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Seismic behavior of steel cabinets considering nonlinear connections and site-response effects

Thanh-Tuan Tran[1,2a], Phu-Cuong Nguyen[3b], Gihwan So[4c] and Dookie Kim[*5]

[1]*Institute of Offshore Wind Energy, Kunsan National University, 558 Daehak-ro, Gunsan-si 54150, Republic of Korea*
[2]*Faculty of Technology and Technique, Quy Nhon University, 170 An Duong Vuong, Quy Nhon city, Binh Dinh, Vietnam*
[3]*Faculty of Civil Engineering, Ho Chi Minh City Open University, 97 Vo Van Tan, Ho Chi Minh city, Vietnam*
[4]*Innose Tech Company, 30 Mirae-ro, Incheon, Republic of Korea*
[5]*Department of Civil and Environmental Engineering, Kongju National University, 1223-24 Cheonan-daero, Seobuk-gu, Cheonan-si, Chungcheongnam-do 31080, Republic of Korea*

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Abstract. This paper presents experimental and numerical studies on the seismic responses of the steel cabinet facility considering the nonlinear behavior of connections and site-response effects. Three finite element (FE) models with differences of type and number of connections between steel plates and frame members have been developed to demonstrate adequately dynamic responses of structures. The screw connections with the bilinear force-deformation relationship are proposed to represent the inelastic behavior of the cabinet. The experiment is carried out to provide a verification with improved FE models. It shows that the natural frequencies of the cabinet are sensitive to the plate and frame connectors. The screw connections reduce the free vibration compared to the weld one, with decreased values of 2.82% and 4.87% corresponding to front-to-back and side-to-side directions. Additionally, the seismic responses are investigated for various geological configurations. Input time histories are generated so that their response spectrums are compatible with a required response spectrum via the time-domain spectral matching. The results indicate that both site effects and nonlinear behavior of connections affect greatly on the seismic response of structures.

Keywords: cabinet facility; site-response effect; nonlinear connection; steel structures; spectral matching; required response spectrum

1. Introduction

Electrical equipment such as motor control centers, switchgear, and small transformers may be vulnerable during an earthquake if it is not properly designed, constructed, and installed (Goodno *et al.* 2011, Cao *et al.* 2020, Salman *et al.* 2020). Therefore, the safety of these instruments must be qualified to demonstrate its operating ability under the earthquake excitation. As illustrated in Fig. 1(a), the entire electrical structure can be failed at the base of the unit, or the enclosure of electrical equipment including plates and frames can be damaged, or the connecting fasteners can be loosened (Stafford 1975, Llambias *et al.* 1989, Tran *et al.* 2019). This failure is mainly caused by the interaction between members in the cabinet with different fasteners (i.e., bolt, screw). Therefore, these connectors should be considered carefully for damage assessments of cabinets during the seismic event.

The connection is a critical element that is used to transfer the load from one member to another (Nguyen and Kim 2013, Ryan *et al.* 2017, Nguyen and Kim 2017, Cai and Young 2019). In the steel cabinet structure, the screw connections are used popular to connect panels with the frame members. These connectors are a rapid and effective method for connecting the members subjected to shear, or tension, or shear and tension forces simultaneously. In 2007, the American Iron and Steel Institute (AISI 2007) released the specification entitled "North American Specification for the Design of Cold-Formed Steel Structural Members" to assess the limit state of combined pull-out and pull-over in screw connections. Several studies are carried out as the foundation of this field. The screw fasteners subjected to pure tension and pure shear loading are conducted by Pekoz (1990), while Zwick and LaBouble (2002) studies the combination of pull-out and shear forces on these connections. For the force-deformation relationship of the fastener, the studies related to its behavior are still limited until today. Many empirical approaches for predicting the characteristic of connections have been performed in work by Cai and Young (2019), Zeynalian *et al.* (2016), Pham and Moen (2015), Nguyen *et al.* (2014), Nguyen and Kim (2016), and so on; yet, there is a lack of verification for these approaches. Although screw connections are easy to install, its stiffness and strength

*Corresponding author, Professor
E-mail: kim2kie@kongju.ac.kr
[a]Ph.D.
E-mail: tranthanhtuan@kunsan.ac.kr
[b]Ph.D.
E-mail: cuong.pn@ou.edu.vn
[c]Ph.D.
E-mail: ghso@innose.co.kr

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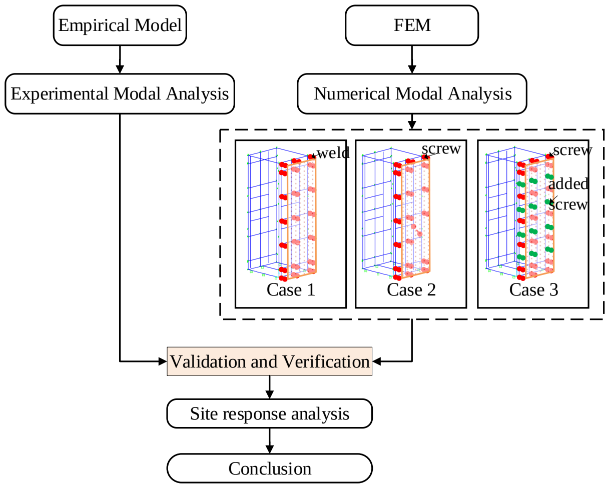
(a) General electric cabinet in Haiti earthquake (Goodno *et al*. 2011)



(b) Flowchart of the strategy

Fig. 1 (a) General electric cabinet, and (b) Flowchart of strategy

contribution to the structural system is difficult to quantify; this happens due to the complex interaction between the screw head and screw thread. For overcoming the mentioned limitations, a bilinear model of the force-deformation relationship of screw connections is proposed in this study.

