix}; \ \boldsymbol{C} = \begin{bmatrix} c_p & 0 \\ 0 & c_s \end{bmatrix}; \boldsymbol{K} = \begin{bmatrix} k_p & 0 \\ 0 & k_s \end{bmatrix} \tag{4}$$

Where $m_p$ and $m_s$ represent the mass matrices for primary and secondary structures (cabinet); $c_p$ and $c_s$ represent the damping matrices of primary and secondary structures; $k_p$ and $k_s$ represent the stiffness matrices of primary and secondary structures, respectively.

As the mass of the cabinet to the total mass of the auxiliary structure is very small. Therefore, the increment in the mass matrix by the $m_s$ as a coefficient of acceleration is very low. As a result, the increasing number of cabinets will not affect the dynamic response of the auxiliary structure. The same pattern is followed for the velocity and displacement response. The mounting of the cabinet will not act as a damper for the primary structure and it can't reduce the response of the primary structure [5]. PSSI can be neglected when the interacting frequency of the primary and secondary are not coinciding [19].

(b) The interaction effect of the primary structure on the secondary was considered. The floor response method which includes the excitation of the Connecticut power plant structure under the strong earthquake. The recorded floor response was then used to excite the cabinet structure, irrespective of the specific location for the cabinets in the primary structure, the maximum floor response was recorded and applied to the cabinet system.

## 3. Theoretical understanding

### 3.1. Structural dynamic modification

To understand the dynamic behavior of the grouping effects of the cabinets more sophisticatedly, the theoretical understanding is followed. The comprehensive analysis for the structural system modification using the physics of the problem is introduced in this section. The increment in the structural modification is from the two entities mainly the mass and stiffness. The resonance and shift in the frequency of a dynamic system are directly influenced by the mass and stiffness of the system. The dynamic modification of structure is improved by predicting the modification induced by adding modification like lumped mass, dampers, and rigid links, etc. [20]. As the stiffness and mass modification which was considered for a cantilever beam in the form of a spring linking it to the ground by its free end. The spring was used for linking the beam to the ground and will not induces any change in the anti-resonance of the frequency response function (FRF), as according to Eqs. (5) and (6). In the same way, the rigid link was assigned between the two and three cabinets for the grouping effect as shown in Fig. 3.

$$\alpha_{ij}(\omega) = \sum_{r=1}^{N} \frac{\varphi_{ir}\varphi_{jr}}{\omega_r^2 - \omega^2} \tag{5}$$

$$\det\left[\mathbf{K} - \Omega^2\mathbf{M}\right] = 0 \tag{6}$$

where $\alpha_{ij(\omega)}$ is the anti-resonance of a receptance FRF, which defines the frequency characteristic of a structure between to coordinates *i* and *j*; $\omega_r$ and $\omega$ are the resonance frequencies; $\varphi_{ir}$ and $\varphi_{jr}$ are the mass-normalized modal displacement, respectively. The $\Omega$ is the anti-resonance; ***K*** and ***M*** represent the stiffness and mass matrices. This stiffness modification addresses the behavior of cantilever beam that is linked with the ground, the addition of the stiffness in the form of spring to the vertical coordinate will significantly increase the stiffness of the system and eventually the natural frequency is dependent on the stiffness properties. On the other hand, if mass modification is considered the natural frequencies are decreased [21].

### 3.2. Response analysis based on Rayleigh damping

As the structural modification was stated due to mass and stiffness that eventually change the structural frequency of the cabinet. These two structural parameters are discussed under the philosophy of Rayleigh damping. Chopra developed the correlation of the four structural parameters (i.e. mass, stiffness, frequency, and damping) and how its effect on the structural response [22]. Based on the Rayleigh damping the corresponding damping provided by the mass and stiffness are given in Eq (7).

$$\omega_n = \sqrt{\frac{\mathrm{K}}{\mathrm{M}}} \; \& \mathrm{D} = \alpha\mathrm{M} + \beta\,\mathrm{K} \tag{7}$$

