Nuclear Engineering and Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Distributed plasticity approach for nonlinear analysis of nuclear power plant equipment: Experimental and numerical studies

Thanh-Tuan Tran [a, b], Kashif Salman [c], Dookie Kim [d, *]

[a] Institute of Offshore Wind Energy, Kunsan National University, Republic of Korea
[b] Quy Nhon University, Faculty of Technology and Technique, Binh Dinh, Viet Nam
[c] Department of Civil and Environmental Engineering, Kunsan National University, Republic of Korea
[d] Department of Civil and Environmental Engineering, Kongju National University, Republic of Korea

ARTICLE INFO

Article history:
Received 30 November 2020
Received in revised form
23 February 2021
Accepted 17 March 2021
Available online xxx

Keywords:
Cabinet facility
Experimental modal analysis
Simplified model
Distributed plasticity
Fiber elements
Constitutive material models

ABSTRACT

Numerical modeling for the safety-related equipment used in a nuclear power plant (i.e., cabinet facilities) plays an essential role in seismic risk assessment. A full finite element model is often time-consuming for nonlinear time history analysis due to its computational modeling complexity. Thus, this study aims to generate a simplified model that can capture the nonlinear behavior of the electrical cabinet. Accordingly, the distributed plasticity approach was utilized to examine the stiffness-degradation effect caused by the local buckling of the structure. The inherent dynamic characteristics of the numerical model were validated against the experimental test. The outcomes indicate that the proposed model can adequately represent the significant behavior of the structure, and it is preferred in practice to perform the nonlinear analysis of the cabinet.

Further investigations were carried out to evaluate the seismic behavior of the cabinet under the influence of the constitutive law of material models. Three available models in OpenSees (i.e., linear, bilinear, and Giuffre-Menegotto-Pinto (GMP) model) were considered to provide an enhanced understating of the seismic responses of the cabinet. It was found that the material nonlinearity, which is the function of its smoothness, is the most effective parameter for the structural analysis of the cabinet. Also, it showed that implementing nonlinear models reduces the seismic response of the cabinet considerably in comparison with the linear model.

1. Introduction

Electric cabinets are one of the essential facilities in the nuclear power plant (NPPs) as it carries relays, switches, etc that are responsible for power distribution. Damage observations from the historical earthquakes show that the failures of any electrical units may lead to a collapse of the equipment [1–3]. Thus, the safety-related NPP components should be considered carefully [4–10]. One of the important aspects to be considered for these structures is the seismic evaluation emphasizing the structural vulnerability [11–16]. Tran et al. [5] performed the collapse risk assessment of an electrical cabinet in NPPs using a finite element model (FEM) developed in Sap2000. Later, this FEM was modified to consider the grouping effect on the seismic vulnerability of cabinet facilities, which was studied by Salman et al. [9,17].

The main shortcoming of the previous studies is how to reduce the computational time for the nonlinear time analysis. To overcome this issue, a framework for developing simple numerical models of the cabinet is necessary. Cho et al. [6] developed a simplified model for the nonlinear seismic response for aiding the seismic qualification (SQ) of this equipment in NPPs. Later, various numerical models of cabinets were also generated by Hur [2] that can capture the nonlinear behavior of support boundary conditions. However, the stiffness-degradation effect for the cabinet's frame members is not highlighted in the present literature. Thus, considering this effect in the numerical analysis is required to be considered explicitly.

The structural configuration of a cabinet consists of plate and frame members, which are connected via connectors. The frames are usually hollow or channel sections which are assembled by the thin-walled section (plates) in such a way that their shear center

* Corresponding author.
E-mail addresses: tranthanhtuan@kunsan.ac.kr, tranthanhtuan@hotmail.com.vn (T.-T. Tran), kashifsalman96@gmail.com (K. Salman), kim2kie@kongju.ac.kr (D. Kim).

https://doi.org/10.1016/j.net.2021.03.017

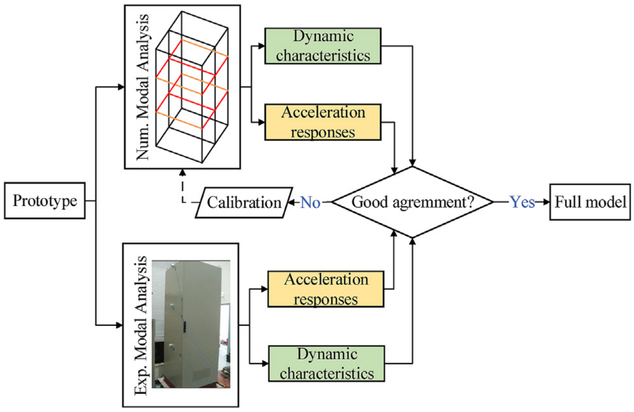


Fig. 1. Flowchart for development of the numerical model.

and the sectional centroid are not coinciding with one another. As a result, they may face buckling or wrap when subjected to dynamic loadings [18]. To simulate more realistic structural behaviors due to local buckling, the plasticity approaches have emerged as a powerful method [19]. The nonlinear behavior of cabinet subjected to earthquake loads can be characterized by the development of yielding points at the end of the element, or any location along the element. Currently, the models used for this purpose include the concentrated plasticity (CP) model and distributed plasticity (DP) model. In the former, the plastic hinge will occur at the monitored points of members. On the other hand, the DP model produced inelasticity along the frame member [20]. These approaches were used by many researchers for various structures [20–24]. For instance, Noh et al. [21] evaluated different parameters for defining the monotonic and hysteretic response of the infill reinforced concrete frame. Nguyen and Kim [23] developed a displacement-based finite element process of plane steel frames considering the nonlinearity of the connections due to dynamic loadings. Besides, this approach is applied to model the response of the steel frame subjected to fire conditions using the user-defined element (UEL) subroutine in ABAQUS [25].

This research aims to develop a simplified model (Fig. 1) that can capture the nonlinear response of the cabinet, especially for the stiffness-degradation effect of framing members. In this regard, the fiber-based approach with various constitutive models (i.e., linear, bilinear, and Giuffre-Menegotto-Pinto model) is considered that can capture the influence of smoothness behavior on the material response [26,27]. The outlines of the paper are as follows. First, the experimental tests of the cabinet are performed (Section 2). Next, modeling with a distributed plasticity approach is proposed for the cabinet facility through the Open System for Earthquake Engineering Simulation (OpenSees) software package [28] (Section 3). Afterward, Section 4 is aimed for the validation and verification of the numerical model. Lastly, the application of a simplified cabinet

(a) Elevation, top, and bottom view

(b) Sections of frame elements (mm)

Fig. 2. Test specimen and cross-section of the tested cabinet.

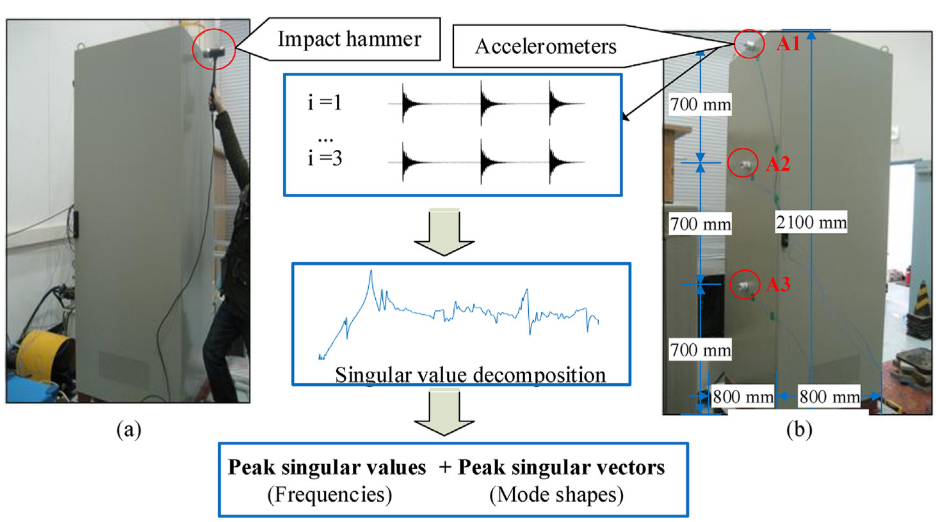


Fig. 3. Schematic representation of test setup.