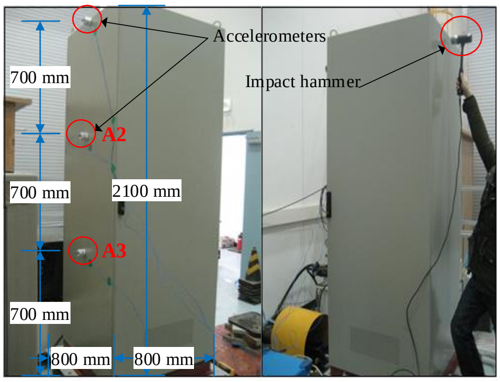
In the seismic design, site response analysis is the initial step for sensitive structures as the electric cabinet, buildings, or bridges. The effects of soil condition on the structural behavior founded on the surface or embedded in the soil are significant (Tyapin 2016) that should be evaluated adequately. Soil deposit will modify the attributes of earthquake shaking when the wave-propagation passes through it. Therefore, the amplitude of earthquake records at the surface will change and depend on the site characteristics, such as layering, or shear wave velocity (V_s) (Kobayashi *et al*. 1986). In the practical geotechnical earthquake engineering, there are many tools developed for ground response analysis using the frequency-domain equivalent linear analysis or time-domain nonlinear analysis, such as SHAKE (Schnabel 1972), DEEPSOIL (Hashash *et al.* 2012), STRATA (Kottke and Rathje 2008), PSHAKE (Tran *et al.* 2018, 2020a), etc. A lot of observational studies have evaluated the importance of site conditions for different structures such as tall buildings (Fatahi *et al.* 2014), bridges (Psarropoulos 2009), or the complexity of soil-pile-structures interaction (Hokmabadi *et al.* 2014), and so on. In this study, to better understand the site effect on the dynamic analysis of the cabinet, two specific sites in Macedonia (Cvetanovska *et al.* 2012) are taken into consideration.

The current study investigates the seismic response of electric cabinets, considering the nonlinearity of plate and frame connections and site-response effects. This approach is applied to three models with different fasteners: (i) welding connections, (ii) screw connections, and (iii) adding screws located at the mid-span of each sub-frame, corresponding with various site conditions. Firstly, the experimental test is conducted for the actual cabinet to obtain the dynamic characteristics of the structure. Secondly, the finite element (FE) models with different connections are created using SAP2000. The proposed bilinear behavior for the force-deformation curve is also applied to the plate-frame connections to consider the connection nonlinearity. Torsion and warping (Nguyen and Kim 2018) of thin-walled members of the structure are ignored in this study. Then, the natural frequencies of the FE models are calculated and validated with the experimental test results. Finally, the dynamic analyses are conducted for different geological configurations. A process of strategy shown in Fig. 1(b) was established to evaluate the vulnerability of the electric cabinet. The combination of site effects and nonlinear behavior of connections points out the great influence on the seismic response of steel cabinet structures.

2. Experimental work

2.1 Description of the investigated structure

Experimental tests such as shaking table tests (Rashad *et al.* 2019, Nguyen *et al.* 2014, Gorgun 2018, Thomas and Sandeep 2018) or impact hammer tests (Tran et al. 2019, Salman *et al.* 2019) are well-known used to assess the performance of the structure. In this work, a prototype of an electric cabinet shown in Fig. 2(a) is used to carry out the impact hammer test. The dimensions of the cabinet are 800×800×2100 (mm×mm×mm), and its weight is approximately 290 kg. The horizontal and vertical members of the test specimen are rectangular and C-shape, and their parameters are displayed in Fig. 2(c). Two large plates form the sides while a single plate forms at the top of the structure. At the front and black faces, doors are mounted to the main-frames via the locks and hinges. The thickness of these plates is 2.3 mm. The SS400 steel with 200 GPa of