$\omega_n$ is the natural frequency; K and M represent the stiffness and mass of the system, respectively; D represents the proportional damping; $\alpha$ and $\beta$ are mass and stiffness coefficients, respectively.

$$\zeta = \frac{\mathrm{D}}{2\sqrt{\mathrm{KM}}} = \frac{\alpha\mathrm{M} + \beta\mathrm{K}}{2\sqrt{\mathrm{KM}}} \tag{8}$$

Where $\zeta$ is the damping ratio based on the mass and stiffness proportional damping.

For damping proportional to mass $\beta = 0$, the damping ratio can be expressed as $\zeta = \frac{\alpha}{2\omega_n}$. That means, the modal damping ratio decreases as the natural frequency increases. While considering the stiffness proportional damping, $\alpha = 0$, (structural damping) Eq (8) can be written as $\zeta = \frac{\beta\mathrm{K}}{2\sqrt{\mathrm{KM}}} = \frac{\beta\omega_n}{2}$. The modal damping ratio increases as the natural frequencies increases that conclude that higher modes are increasingly more damped than lower modes [22].

A modal frequency is mainly increased by the two reasons and this is valid for all structures, even more complicated ones, that is decreasing mass or increasing stiffness [23]. This alteration effect in the cabinet system due to mass and stiffness can be easily summarized by the Rayleigh damping mechanism.

### 3.3. Frequency response

The validation process for the numerical simulation is mostly followed by the frequency response (FR). The frequency response function reveals the fundamental natural frequency of the structure. The frequency domain contains the resonant peaks which correspond to the natural frequency. The most common method followed by FR is the ratio of response of the structure to the input force. It may be acceleration, displacement and velocity responses. The ratio of acceleration to the force is the currently accepted method for model testing [24].

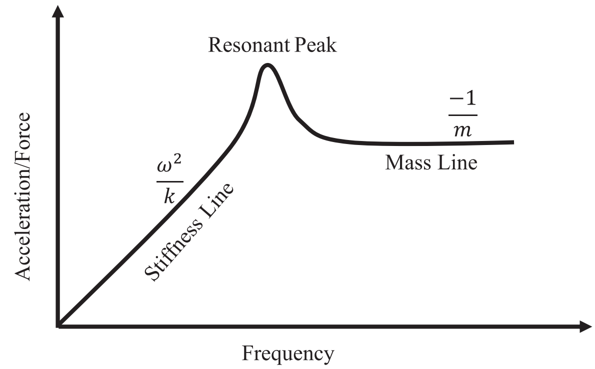


**Fig. 5.** Acceleration/force frequency response at resonance [24].

In the dynamic frequency response, the damping of the system is the only governing factor to the magnitude of the response of the excited structure at resonance [25]. The behavior of a single resonant peak by the frequency response is shown in Fig. 5. The resonant peak is primarily controlled by the stiffness of the system, the related stiffness $(\omega^2/k)$ increases at a slop of 2 on a log plot. Contrarily, after the resonance, the inertance $(-1/m)$ of a mode explains the properties of the peak response. The frequency of the excited mode decays to the modal inertance which is known as mass line. The overall effect of the frequency response is governed by the stiffness and mass of the system [26].

## 4. Results and discussions

### 4.1. Calibration of cabinet

#### 4.1.1. Experimental outcomes

The natural frequencies of the cabinet from the vibration test are determined using the frequency domain decomposition (FDD) method [27]. The FDD is a modal analysis technique which generates a system realization using the frequency response given multi-output data. This technique involves the main steps which are listed below:

- Computing Power Spectral Density (PSD) matrix $S_{yy}(w)$ from the time series data as follows

$$S_{yy}(w) = U(w)^T \Sigma(w) V(w) \tag{9}$$

where $\Sigma$ is the diagonal matrix consists of the singular values $(\sigma_i's)$ and $U$ and $V$ are unitary matrices.