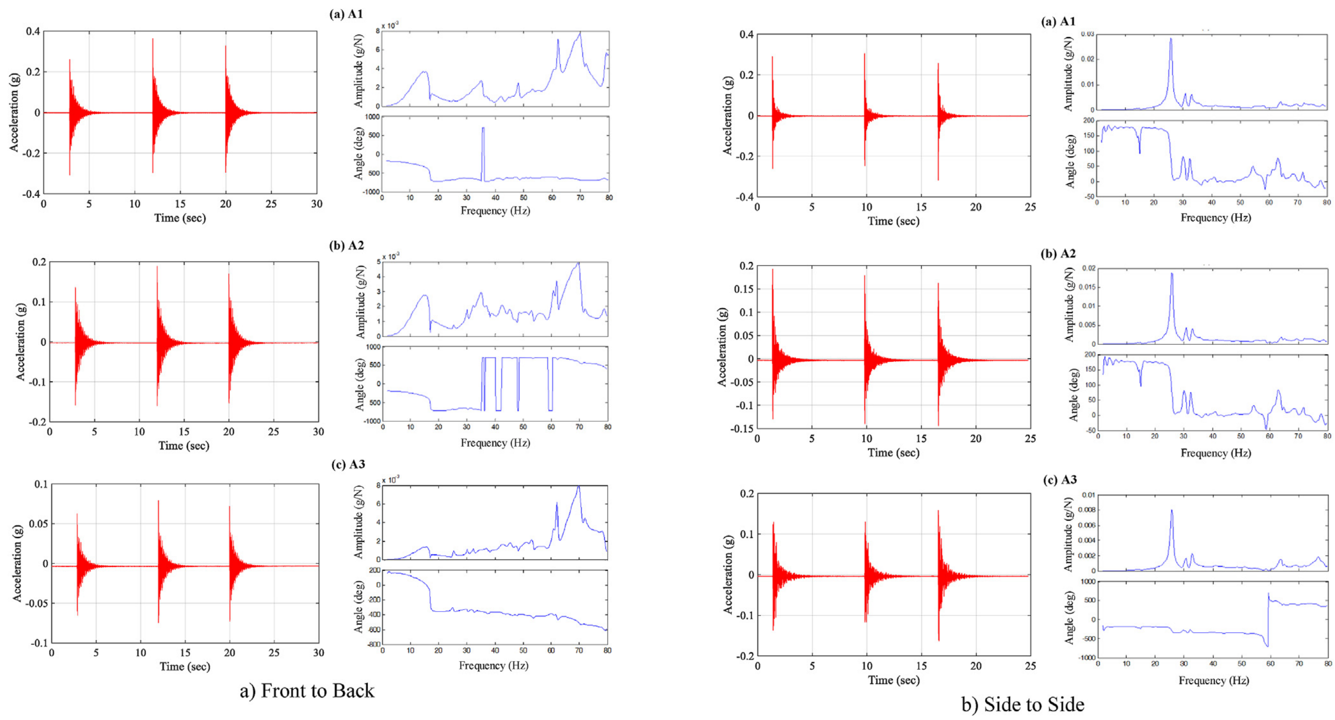


Fig. 4. Measured acceleration at sensors.

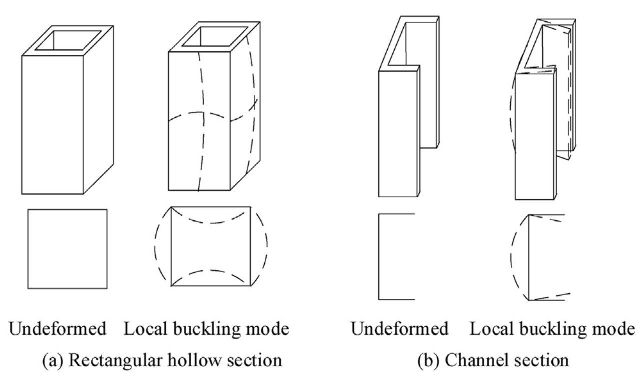


Fig. 5. Local buckling modes of rectangular hollow and channel sections.

model is presented to consider the seismic behavior of the cabinet under different constitutive material models (Section 5).

2. Modal testing

The modal testing of the cabinet facility is first performed, aiming to determine the dynamic characteristics of the structure (i.e., natural frequencies, mode shapes, and damping ratios). To achieve this aim, the impact hammer test was conducted. The descriptions of the prototype and its results are described in the following subsections.

2.1. General description of the test structure

The electrical cabinet used in the test is a prototype provided by INNOSE Tech Company, as shown in Fig. 2a [5]. The height, width, and depth of cabinet are 2100 mm, 800 mm, and 800 mm, respectively, and the total weight of the cabinet is about 290 kg. The main components of the test specimen are main-frames, sub-frames, and steel plates. Main-frames are built up with the rectangular steel section, while the sub-frames are built up with L- and C-shape sections (Fig. 2b). The structural frames are covered by the steel panels (having a thickness of 2.3 mm) at the top and all four sides to form a box. All panels are attached to the frames with screws. The cabinet has two doors, and the door's weight is around 44 kg for each one. These doors are locked at one edge and hinged at the opposite edge. The material of the test prototype is characterized by the elastic modulus, the density (ρ), and Poisson's ratio (ν) of 200 GPa, 7850 kg/m^3, and 0.3, respectively. The specimen is anchored in to channels through eight M14x80 bolts, while the channels are attached to the rigid system on a shaking table test.

The vibration test was conducted using the impact hammer and three accelerometers mounted in the cabinet's panel. The overall schematic of the experimental test is presented in Fig. 3. The tests are performed with both front-to-back and side-to-side directions of the cabinet. In the experiment, the input force was applied at the top of the cabinet (Fig. 3a). While the accelerometers were installed on the cabinet's panel, and their positions are displayed schematically in Fig. 3b. During the tests, the free vibration responses of the cabinet were recorded, and they are analyzed to determine the dynamic characteristics of the cabinet.

2.2. Experimental results

The acceleration responses due to the impact force of the cabinet at the specified locations are displayed in Fig. 4 (left column). The outputs are then transformed into frequency response function (FRF), as showed in right column in Fig. 4. To further investigate the seismic response of the cabinet, the modal parameters are required; therefore, the modal analysis was performed to obtain its dynamic characteristics. The modal analysis methods are classified into two categories, including Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA). In this research, the frequency domain decomposition (FDD) method [29] that known as a

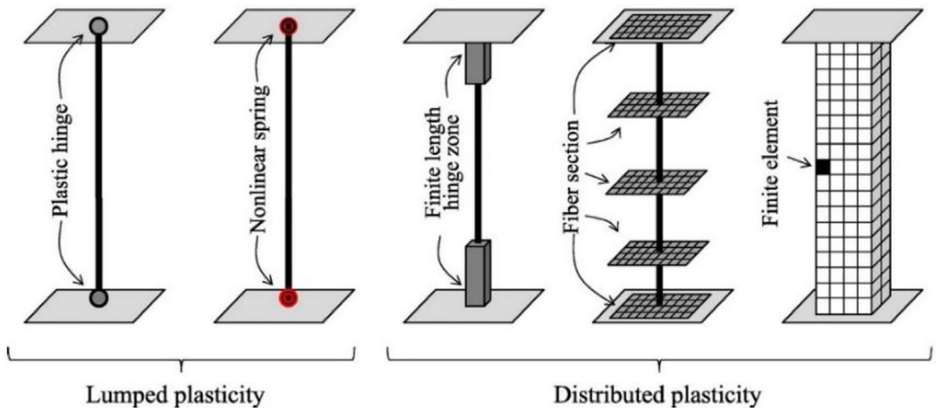


Fig. 6. Plasticity models for elements [32].