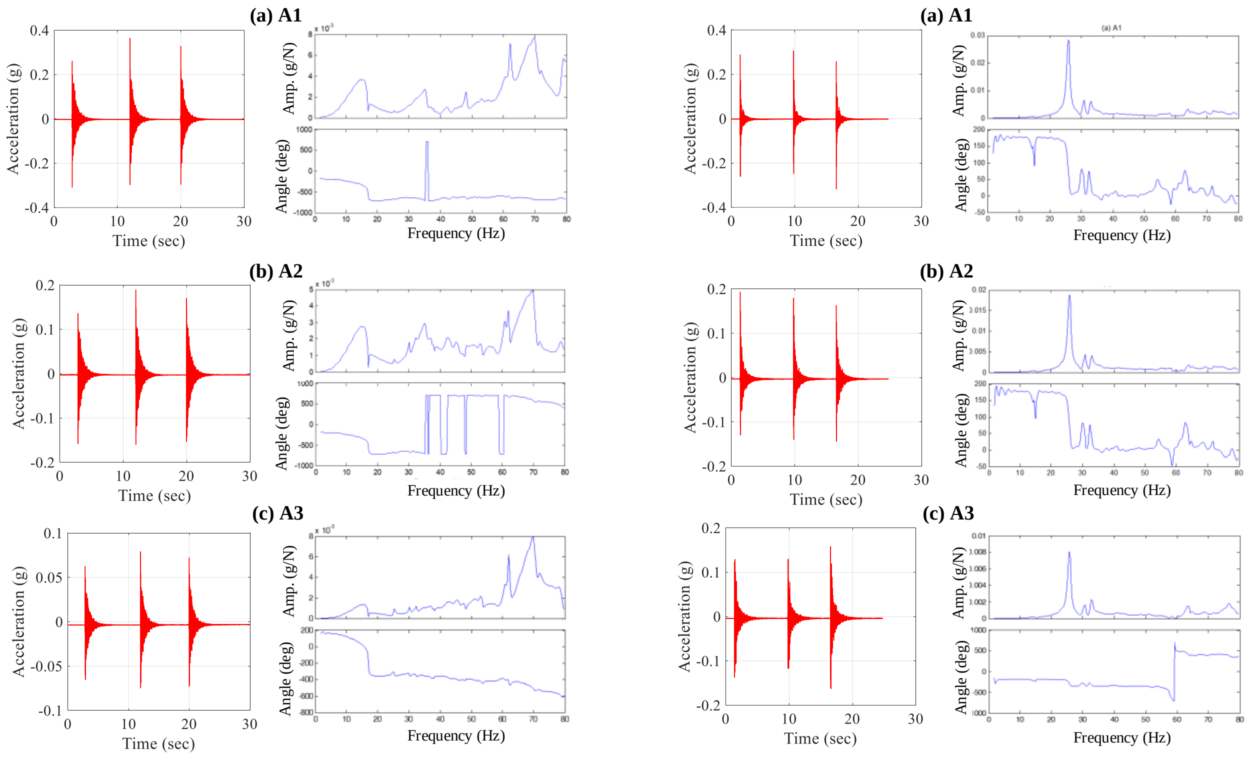


(a) Dimension and accelerometers setup

(b) Cabinet mount on shaking table test

(c) Sections of frame elements [unit: mm]

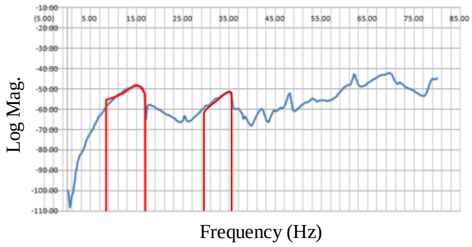
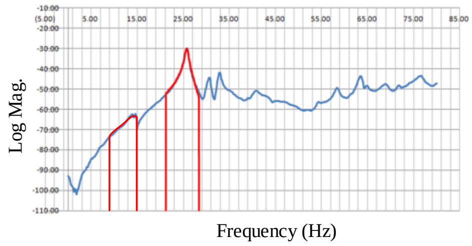
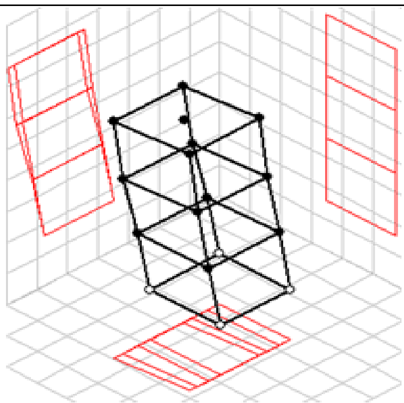
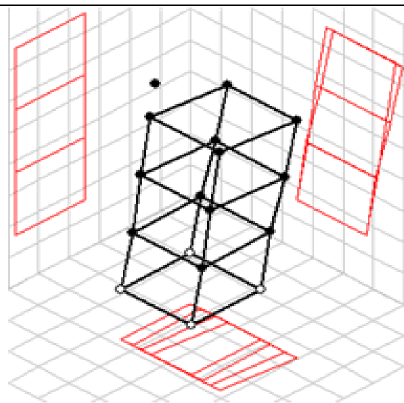
Fig. 2 Test specimen