- Performing singular value decomposition of the spectral density matrices.
- If multiple test setups are available, then averaging of the singular value for all test setups are considered.
- To estimate the natural frequency Peak picking of the singular values are considered.

Based on the FDD technique, the fundamental frequencies of the cabinet in front-to-back (FB) and side-to-side (SS) was obtained from the experimental test are shown in Fig. 6.

The experimental analysis using signal processing reveals some of the fundamental parameters for the modal analysis. The

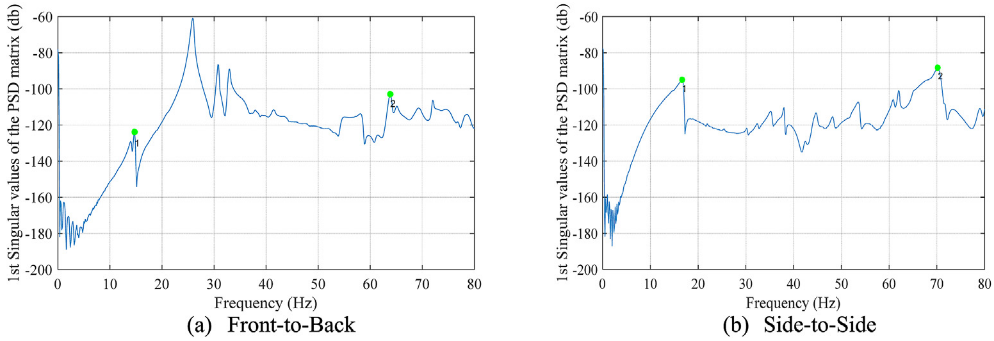


**Fig. 6.** The fundamental frequencies of the test result.

recorded response from the accelerometer was studied and the peak picking method was proposed as shown in Fig. 6. The selection of peak was considered for the resonant frequencies for both FB and SS direction which contain the higher modal participation ratio. Fundamental frequencies of 14.75 Hz and 15.12 Hz were extracted for FB and SS direction as given above.

#### 4.1.2. Analytical solution

To compare the performance of the analytical solution with the numerical solution, a time history analysis was carried out using the floor response of the primary structure. The time history and the response spectra of the input floor response are given in Fig. 7.

Only the horizontal component of the floor motion was considered. The transfer function (TF) was determined by the response ratio for the top and bottom of the cabinet. Fig. 8 represents the TF of the two models, in which 15.12 Hz and 15.63 Hz were obtained for numerical and analytical models. This agreement of the two modeling techniques can be regarded as a validation of the proposed method that can be used for the response analysis of cabinet structure.

### 4.2. Dynamic characteristics of the grouping effect

The response analysis of a single cabinet was examined based on the analytical, numerical and experimental procedures. The numerical modal analysis was carried out for the two selected reasons.

- Local panel excitation
- Cantilever action of the cabinet

To make a close interpretation of the real behavior, the cabinets were analyzed under the same floor response in X- and Y-direction. The principal modes of vibration were selected based on model participating ratios, local and global modes effect.

Fig. 9 illustrates the analysis of the cabinet system under these considerations. In figure, the X- and Y-directions refer to the front-to-back and the side-to-side directions, respectively. The boundary condition in the X-direction is different from the Y-direction. The high stiffness in the X direction due to the support boundary condition is responsible for the higher frequency.

High amplitude is required for the excitation of the mainframe in the FB direction and lower amplitude to excite the panels connected in the same direction. Contrarily, the less stiffness in the Y direction allowing to excite the structure under the low amplitude and higher for the panels. The effect of the boundary condition and stiffness is responsible for the change in frequency of the cabinet in both the global and local mode of the cabinet, as it was investigated that support boundary conditions can directly affect the global behavior of the structure [6]. The selected mode shapes for X and Y direction for the cantilever action of the cabinets and the local panel deformation for three different cases are presented in Fig. 10.