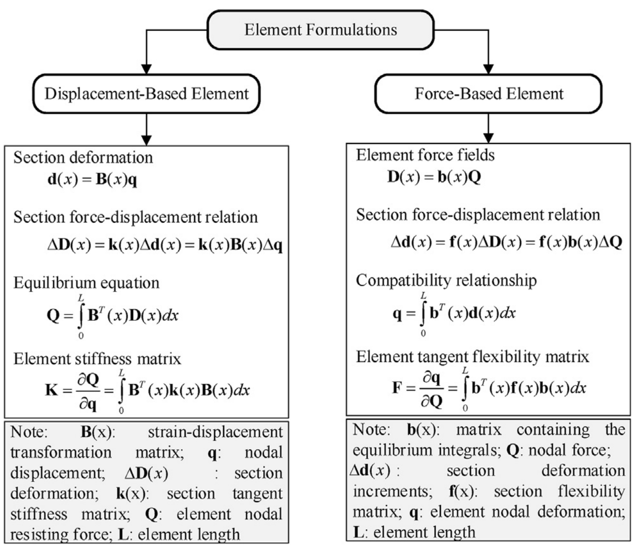


Fig. 7. Element formulation.

non-parametric OMA method, was employed to determine the modal parameters of the cabinet. The method can extract the natural frequencies and mode shapes by taking the peak singular values and vectors from the singular value decomposition (SVD). Step-by-step of the method and the dynamic characteristics of the cabinet are explained in Section 4.1.

3. Development of simplified finite element model for electrical cabinet

This section aims to develop a simplified finite element model for the cabinet. This is essential since it can efficiently reduce computational time for the nonlinear time history analysis. First, the characteristics of the prototype are introduced, followed by the approaches for simulation of the nonlinear behavior of the cabinet. Lastly, the numerical modeling of the cabinet is developed. The proposed model is constructed without plate enclosures, that called the bare-frame model.

3.1. Characteristics of the prototype

Framing members, steel plates, connections between framing members and plate/framing members are the main components of a cabinet. The enclosure steel panels are connected to the framing members via screw fasteners, while the framing members are usually connected together by weld/bolt fasteners. The frame members of the cabinet work in the same way as the steel frames of a structure. Under seismic loadings, they may fail due to the following reasons: (1) the failure of connections at the base of the unit, or the connections between plates with frame members, (2) the buckling of the plates, or (3) the buckling of the frame members.

It is noted that the frame members of the cabinet are generally assembled by the I-section, channel, and angle sections (called open sections), or rectangular and circular tubes (called closed sections). Their cross-sections consist of an assembly of thin-walled plates; thus, the local buckling of these elements may occur (Fig. 5). The local buckling is the failure of cross-section under the compression/shear stresses. This phenomenon may take place before the overall structural failure by yielding, and it is the reason for the reduction in the load-carrying capacity of the cabinet due to the decrement of the stiffness and strength of these members. Consequently, defining thin-walled sections for the frame elements due to the local buckling in the cabinet becomes a concern.

3.2. Plasticity models

Over the past years, several approaches are used to model the nonlinear behavior of frame structure due to earthquake loadings. These methods can be classified into two main categories (Fig. 6): lumped plasticity and distributed plasticity [19,24]. The lumped plasticity assumes that the nonlinearity can occur at the end of the structural element. In this approach, the major parameter is the plastic hinge length of the element, which depends on the input parameters, including geometrical and material parameters (i.e., compression, tension, the stress-strain curve) [30]. On the other hand, the distributed plasticity assumes that the nonlinear behavior can occur at any element cross-section along the element. The simulation of section nonlinear response behavior can be described using the fiber modeling approach through constitutive material laws. This approach requires more computational time and capacity, and it reflects the real behavior [31].

In order to study the plasticity behavior along the element, two main elements, namely displacement-based element (DBE) and force-based element (FBE), are introduced. The procedure for the element state is described in Fig. 7. The DBE approximates the displacement fields of the element as a function of nodal displacements. On the other hand, the latter is based on the interpolation functions for the internal forces within the element.

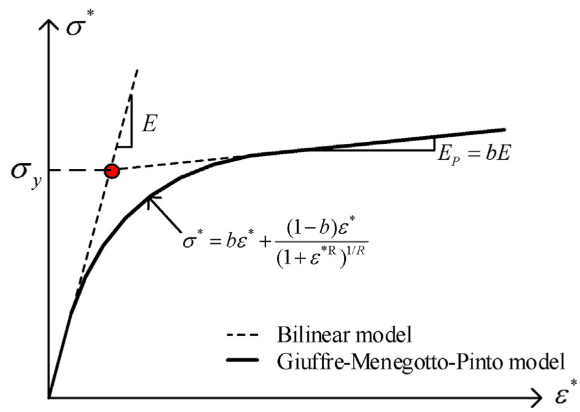


Fig. 8. Stress-strain relationship of different constitutive material models.

Table 1
Mechanical properties of the constitutive material models.

Properties	Linear	Bilinear	GMP
Initial Elastic Modulus, E_0 (GPa)	200	200	200
Yield strength, σ_y (MPa)	–	345	345
Strain-hardening ratio, r	–	0.03	0.03
R_0, cR_1, cR_2*	–	–	20, 0.925, 0.15

*parameters of curved transitions.

3.2.1. Material models

To observe the nonlinear behavior of the cabinet, various material constitutive models based on the smoothness effect are investigated. The J_2 plasticity model [26] and the Giuffre-Menegotto-Pinto (GMP) model [27] are applied in the material modeling, as shown in Fig. 8. The former is known as a bilinear model with kinematic hardening, H_{kin}, and isotropic hardening, H_{iso} and described by a nonlinear evolution equation. This model can be considered as a non-smooth model. The latter is adopted to account for the isotropic strain hardening for the inelastic material. The stress-strain relationship is described in the form of the curved transitions, which is started from a straight-line asymptote (E) to another straight-line asymptote (bE) (Fig. 8), and is expressed as the following equations:

$$\sigma^* = b\varepsilon^* + \frac{(1-b)\varepsilon^*}{\left(1+\varepsilon^{*R}\right)^{1/R}} \tag{1}$$

where R corresponds to an independent parameter which defines the curvature of the transition, and b is the strain hardening ratio. The dynamic responses from these models are compared with those of the elastic material model. Table 1 summarizes the mechanical properties of material models (Fig. 8) used for the FEMs.

3.3. Numerical modeling with distributed plasticity approach

In order to evaluate the dynamic behavior of the cabinet, the FEM with all structural elements (i.e., frame and plate members) should be modeled. However, this model is time-consuming for nonlinear time history analysis. As a result, a simplification of the numerical modeling that can capture the possible nonlinear behavior is recommended. Herein, the proposed model was constructed without plates, which is called the bare-frame model. This approach can be used due to the following reasons:

- The side panels are connected with the main-frames by welded or screwed connections. Thus, the frame controls the displacement of the cabinet, and the failure of frame members leads to the failure of the plates.
- This model extends in understanding the global behaviors due to the frame of the cabinet.

According to the previous discussions, during a dynamic load, the local buckling of the member may occur due to the stiffness-reducing effect. To capture this issue, the proposed distributed plasticity model was proposed. This method has the capacity to capture the nonlinear behavior at any element cross-section along the element. This approach was applied for the following reasons:

- The frame members of the cabinet can be the open or closed sections. The shear center of these members may not coincide with the sectional centroid. As a result, local buckling can occur.
- Thin-walled sections are prone to local buckling, as the compressive strength of members depends on their width-to-thickness ratios.

Based on the above interpretation, the numerical model was developed and implemented in OpenSees using the fiber-based plasticity approach. This approach allows the spread of the nonlinear behavior by requiring a number of integration points corresponding to the cross-section along the member length. The model requires the discretization of the element into fibers, as shown in Fig. 9. Five integration points divide elements into sub-elements. The nonlinear characteristic of the cross-section was considered by defining a relationship of stress-strain of each fiber on the cross-section of sub-element (i.e., steel01, steel02).