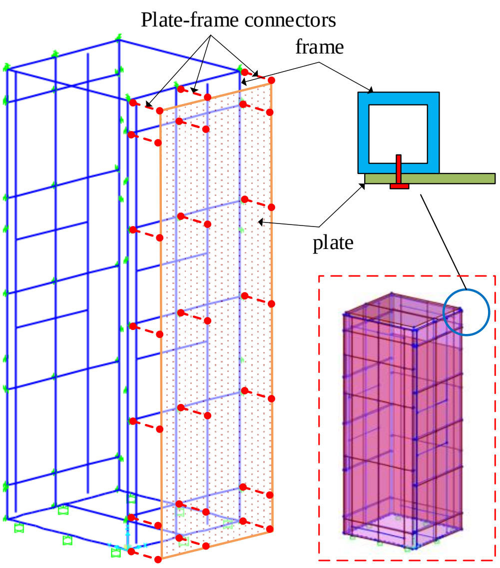


(a) Front-to-back (b) Side-to-side

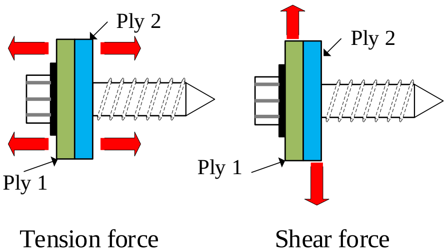
Fig. 3 Measured data at sensors: acceleration signal (left) and FRF (right)

Table 1 Dynamic characteristics of the cabinet

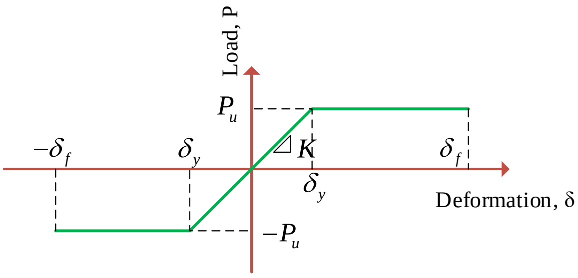
	Front-to-back	Side-to-side
Polynomial curve fitting		
Freq. (Hz)	15.10; 35.12	14.75; 25.76
Damping (%)	13.94	1.31
Mode shape		



(a) Connections between plates and frames



(b) Failure types of the screw connection



(c) Force-deformation of the screw connection

Fig. 4 Detailing of connection and their failure type

elastic modulus, 7850 kg/m^3 of density (ρ), and 0.3 and Poisson's ratio (ν) are assigned for all members. Additionally, accelerometers are attached to the panel to investigate the significant modes of the structure. The cabinet is anchored onto channels by eight M14x80 bolts, while the channels are mounted on a shaking table test (Fig. 2(b)).

2.2 Experimental results

Test specimens, as displayed in Fig. 2, are conducted. The experimental modal analysis, where the impact hammer is excited at the top of the cabinet (Fig. 2(a)), is carried out to get the dynamic structural parameters. By using signal analysis, the vibration response of the cabinet has been

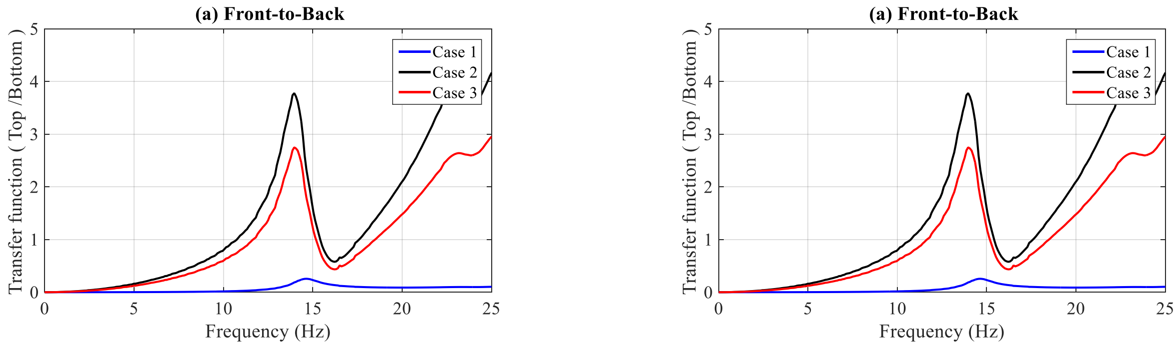


Fig. 5 Frequency response curves of the acceleration for different cases

measured and transformed into a frequency response function (FRF). Fundamentally, the FRF is a mathematical representation of the relationship between input and output of a linear system. The FRF is a complex function, which contains both amplitude (the ratio of the input force to the response) and phase (expressed in degrees, which indicates whether the response moves in and out of phase with the input). The outcomes from the experimental test are displayed in Fig. 3. These sub-figures consist of the acceleration signal of sensors at three locations (left column) and the FRF (right column) in each direction.

The dynamic characteristics of cabinets obtained from the experimental test are summarized in Table 1. These results were analyzed using the FRF, where the log magnitudes were displayed in the first row against frequencies. Based on the figure, the dominant frequencies are 15.10 and 35.12 Hz for front-to-back (FB) direction, as well as 14.75 and 25.76 Hz for side-to-side (SS) direction. The corresponding mode shape of the cabinet at the first mode is shown in the last row of Table 1.