Table 3 represents the shift in the natural frequencies for three cases under the dynamic modification induced by the grouping effect of the cabinets.

### 4.3. Dynamic response analysis

The dynamic response of cabinets is investigated using the experimental, analytical and numerical techniques. Some of the selected parameters are explained for the real dynamic behavior of

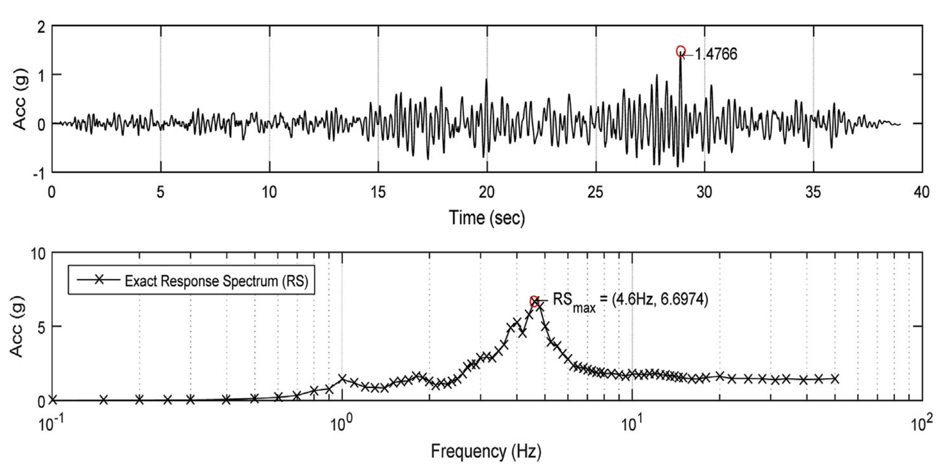


**Fig. 7.** Time history and response spectra of the floor response.

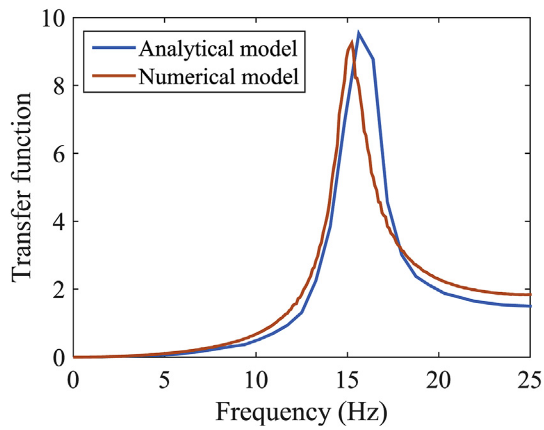


**Fig. 8.** Transfer function for analytical and numerical models.

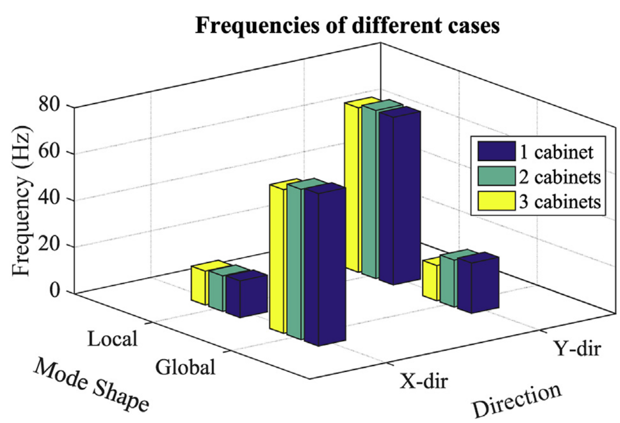


**Fig. 9.** Modal characteristics for the cabinets.

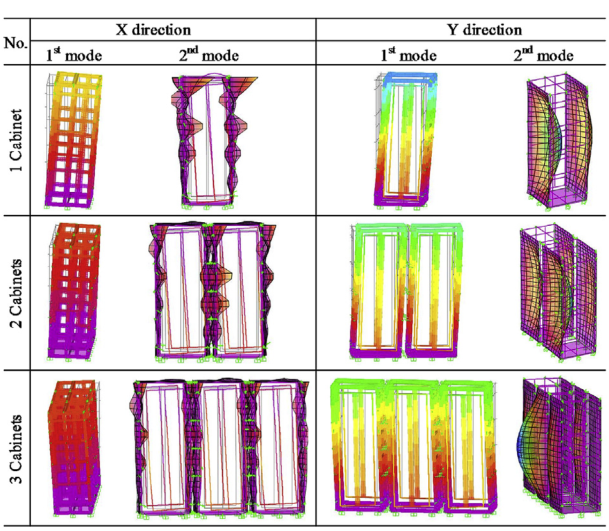


**Fig. 10.** Principal modes of vibration for three cases.

the cabinet and its grouping effect under seismic excitation.

*4.3.1. Acceleration response*

The sensitivity of the nuclear power plant component to the seismic acceleration is one of the highlighted aspects of its performance evaluation. These acceleration sensitive cabinets were examined under the primary-secondary structure interaction using the floor response that is recorded from the Connecticut power plant structure under Tabas earthquake. Parametrically calibrated stick models were used for the simplest solution and for understanding the increment of the mass and stiffness entities to the structural system. The acceleration response of the stick model in the time domain is given in Fig. 11a that gives a clear idea about the peak acceleration decrement due to the structural modification in the cabinet system. Increasing the number of cabinets results in a significant change in the response. Response spectra for the acceleration response are given in Fig. 13a which demonstrates the reduction in the peak response and the shift in the resonant frequency of the system.