3.4. Limitation

The simplified model provides a significant reduction in structural complexity, and it is useful for the nonlinear analysis required time-consuming. However, there are several limitations as follows:

- The effect of local modes is not considered.
- The accuracy of the above models depends on the assumptions for idealization.

4. Verification and validation

The effectiveness and accuracy of the proposed model was recorded against the impact hammer test. Since the force pulse in impact hammer test is very short relative to the length of the time record, and the force amplitude is small, the effect of the smoothness of material may not occur. Thus, to highlight the effect of material models on the nonlinearity, two numerical models were developed. The first approach, called linear model, with elastic behavior was employed for each element, as shown schematically in Fig. 10a. The second approach is the nonlinear model, used the distributed plasticity (Section 3.2). In this model, the nonlinearity was considered by tracing the stress-strain curve for each fiber on the cross-section, as shown in Fig. 10b.

In order to validate the proposed models, the dynamic characteristics (i.e., dominant frequencies and mode shapes) and acceleration responses from the impact hammer test and numerical models were compared.

4.1. Dynamic characteristics of cabinet

As mentioned in Section 2.2, the natural frequencies of the electrical cabinet are determined using the frequency domain

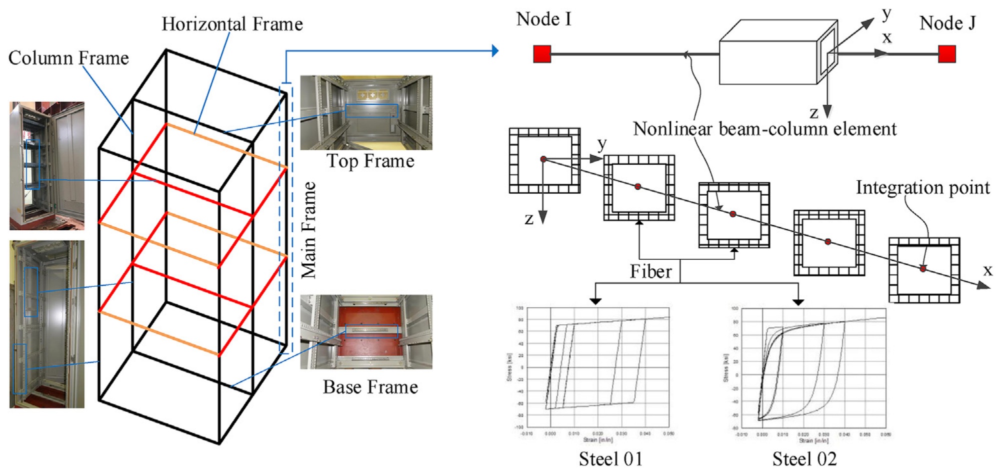


Fig. 9. Frame modeling using the distributed plasticity elements.

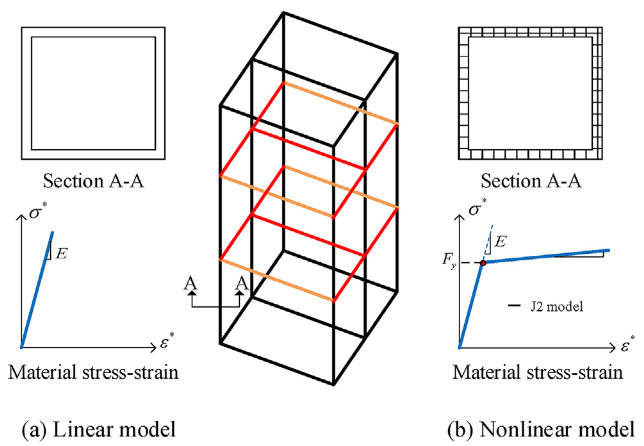


Fig. 10. Two approached numerical models.

decomposition method [29]. The FDD is an important tool in operational modal analysis, and it can determine the dominant modes by singular value decomposition. This technique involves the main steps which are briefly described below:

- Compute Power Spectral Density (PSD) matrix $G_{yy}(jw)$ from the time series data as follows:

$$G_{yy}(jw) = \overline{H}(jw) G_{xx}(jw) H(jw)^T \quad (2)$$

where matrix $G_{yy}(jw)$ with a size $(m \times m)$ is PSD of system responses, m is number of output signals; matrix $G_{xx}(jw)$ with a size $(r \times r)$ is PSD of input signals, r number of input signals; $H(jw)$ with a size $(m \times r)$ is Frequency Response Function (FRF) of the system.

- Perform singular value decomposition of the spectral density matrices.

$$G_{yy}(w_i) = U_i S_i U_i^H \quad (3)$$

where U_i is a unitary matrix including singular vectors u_{ij}; S_i is a diagonal matrix including the scalar singular values s_i.

- If multiple test setups are available, then average for all test setups are taken.
- Pick peak on the singular values to estimate the natural frequency.

Based on the FDD technique, the comparison of the graph log magnitude using the SVD is plotted against frequencies, as shown in Fig. 11. The fundamental natural frequencies of the electrical cabinet can be obtained from the peaks of the graph, for the numerical results and the experimental test. The natural frequencies estimated corresponding to the peaks are tabulated in Table 2. Both experimental tests and numerical results are found in good agreements. Compared to the experimental results, the maximum differences recorded in natural frequencies are 8.64% and 2.86% for linear and nonlinear approaches, respectively.

It is essential to note that the actual cabinet generated with plate and frame members has more peaks compared to the bare-frame model (without plate enclosures) (Fig. 11). This happens because the bare-frame model has a negligible effect due to plates, so only the overall global modes of the cabinet are considered. However, the actual cabinet was generated with the plate and frame elements that can capture the local modes of steel panels [2,3]. Due to the complexity of the cabinet's configuration, the higher modes effect due to the plates is less significant in the bare-frame model therefore a difference in the higher mode occurs. Although the

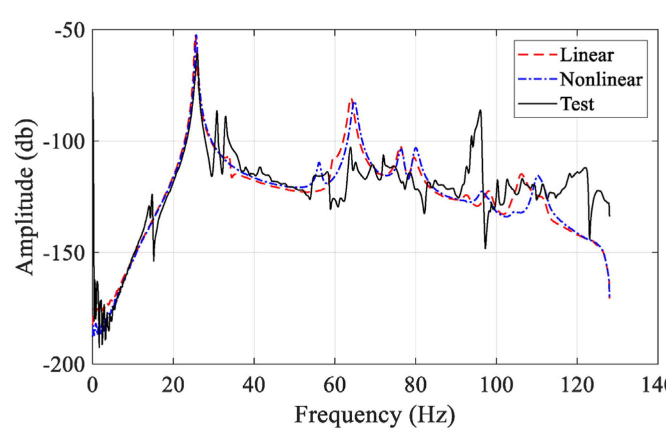


Fig. 11. Single value spectrum between experimental and numerical results.

Table 2
Comparison of natural frequencies (Hz) and mode shapes obtained from experiment and numerical model.

Mode	Natural frequencies (Hz)			Mode shape	
	Exp.	Linear	Nonlinear	MAC(L)	MAC(NL)
1	25.88	25.38	25.63	0.9952	0.9952
2	55.00	59.75	56.13	0.9285	0.9285
3	63.88	64.00	64.88	0.9838	0.9842
4	78.63	76.25	76.38	0.9774	0.9776

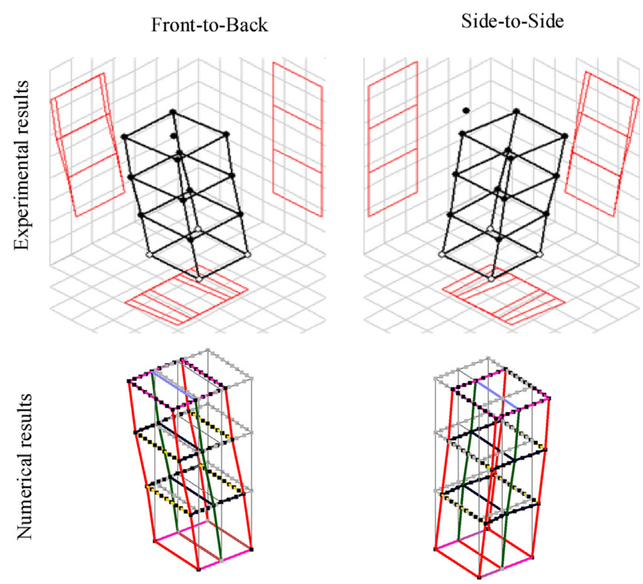


Fig. 12. Comparison of global mode shapes between experimental and numerical results.

general trends of mode shapes can be considered.