3. Numerical simulation and its validation

3.1 Description of the numerical model

The SAP2000 software is used to create the FE model of the cabinet. The main-frames and sub-frames are modelled using the frame elements, and the steel plates are modelled using the shell elements. In order to get accurately model, the FE model should be composed close to the real behavior of the cabinet. Therefore, the connections between plates and frames are simulated as link elements. The hinges between doors and frames are considered to be fixed at five degrees of freedom, and the sixth degree of freedom is considered to be free (which is the rotation about the hinge axis). Meanwhile, the locks between panels and frames are fixed at three translational degrees of freedom. Welding is used to connecting plates and frames together; thus, the rigid links are applied in the FE model. For the boundary condition of the structure, a total of 8 bolts connect the base-frames with the floor. These connections are considered to be fixed at five degrees of freedom, only the rotation around the bolt axis is released.

Table 2 Natural frequencies (Hz) obtained from different FE models (first mode)

		Case 1		Case 2		Case 3	
Direction	Exp.	Freq.	Error (%)	Freq.	Error (%)	Freq.	Error (%)
FB	15.10	14.55	-3.64	14.14	-6.36	14.19	-6.03
SS	14.75	14.99	1.63	14.26	-3.32	14.35	-2.71

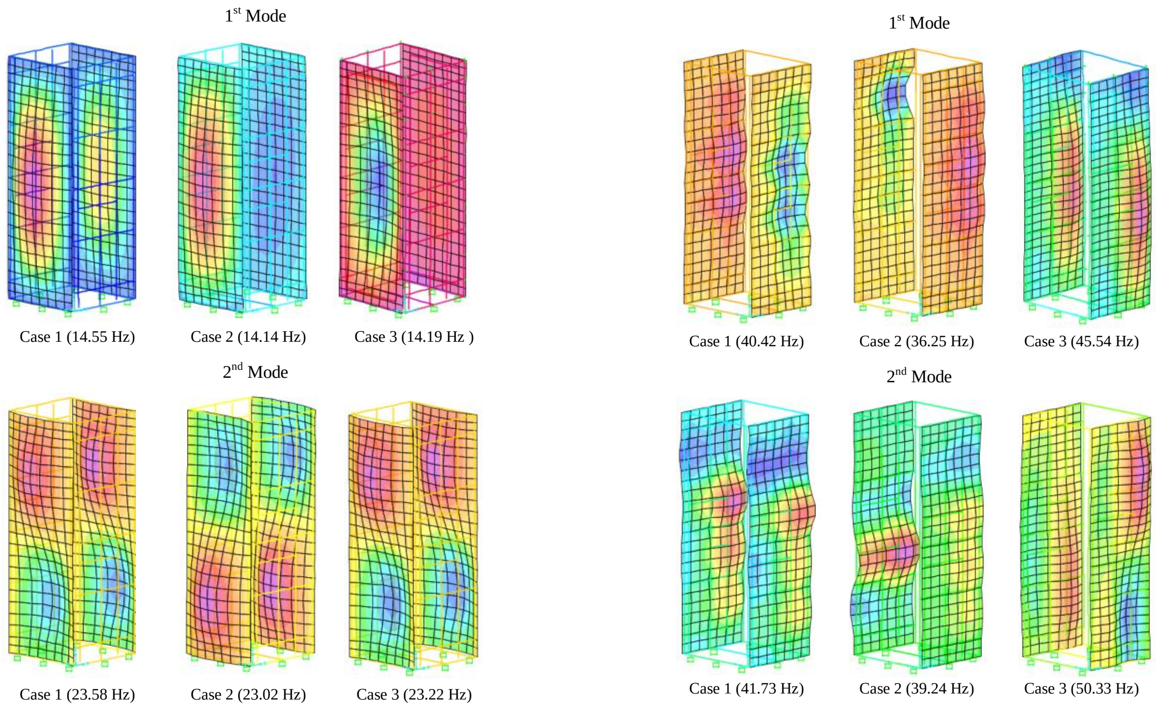
3.2 Modeling of interaction between the plate and frame members

The previous section represents the FE model using weld connectors between the plate and frame members. However, in the real, the steel panels may attach with the frame members with the screws. As a result, these fasteners may not fully rigid as assumed. Consequently, their stiffness should be considered to evaluate the behavior of the electric cabinet under excitations.

The screw-fastened connections between plate and frame members are addressed for understanding their nonlinear behavior (Fig. 4(a)) (Tran *et al.* 2019). The proposed model highlights the load-deformation response, which using the simple model to predict the connection strength.

Screw-fastened performance relates to the ultimate displacement, δ_f, and screws can be failed under shear or tension forces, that they relate to the steel thickness of fasteners. According to AISI (2007), the failure modes depend on the strength as well as the ratio of the bottom ply (Ply 2) over the top ply (Ply 1) of connectors. In this research, it is assumed that the failure of screw fasteners will occur under shear and tension forces. As illustrated in Fig. 4(b), the shear force with the bearing or tilting mode controls the in-plane failure while the tension force with the pull-out mode controls the out-of-plane failure.