Simultaneously, the 3D FEM of the system and its seismic response under the same floor excitation is given in Figs. 11b and 13b. The varying acceleration from the bottom to the top of the cabinet is given in Fig. 12. This reduction in the acceleration response is due to the structural behavior modification that increases the inertia of the system which is provided by the additional stiffness by the increasing number of cabinets.

**Table 3**
Natural frequencies (Hz) of cabinets due to grouping effect.

| Direction | FE Models | | |
|---|---|---|---|
| | 1 cabinet | 2 cabinets | 3 cabinets |
| Front-Back | 14.55 | 15.24 | 15.76 |
| | 61.85 | 64.74 | 67.77 |
| Side-Side | 15.12 | 20.15 | 21.61 |
| | 70.74 | 71.33 | 72.10 |

*4.3.2. Response spectrum*

The recorded responses for the three different cases were transferred from the time domain to the frequency domain using Fourier transformation that is generally called the response spectra. Frequency response spectrum is used to investigate the seismic dynamic characteristic of the cabinet structure. The structural modification is studied, and the resonant peaks for the three cases are presented in Fig. 13 that reflects the change in the resonant frequency due to the grouping effect of the cabinets. The addition of cabinet and a corresponding shift in the resonant peaks is directed to the structural modification induced by the stiffness of the systems. Fig. 13 illustrates the significant change in the response. Considering a single cabinet, the peak acceleration response of 23.90 $m/s^2$ was recorded. While the peak responses of 10.50 $m/s^2$ and 6.948 $m/s^2$ were recorded for the two and three cabinets, respectively. This reduction in the response was more than two times in the case of two and it increases with the number of cabinets.