The comparison of mode shapes from the experimental and numerical results are displayed in Fig. 12 for dominant frequencies. Only the first mode, which represents the dominant vibration of the cabinet structure, is presented. The results exhibit that the numerical modal vectors (second row) are the same with those from the experimental test (first row). Note that the mode shapes in two approaches (linear and nonlinear) are almost the same. In order to have a fair comparison between linear and nonlinear approaches, the Modal Assurance Criterion (MAC) matrix is used.

The MAC is calculated as the normalized scalar product of the two vectors. The MAC between the experimental mode shape, Φ_e and numerical mode shape, Φ_n is defined as:

$$\mathrm{MAC_j} = \frac{\left|\{\Phi_{ej}\}^{\mathrm{T}}\{\Phi_{nj}\}\right|^2}{\left(\{\Phi_{ej}\}^{\mathrm{T}}\{\Phi_{ej}\}\right)\left(\{\Phi_{nj}\}^{\mathrm{T}}\{\Phi_{nj}\}\right)} \tag{4}$$

The MAC value is bound between 0.0 and 1.0. A value of one indicates that the mode shapes are identical, whereas the value close to zero denotes that the mode shapes are not identical. The correlation between mode shapes of experimental and numerical models is plotted in Fig. 13. As shown, along the diagonal, all mode pairs are identical with the MAC values of over 92% (Table 2) for two cases. While off diagonal, MAC values are lower. Based on the obtained results, the proposed models with various approaches were validated with the experimental test in predicting the dynamic characteristics. However, more agreement is found in the nonlinear approach based on the comparison in Table 2.

4.2. Acceleration response

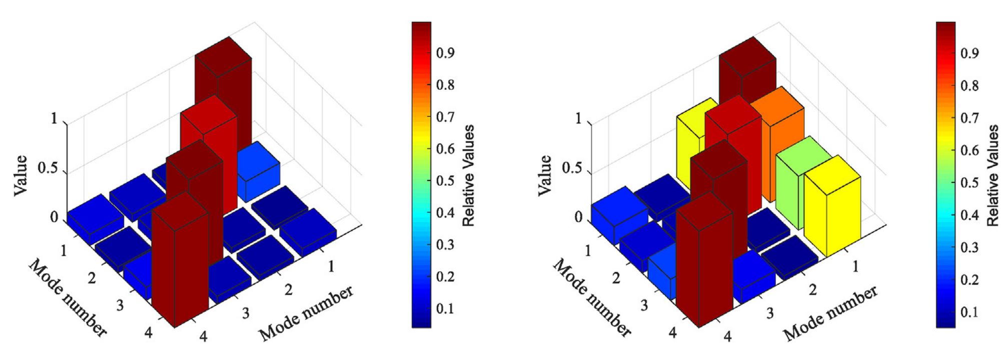
The acceleration responses obtained from the experimental and numerical results under impact hammer force are presented in this section. Fig. 14 compares the time histories and the response spectra from the measured and predicted acceleration responses at the different locations of the cabinet. In general, under impact hammer force response is not effective to distinguish different approaches linear and nonlinear of the test structure. This is due to the low intensity of the impact hammer force. As usually the nonlinear effect in a structure occurs at a high level of excitation. A detailed description for the nonlinear analysis is presented in Section 5.

Additionally, the outcomes from predicted results follow the acceleration responses from experimental results. The differences between experimental and numerical models may happen due to the possible reasons that includes the exact location of the sensor on the prototype and the response location from a numerical may vary. Also, in the simplified model, the response locations are different on the frame; however, the sensors are installed on the panels. Lastly, the bare-frame model may cause some prediction errors because of some assumptions for idealization.

Based on the obtained results from the vibration test, the proposed models can represent the test specimen and can be used to further investigate the influence of the smoothness of constitutive material models.

5. Nonlinear seismic response of the cabinet facility

The effectiveness and accuracy of the numerical model for the cabinet facility are examined in the previous sections. This section aims to perform the nonlinear time history analysis of the cabinet



(a) Linear (b) Nonlinear

Fig. 13. MAC matrix between experimental and numerical models.

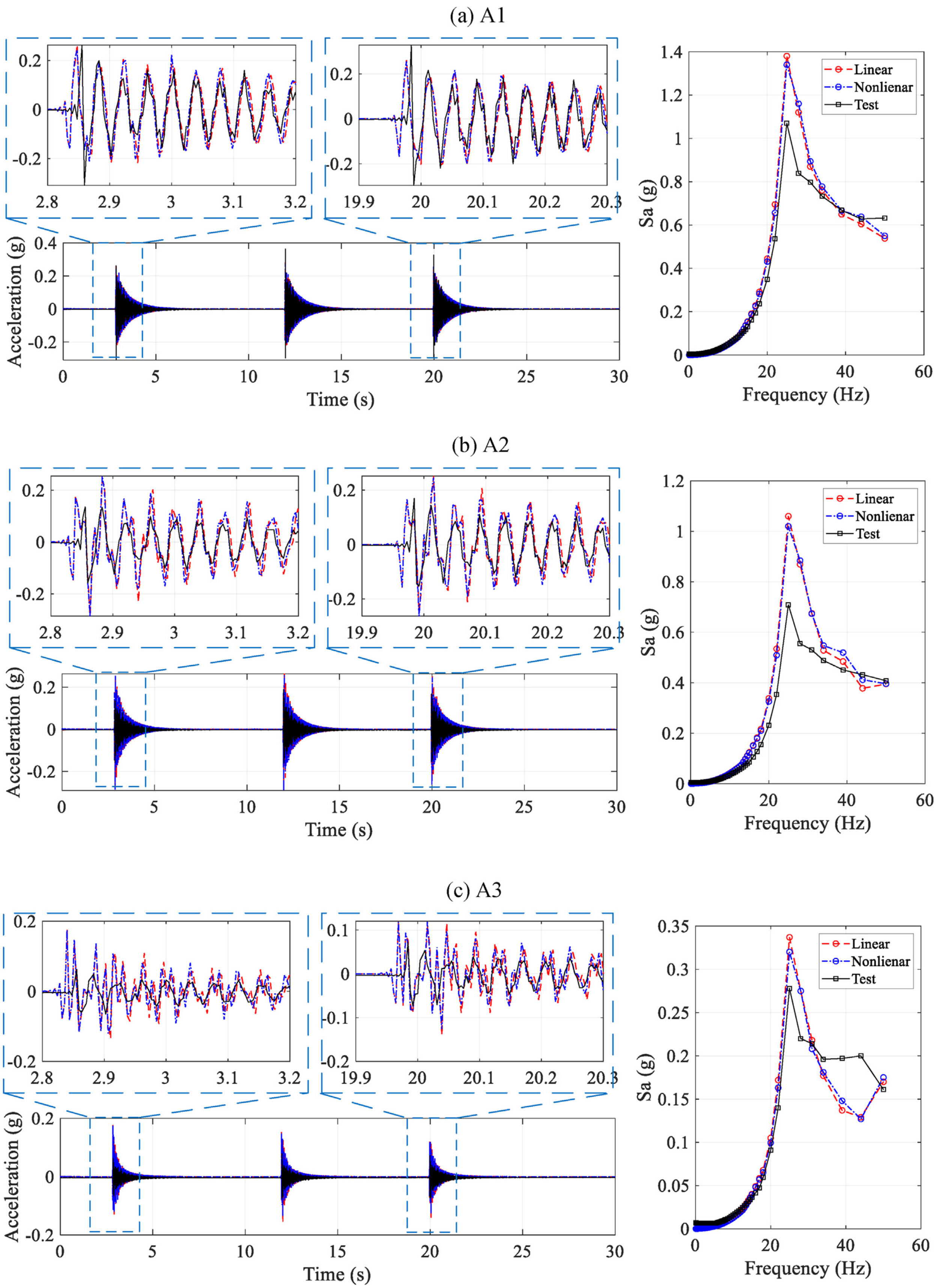


Fig. 14. Comparison of acceleration histories and spectral acceleration response at different locations between experimental and numerical results.