As mentioned in the previous section, the force-deformation characteristics of screw fasteners are difficult to quantify. Therefore, the simple model with bilinear behavior in Fig. 4(c) is assumed for these fasteners. For the shear-force deformation, V_{AISI} per fastener is calculated as the minimum of the nominal bearing and tilting strengths as Eqs. (1) and (2), assuming the connected members (Ply 1 and Ply 2) have the same thickness $(t_1 = t_2 = t)$ and the



(a) Front-to-Back (b) Side-to-Side

Fig. 6 Local mode shapes and frequencies of steel plates

same minimum specified tensile strength $(F_{u1} = F_{u2} = F_u)$

$$V_{AISI} = 4.2\sqrt{t^3 d}\,F_u \qquad (1)$$

$$V_{AISI} = 2.7tdF_u \qquad (2)$$

where d is the nominal diameter of screws.

For the tensile-force deformation, the nominal tensile strength, T_{AISI} per screw is computed due to the pull-out failure mode. Again, assuming $t_1 = t_2 = t$ and $F_{u1} = F_{u2} = F_u$, T_{AISI} is computed as follows:

$$T_{AISI} = 0.85tdF_u \qquad (3)$$

In order to evaluate the effect of fastener on the dynamic response of the cabinet, three cases of connection system are presented in the following: modeling with the welding connections (case 1), modeling with screw connections (case 2), and (c) modeling that is increasing the number of screws by adding additional screws at the mid-span of each sub-frame (case 3).

3.3 Dynamic characteristics of the cabinet

3.3.1 Comparison with experimental data

Through the modal analyses, the natural frequencies from the FE models are evaluated and compared with the experimental results. The results for three cases are summarized in Table 2. It is worthy to note that the natural frequencies from FE model results are very close with those from the experimental modal analysis. Additionally, it can be seen that the first model with fixed connections produces lower errors than rest models. When considering the nonlinear behavior of connections, the frequency contents change slightly for various models.

3.3.2 Effects of connections on the dynamic parameters of the cabinet

In order to evaluate the effects of connections on the dynamic characteristics of the cabinet, the transfer function (TF) determined by responses at the top and bottom of the FE models is performed. In this section, the TFs of nonlinear cabinets (second and third cases) are calculated and compared with the linear one (first case). The comparison is conducted for dominant frequencies, as shown in Fig. 5. The variability in the transfer function describes the influence of connections in the frequency range. As can be seen in the figure, the dominant frequencies from the nonlinear cases shift leftwards compared to those obtained from the linear case. As expected, the fundamental frequencies of cabinets with the screw fasteners decrease because of the decrement of stiffness. The maximum peaks in the first mode are shifted about 2.82% (14.14 Hz) and 2.47% (14.19 Hz) for case 2 and case 3, respectively in the FB direction. While in the SS direction, the reduction values are 4.87% (14.26 Hz) and 4.27% (14.35 Hz) for second and third cases, respectively. Since the mass of structures in all cases is similar, the only parameter that could affect the natural frequency is stiffness. This means the screw connections have reduced the flexural rigidity in comparison to the welding connections. Also noticeable in two directions, the amplitude in the SS direction is larger than FB direction for all cases. This causes the sub-frames with vertical and horizontal members and side plates to control the response

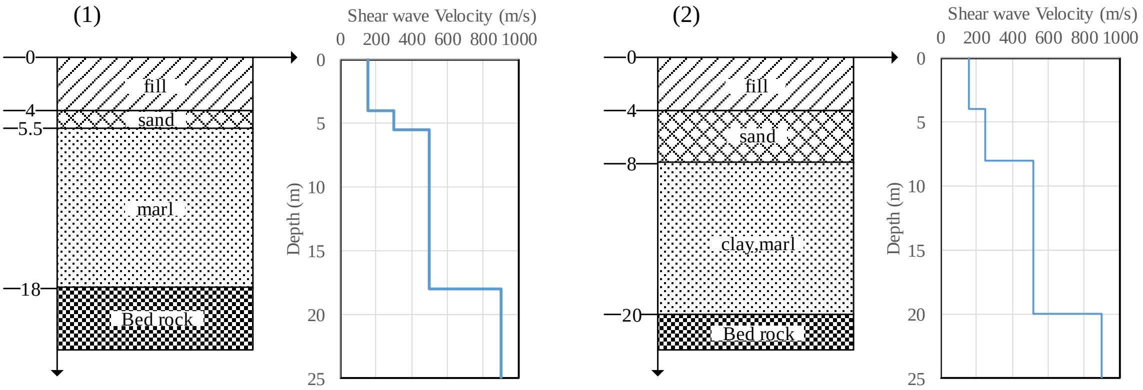


Fig. 7 Characteristics of soil profile

in the FB direction. This result reveals that the screw fasteners can reduce the vibration in the assembly cabinet.