Comparatively the resonant frequency modes for a single cabinet are less damped as compared to the multi cabinets which can be regarded to the damping effect provided by the increased mass and stiffness. This additional damping provided by the grouping of the cabinets is responsible for the depletion observed in the cabinet's dynamic response. The resonant frequency of 16 Hz was recoded for one cabinet, a frequency shift of 4 Hz for two cabinets and 6 Hz for the three cabinets was recorded. This shift in the frequency indicates the change in the total stiffness of the system which is responsible for changing the model characteristic. As the modal frequency is mainly increased by the two reasons and this is valid for all structures, even more complicated ones, that is decreasing mass or increasing stiffness [23]. This increment in the frequency relates to the increase in the number of cabinets, indicating a significant change in the response. It should be noted that for a cabinet the fundamental mode is not always its dominant

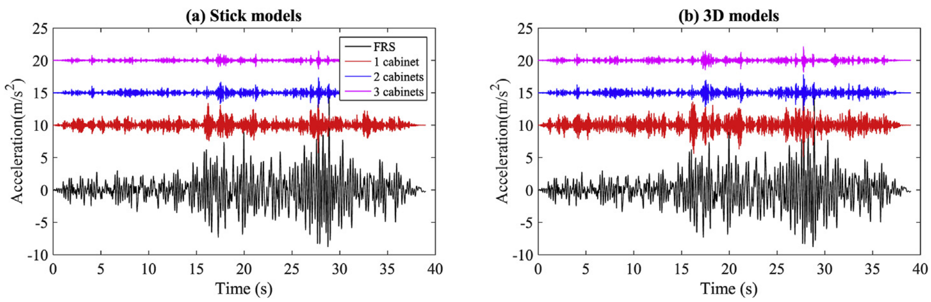


**Fig. 11.** Acceleration responses of different models under floor response.

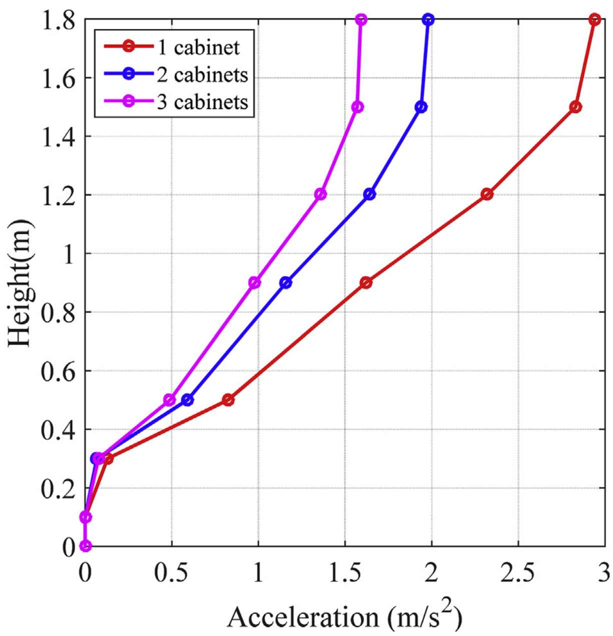


**Fig. 12.** Acceleration responses of the 3D model.

**Table 4**
Dynamic characteristic of cabinets.

| Case | Significant Mode | Modal mass Participation | Resonant Frequency (Hz) |
|---|---|---|---|
| 1-Cabinet | Mode 3 | 69.55% | 15.12 |
| 2-Cabinet | Mode 5 | 68% | 20.15 |
| 3-Cabinet | Mode 7 | 69% | 21.60 |

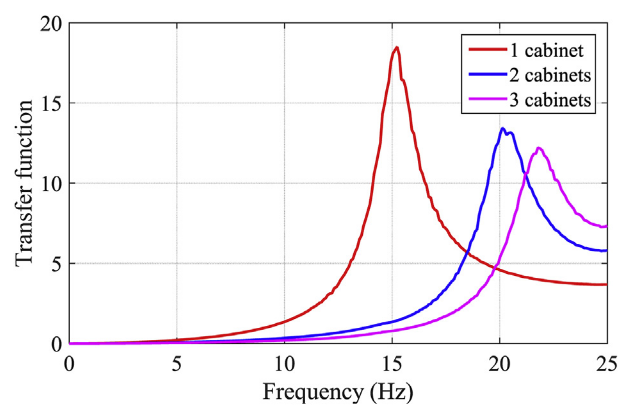


**Fig. 14.** Transfer function from the cabinet's response.

mode. The significant mode is based on the type of cabinet and the instruments installed on the cabinet panels that are stated as local and global modes [28]. For instance, the significant mode for three cases with the dominant frequency and maximum mass participation ratio are listed in Table .4.