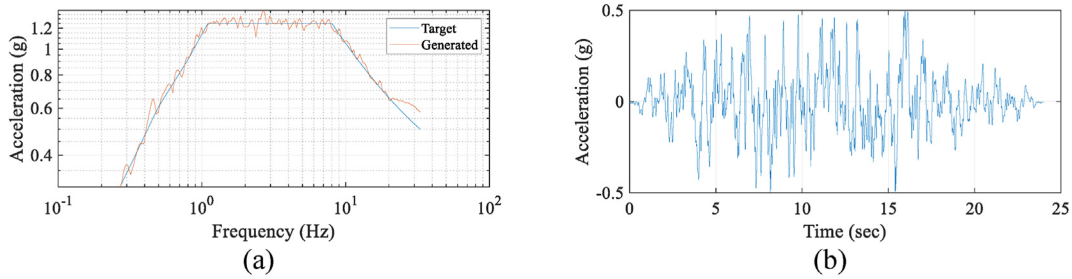


Fig. 15. (a) Design code and simulated response spectrum, and (b) artificial acceleration time history.

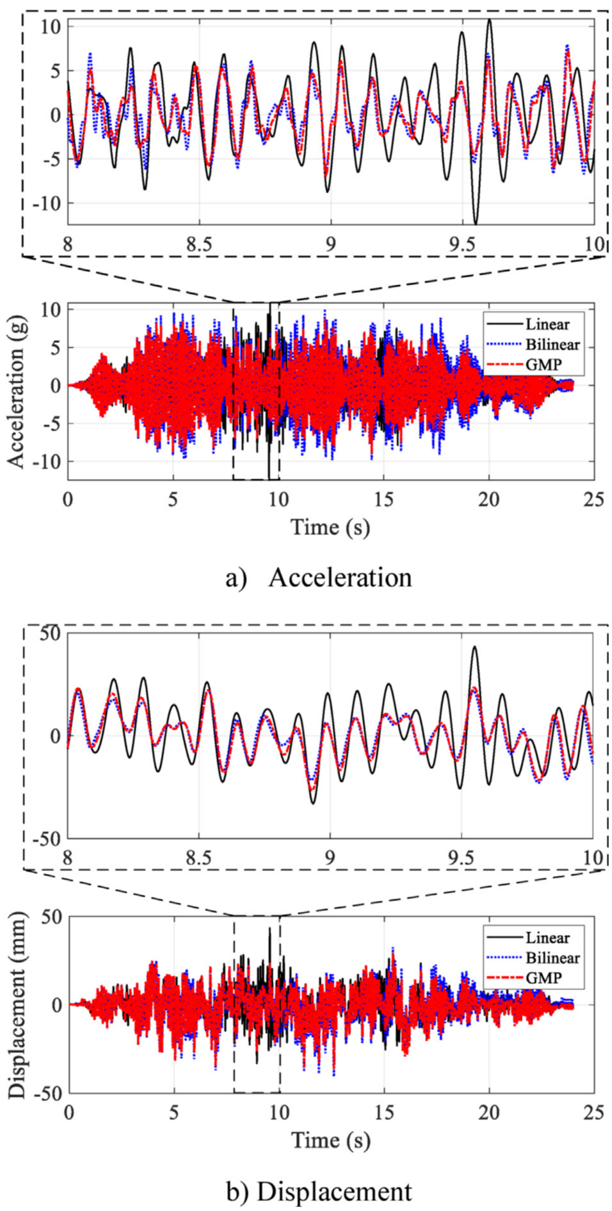


Fig. 16. Top responses of cabinet: a) acceleration, b) displacement.

considering the influence of constitutive material models. Comparative evaluations of acceleration, displacement responses, and the stress-strain curves are presented.

5.1. Input ground motion

Different types of ground motions (i.e., artificial, real ground motion) can be used to evaluate the seismic response of cabinets. For sensitive non-structural components, the input loadings are recommended to satisfy the seismic qualification standards [33,34]. In this study, the IEEE 693 is used to generate the artificial acceleration time history. In IEEE 693, the electrical equipment is evaluated for various Required Response Spectrum (RRS) levels (i.e., high, moderate, and low). Based on the RRS, an artificial earthquake is generated using the SIMQKE software [35].

A report of the characteristic of selected ground motion is illustrated in Fig. 15. The ground motion is generated to meet with the high level of IEEE 693 requirement corresponding 0.5g peak ground acceleration (PGA), as shown in Fig. 15b. The comparison between the response spectra of the artificial earthquake and RRS are displayed in Fig. 15a.

5.2. Influence of constitutive material models on the seismic response

The effects of constitutive material models on the nonlinear responses of the cabinet are given in this section. The time history analyses have been imposed for three material models mentioned in Section 3.3, including two nonlinear models (i.e., bilinear and GMP models) and the linear model. Here, it should be noted that cabinets are sensitive equipment that physical damage to the frame will occur with a high magnitude of acceleration; thus, the input ground motion is scaled to 5.0g. The comparison of acceleration, displacement responses of the cabinet is given in Fig. 16.

The variation of top acceleration and displacement responses with the different material models are displayed in Fig. 16. During the earthquake, the responses of nonlinear models are smaller in comparison to the linear case. Specifically, the reduction percentages of the bilinear and GMP are 19.31% and 28.44% for acceleration responses, respectively and the corresponding values are 6.55% and 16.90% for displacement response. These differences are explained due to the softening behavior in nonlinear analyses that are described as follows: in the plasticity approach, each fiber is represented by its material, and fiber failure states depend on the fiber location as illustrated in Fig. 17 [18].

This phenomenon is also presented in Fig. 18, which shows the maximum acceleration and displacement along the height of the cabinet. As shown, the higher location of the cabinet leads to a higher response. Notably, the responses from nonlinear cases are larger than the linear case at the bottom of the cabinet. This causes the failure modes due to the yielding of the cross-section, which is explained in detail in Fig. 19b.

Furthermore, the results for two nonlinear models show that the smoothness of the steel model has a considerable contribution to the reduction of the nonlinear response. Compared to the

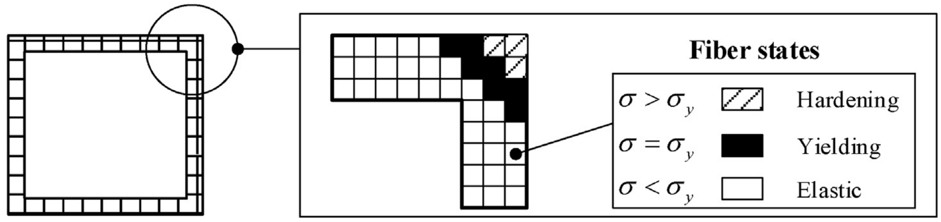


Fig. 17. Illustration of fiber states.