In addition, the influences of fasteners on the local mode shapes and the frequencies of plates are investigated, as shown in Fig. 6. It should be considered how the response of plates with different boundary conditions. Note that in the FB direction, the links between doors and frames are still using the hinge and shim connectors. This can be understood easily based on the results in Fig. 6(a). As shown, the frequencies have a slight change in different cases. Against, in the SS direction, the panels are controlled by various boundary conditions. In case 1, the panels are fixed to main-frames using weld connectors, while in case 2 and case 3, these connections are replaced by screw one. Note that the third case increases the number of boundary conditions. Comparing the mode shapes of different models, the frequencies change a lot since the effects of fasteners (Fig. 6(b)). The frequencies decreased when the displacement force curve between plates and frames are considered. The frequencies (case 2) decrease about 4 and 2 Hz for the first and second modes, respectively when compared to case 1. However, the frequencies for the first (45.54 Hz) and second (50.33 Hz) modes of the case 3 are much higher than that of the case 1 (40.42 and 41.73 Hz for the first and second modes, respectively). This causes the increment of the number of screw connectors, and the modal frequencies increase with the increasing of stiffeners. This highlights that the stiffness of screw connections gives a sensitivity in the fundamental frequencies of the cabinet structure.

4. Site-specific ground motion

4.1 Soil profile and material parameters

Two site profiles in Macedonia (Cvetanovska *et al.* 2012) shown in Fig. 7 are applied to investigate the influence of site conditions in the seismic assessment of the cabinet. The soil profile mainly consists of sand, clay and marl, and total depth is about 20 m above bedrock. The thickness of the surface filled layer is about 4 m with 155 m/s of V_s. The middle layers consist of sand and clay with V_s ranged between 250 and 520 m/s. The layer of rock with V_s around 900 m/s is below a depth of 20 m. For the fill soil, the relationships for the $G/G_{\max}$ and damping proposed by Vucetic and Dorby (1991) are used, whereas the Seed and Idriss (1970) relations are applied for the sand and clay soil.

The effect of local site conditions on the characteristics of earthquake loading is often quantified via an amplification factor (AF), which is defined as the ratio of the spectral accelerations at the surface $(S_{a,soil})$ to the bedrock $(S_{a,rock})$. The AF for a site can be evaluated by conducting ground response analysis. The $S_{a,soil}$ can be computed in the general form

$$S_{a,soil} = S_{a,rock} \times AF \tag{4}$$

The functional form of AF has been developed in many researches (Boore *et al.* 1997, Choi and Stewart 2005, Chiou and Youngs 2008) using different parameters. The AF models may not be included in the nonlinear effect or maybe considered both linear and nonlinear site amplification effects (Choi and Stewart 2005, Chiou and Youngs 2008). The general form of AF is the function of shear wave velocity at 30 m $(V_{s,30})$ and the peak ground acceleration at the bedrock (PGA_{rock}), with $V_{s,30}$ is the shear wave on the top 30 m of a site and is computer as follows

$$V_{s,30} = \frac{30}{\sum_{i=1}^{n} \frac{h_i}{V_{s,i}}} \tag{5}$$

where h_i and $V_{s,i}$ are thickness and shear wave velocity of layer i. In Fig. 7, two profiles with different $V_{s,30}$ values, 456 and 393 m/s for soil 1 and soil 2, respectively, are used to analyze the site effects on the cabinet.

4.2 Selection of earthquake records

There are many earthquake records which can be applied to the cabinet, and the selection has been made based on the purpose of the analysis. In this study, a suite of seven ground motions is firstly obtained from the PEER NGA databases considering geological and seismological