#### 4.3.3. Transfer function

The fundamental frequency for the global mode of the cabinet was measured from the top and mid-point response of the cabinets. Response under the floor excitation was measured for the three cases and the transfer function was defined that relates the input excitation to the output response of the cabinet. The resonant frequency varies significantly due to a change in the boundary condition and the structural modification in the form of an increasing number of cabinets. Fig. 14 shows the shift in the resonant frequencies due to the grouping effect. This variation of the resonant frequency and the response decrement from one cabinet to multi-cabinets reveals the importance of considering the grouping effect

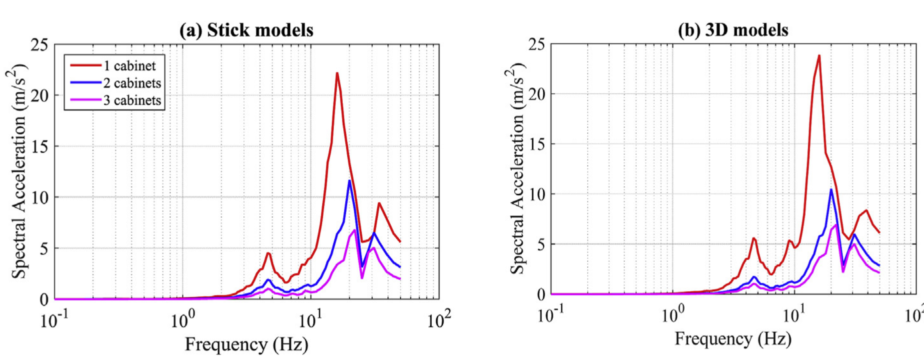


**Fig. 13.** The acceleration response spectra.

of the cabinet facility in its seismic response analysis.

## 5. Conclusions

A systematic approach was considered for the linear dynamic behavior of the electrical cabinet that consists of an experimental, analytical and numerical solution. The effect of structural modification on the modal characteristics due to the grouping effect was investigated. A theoretical explanation was followed for a better understanding of the proposed solution that includes frequency response, Rayleigh damping and structural dynamic modification. Based on this research some of the findings are listed below that are significant to be considered in the seismic analysis of the cabinet structures.

- A noticeable change in the response was observed due to the grouping effect of two cabinets that results in 56% depletion in the peak acceleration response and this increased up to 70% for three cabinets. This reduction was investigated due to the structural modification induced by the mass and stiffness of the system. Comparatively, this change was higher between one and two cabinets and it was lower between two and three cabinets.
- A noticeable shift in the resonant frequency of the cabinet system was observed that accounts for a 32% increase between a single and two cabinets, and this increase up to 45% for one to three cabinets. This shift in the resonant frequencies due to the grouping effects is important, which eventually controls the response of acceleration sensitive electrical cabinets.
- The effect of the primary-secondary structure interaction should be considered as the seismic response of the cabinet was found to be affected by the floor response. Although the lower mass of the cabinet was negligible as compared to the mass of the primary structure.
- Based on the obtained results, it was concluded that the experimental and numerical analysis of a single cabinet and its integration into the multi cabinet is a conservative approach. Both the experimental and numerical solutions are needed to be tested to counter these effects which can be eventually significant for an accurate seismic analysis of the electrical cabinet.
- The response analysis and its outcomes are important for the seismic evaluation of acceleration sensitive cabinets and their dynamic properties as a secondary structure in the nuclear industry. The future extension can be considered by including the nonlinear behavior of the cabinets and its interaction with the soil under the grouping effects.

## Declaration of competing interest

The authors declare no conflict of interest in this research.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.11.024.

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