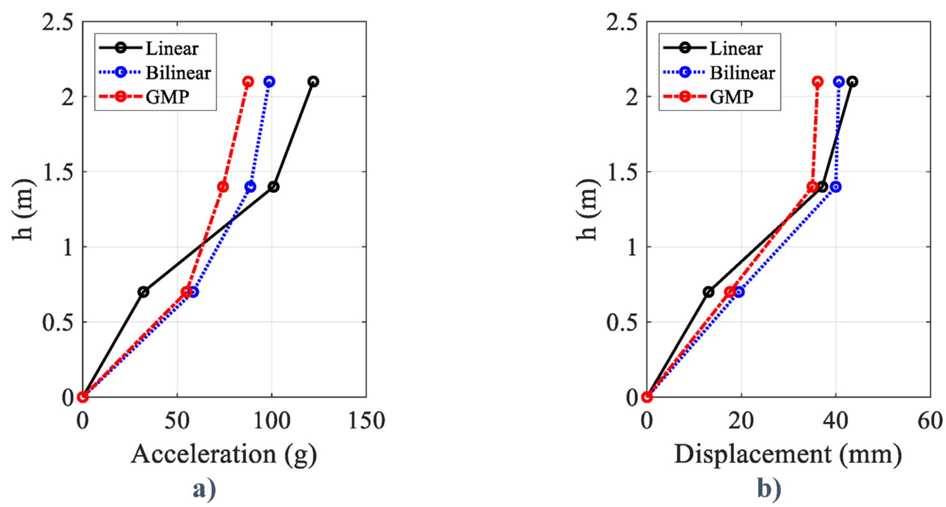


Fig. 18. Maximum responses of cabinet: a) acceleration, b) displacement.

bilinear model, the maximum reductions of the GMP model are 16.34% and 12.36% for acceleration and displacement responses, respectively. This happens due to the characteristic of various material models. The bilinear model is known as a non-smooth plasticity model that shows the discontinuities in the responses when the material comes to the plastic region. In contrast, the GMP model can account for the isotropic strain hardening effects, and it has a good agreement that reflects the real behavior of the structure.

The influence of smoothness in the constitutive law of material model on the overall cabinet response is explained in Fig. 19. In Fig. 19a, the normalized spectral accelerations of the cabinet are illustrated to consider the differences between linear and nonlinear models in the frequency domain. The results indicate that the higher location procedures a higher amplitude in response. Additionally, there is a shift in frequencies between linear and nonlinear approaches. The shift in the frequency is due to the flexibility of the cabinet structure with material consideration. In Fig. 19b, the stress-strain curves (i.e., hysteresis) of two nonlinear material models are compared at different locations of the cabinet. It is obvious that the yield location occurs at the bottom of the cabinet. At the top of cabinet, consideration of the nonlinearity is insignificant even though the responses are higher at the top. The different responses in the material model are clearly shown at the cabinet bottom in Fig. 19b. As seen, for the GMP model, the transition point from elastic to plastic is continuous through a curve that can simulate the accuracy of the real behavior of steel material [36].

6. Conclusions

The development of reliable numerical modeling is significant for structural analysis of the cabinet. The complexity of the analysis model depends upon the required analysis. A full finite element model is often time-consuming and expensive for nonlinear time history analysis. As a result, this study aims to develop a simplified numerical model that can achieve an important reduction in the modeling complexity. The proposed model is a cabinet without covering of steel panels, called the bare-frame model. Regarding the nonlinear behavior, the distributed plasticity approach is utilized to account for the stiffness-degradation effect. The simplified model is verified and validated with the outcomes from the experimental results. The main findings can be drawn as follows:

- The outcomes obtained from the proposed model show good agreement with the test results. The maximum difference in natural frequencies from the simplified model is 8.64% in comparison with experimental results.
- The simplified model provides the initial understanding for the dynamic behavior of a complex cabinet and it is preferred in practice to depict the global behavior of the cabinet.

Further studies on the effects of the constitutive material models on the nonlinear response of the cabinet are also observed. Three material models (i.e., linear, bilinear, and Giuffre-Menegotto-Pinto (GMP) model) based on the smoothness effect are considered to provide an enhanced understanding of the structural behavior of the cabinet during the earthquakes. The following conclusions can be drawn:

- Implementing nonlinear models reduces the seismic response of the cabinet considerably. Compared to the linear case, the corresponding reductions of the bilinear and GMP are 19.31% and 28.44%, respectively, for acceleration responses, whereas these values are 6.55% and 16.90% for displacement responses.

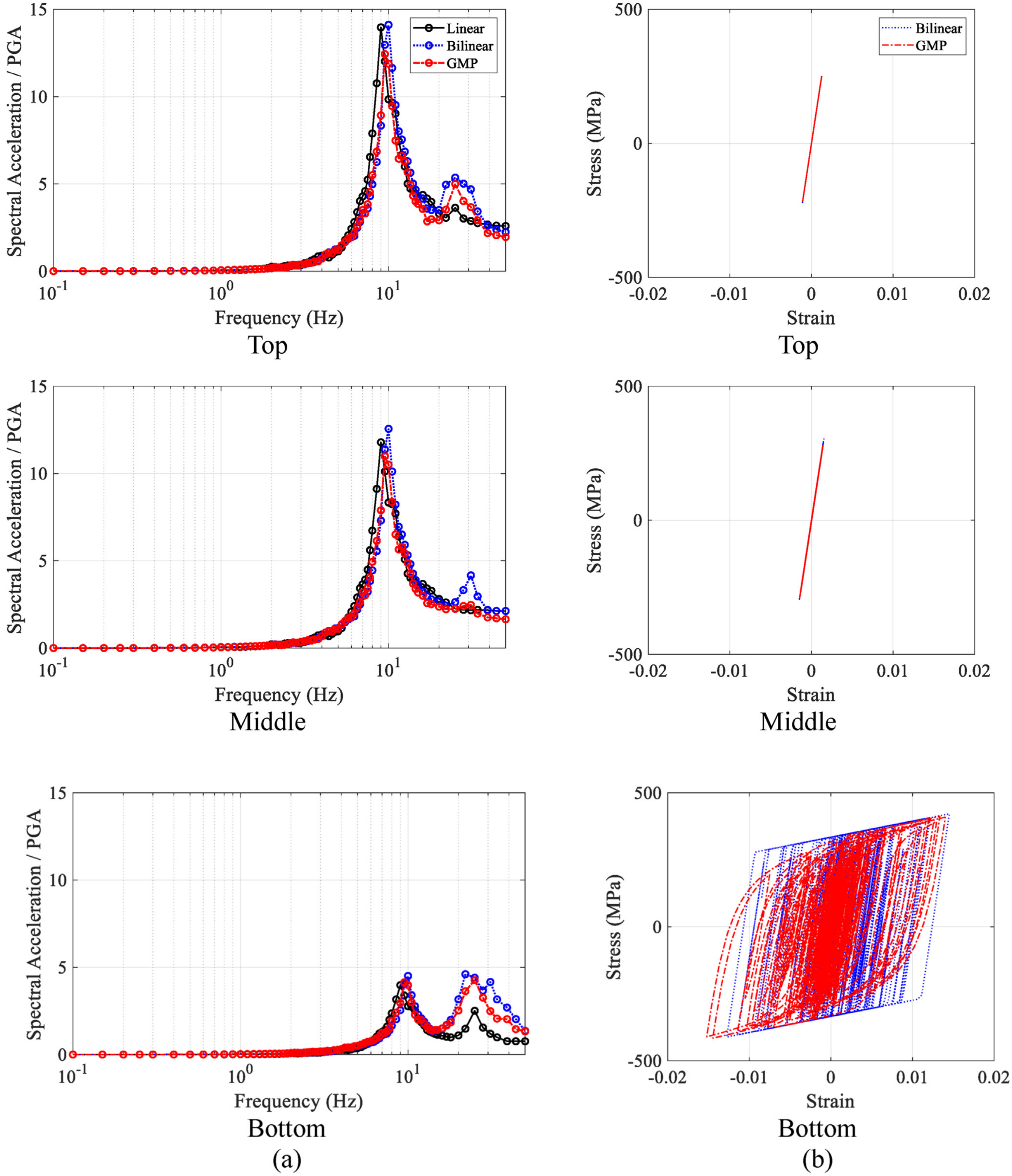


Fig. 19. (a) Normalized spectral acceleration and (b) hysteresis stress-strain curves of cabinet.

- The GMP constitutive model can accurately predict the responses of the cabinet due to the smoothness of the material model that can reflect the real behavior of a structure. The finding emphasizes that for a more accurate seismic evaluation of the cabinet, the nonlinear behavior of material should be employed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20171510101960).

References

[1] B.J. Goodno, N.C. Gould, P. Caldwell, P.L. Gould, Effects of the January 2010 haitian earthquake on selected electrical equipment, Earthq. Spectra 27 (2011) 251–276, https://doi.org/10.1193/1.3636415.
[2] J. Hur, Seismic Performance Evaluation of Switchboard Cabinets Using Nonlinear Numerical Models, Georgia Institute of Technology, 2012.
[3] E. Lim, A Method for Generating Simplified Finite Element Models for Electrical Cabinets, Georgia Institute of Technology, 2016.
[4] L. Baccarini, M. Capretta, M. Casirati, A. Castaldi, Seismic Qualification Tests of Electric Equipment for Caorso Nuclear Plant: Comments on Adopted Test Procedure and Results, IASMiRT, 1975.
[5] T.-T. Tran, A.-T. Cao, T.-H.-X. Nguyen, D. Kim, Fragility assessment for electric cabinet in nuclear power plant using response surface methodology, Nucl. Eng. Technol. 51 (2019), https://doi.org/10.1016/j.net.2018.12.025.
[6] S. Cho, D. Kim, S.C. Design, A simplified model for nonlinear seismic response analysis of equipment cabinets in nuclear power plants, Nucl. Eng. Des. 241 (2011) 2750–2757.
[7] M.K. Kim, I.K. Choi, A failure mode evaluation of a 480V MCC in nuclear power plants at the seismic events, in: 20th Int. Conf. Struct. Mech. React. Technol., Espoo, Finland, 2009.
[8] A.T. Cao, T.T. Tran, T.H.X. Nguyen, D. Kim, Simplified approach for seismic risk assessment of cabinet facility in nuclear power plants based on cumulative absolute velocity, Nucl. Technol. 206 (2019) 1–15, https://doi.org/10.1080/00295450.2019.1696643.
[9] K. Salman, T.T. Tran, D. Kim, Grouping effect on the seismic response of cabinet facility considering primary-secondary structure interaction, Nucl. Eng. Technol. 52 (2019) 1318–1326, https://doi.org/10.1016/j.net.2019.11.024.
[10] T.T. Tran, A.T. Cao, D. Kim, S. Chang, Seismic vulnerability of cabinet facility with tuned mass dampers subjected to high- and low-frequency earthquakes, Appl. Sci. 10 (2020), https://doi.org/10.3390/app10144850.
[11] W. Djordjevic, J. O'Sullivan, Guidelines for Development of In-Cabinet Amplified Response Spectra for Electrical Benchboards and Panels, 1990.
[12] A. Gupta, J. Yang, Modified Ritz vector approach for dynamic properties of electrical cabinets and control panels, Nucl. Eng. Des. 217 (2002) 49–62.
[13] A. Gupta, S. Rustogi, A. Gupta, Ritz vector approach for evaluating incabinet response spectra, Nucl. Eng. Des. 190 (1999) 255–272.
[14] T.-T. Tran, D. Kim, Uncertainty quantification for nonlinear seismic analysis of cabinet facility in nuclear power plants, Nucl. Eng. Des. 355 (2019) 110309, https://doi.org/10.1016/j.nucengdes.2019.110309.
[15] T.-T. Tran, P.-C. Nguyen, G. So, D. Kim, Seismic behavior of steel cabinets considering nonlinear connections and site-response effects, Steel Compos. Struct. 36 (2020) 17–29.
[16] T.T. Tran, A.T. Cao, K. Salman, P.C. Nguyen, D. Kim, Experimental and numerical modal analysis of cabinet facility considering the connection nonlinearity, in: Lect. Notes Civ. Eng., Springer, 2020, pp. 1093–1100, https://doi.org/10.1007/978-981-15-5144-4_106.
[17] K. Salman, T.T. Tran, D. Kim, Seismic capacity evaluation of NPP electrical cabinet facility considering grouping effects, J. Nucl. Sci. Technol. 57 (2020) 1–13, https://doi.org/10.1080/00223131.2020.1724206.
[18] P.C. Nguyen, S.E. Kim, A new improved fiber plastic hinge method accounting for lateral-torsional buckling of 3D steel frames, Thin-Walled Struct. 127 (2018) 666–675, https://doi.org/10.1016/j.tws.2017.12.031.
[19] F. Taucer, E. Spacone, F.C. Filippou, A Fiber Beam-Column Element for Seismic Response Analysis of Reinforced Concrete Structures, 1991.
[20] F. Mazza, A distributed plasticity model to simulate the biaxial behaviour in the nonlinear analysis of spatial framed structures, Comput. Struct. 135 (2014) 141–154.
[21] N. Noh, L. Liberatore, F. Mollaioli, S. Tesfamariam, Modelling of masonry infilled RC frames subjected to cyclic loads: state of the art review and modelling with OpenSees, Eng. Struct. 150 (2017) 599–621.
[22] A. Zendaoui, A. Kadid, D. Yahiaoui, Comparison of different numerical models of RC elements for predicting the seismic performance of structures, Int. J. Concr. Struct. Mater. 10 (2016) 461–478, https://doi.org/10.1007/s40069-016-0170-7.
[23] P.C. Nguyen, S.E. Kim, Distributed plasticity approach for time-history analysis of steel frames including nonlinear connections, J. Constr. Steel Res. 100 (2014) 36–49, https://doi.org/10.1016/j.jcsr.2014.04.012.
[24] T.-T. Tran, M. Hussan, D. Kim, P.-C. Nguyen, Distributed plasticity approach for the nonlinear structural assessment of offshore wind turbine, Int. J. Nav. Archit. Ocean Eng. 12 (2020) 743–754.
[25] A.E. Jeffers, A Fiber-Based Approach for Modeling Beam-Columns under Fire Loading, Virginia Polytechnic Institute and State University, 2009.
[26] J.P. Conte, P.K. Vijalapura, M. Meghella, Consistent finite-element response sensitivity analysis, J. Eng. Mech. 129 (2003) 1380–1393, https://doi.org/10.1061/(ASCE)0733-9399(2003)129:12(1380).
[27] M. Menegotto, Method of analysis for cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending, in: Proc.. of IABSE symposium on resistance and ultimate deformability of structures acted on by well defined repeated loads. Lisbon, Portugal, Vol. 11, 1973, pp. 15–22.
[28] F. McKenna, OpenSees: a framework for earthquake engineering simulation, Comput. Sci. Eng. 13 (2011) 58–66.
[29] R. Brincker, L. Zhang, P. Andersen, Modal identification of output-only systems using frequency domain decomposition, Smart Mater. Struct. 10 (2001) 441–445, https://doi.org/10.1088/0964-1726/10/3/303.
[30] H. Roh, A. Reinhorn, J. Lee, Power spread plasticity model for inelastic analysis of reinforced concrete structures, Eng. Struct. 39 (2012) 148–161.
[31] A. Calabrese, J.P. Almeida, R. Pinho, Numerical issues in distributed inelasticity modeling of RC frame elements for seismic analysis, J. Earthq. Eng. 14 (2010) 38–68, https://doi.org/10.1080/13632461003651869.
[32] R. Astroza, H. Ebrahimian, J.P. Conte, Material parameter identification in distributed plasticity FE models of frame-type structures using nonlinear stochastic filtering, J. Eng. Mech. 141 (2015), https://doi.org/10.1061/(ASCE)EM.1943-7889.0000851.
[33] IEEE-693, IEEE Recommended Practice for Seismic Design of Substations, 2005.
[34] AC156, Acceptance Criteria for Seismic Certification by Shake-Table Testing of Nonstructural Components, 2006.
[35] D. Gasparini, E. Vanmarcke, SIMQKE: User's Manual and Documentation, 1976.
[36] M. Barbato, J.P. Conte, Finite element structural response sensitivity and reliability analyses using smooth versus non-smooth material constitutive models, Int. J. Reliab. Saf. 1 (2006) 3–39, https://doi.org/10.1504/ijrs.2006.010688.