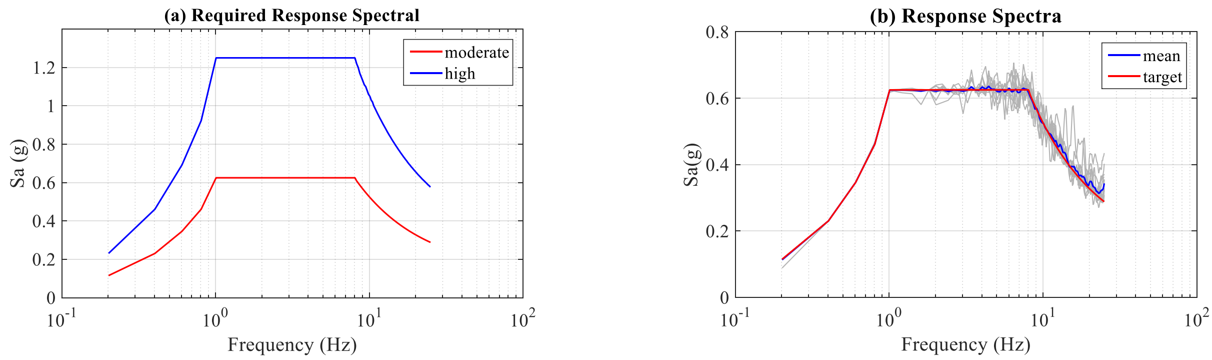


Fig. 8 Required response spectra and calculated response spectra

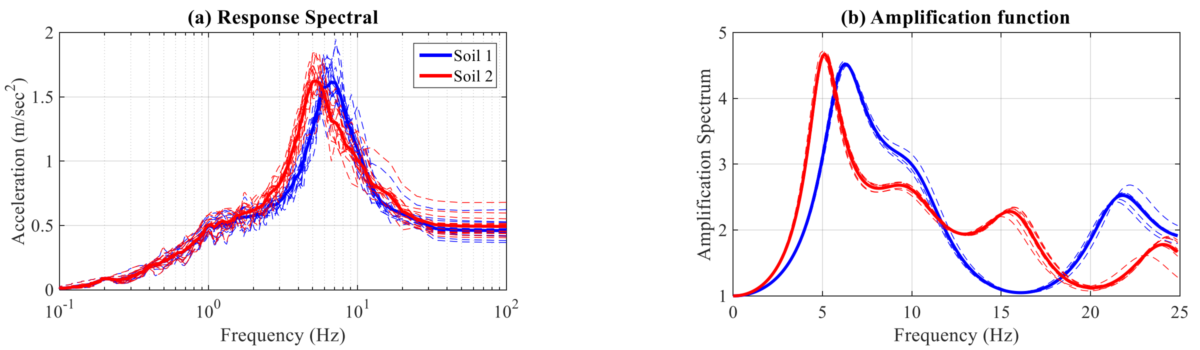


Fig. 9 Median response spectral and amplification functions for two sites

characteristics. The records are selected in such way that it will satisfy with the required seismic conditions suggested by IEEE 693 Recommended Practice for Seismic Design of Substations (IEEE-693 2005) as listed in Table 3. These earthquakes were recorded on the soil sites with the closest distance-to-ruptured area (denoted as R_{RUP}) range from 0 to 50 km, and the range of magnitude is between 6.0 and 7.0.

Because of the difference of earthquake characteristics (magnitude, distance, site condition, …), the real ground motion records have to match with required response spectrums (RRS) over the range of an interesting period in the seismic design code. The RRS for the electric cabinet suggested by IEEE 693 is used. This instruction shows the shape of the horizontal response spectrum, which is defined by three branches using the fixed value of frequencies with three seismic qualification levels (i.e., high, moderate, low) with no spectrum for the low level, shown in Fig. 8(a). This research has used the moderate level of the RRS with 5% damping for matching purposes. A time-domain spectral matching procedure is adopted for scaling the time histories to the target spectrum. In this approach, the adding adjustment wavelets to an initial acceleration time series to generate a modified time series whose response spectrum is compatible with the RRS. This procedure is performed using the computer code RspMatch, developed by Abrahamson (1992), which generally follows the proposed algorithm by Lihanand and Tseng (1998). Details of spectrally matched motions are displayed in Fig. 8(b).

4.3 Ground response analysis

The influence of site conditions on the ground motions recorded at the surface is investigated in this section. A methodology for addressing the ground response analysis during the earthquake is an equivalent linear procedure. The computer program Shake91 (Idriss and Sun 1992, Tran et al. 2020b) is used to compute the seismic response of the horizontally layered soil deposit subjected to motion at the bedrock.

Table 3 List of earthquake records

No	Earthquake	Station	Year	Mag.	R_{RUP} (km)
1	Imperial Valley-02	El Centro Array #9	1940	6.95	6.09
2	Northern Calif-01	Ferndale City Hall	1941	6.4	44.68
3	Northern Calif-03	Ferndale City Hall	1954	6.5	27.02
4	San Fernando	Lake Hughes#4	1971	6.61	25.07
5	Managua_ Nicaragua-01	Managua_ ESSO	1972	6.24	4.06
6	Friuli_ Italy-01	Tolmezzo	1976	6.5	15.82
7	Imperial Valley-06	El Centro Array #13	1979	6.53	21.98

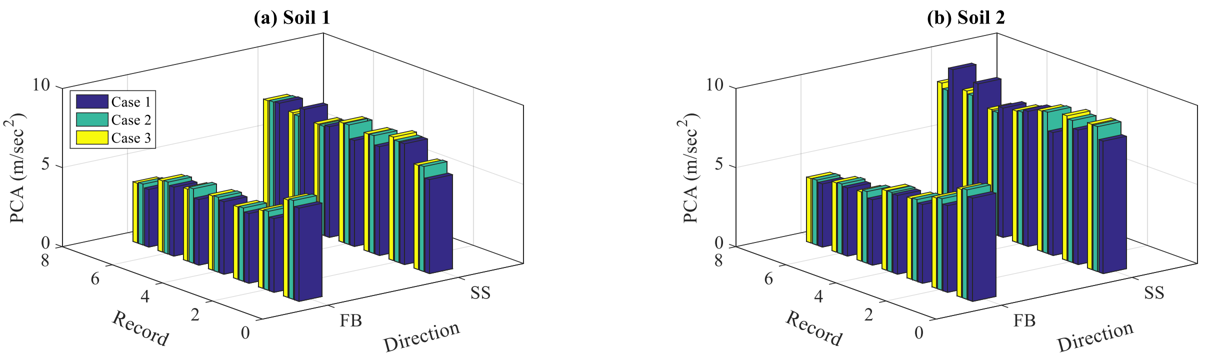


Fig. 10 Peak acceleration at the top of the cabinet

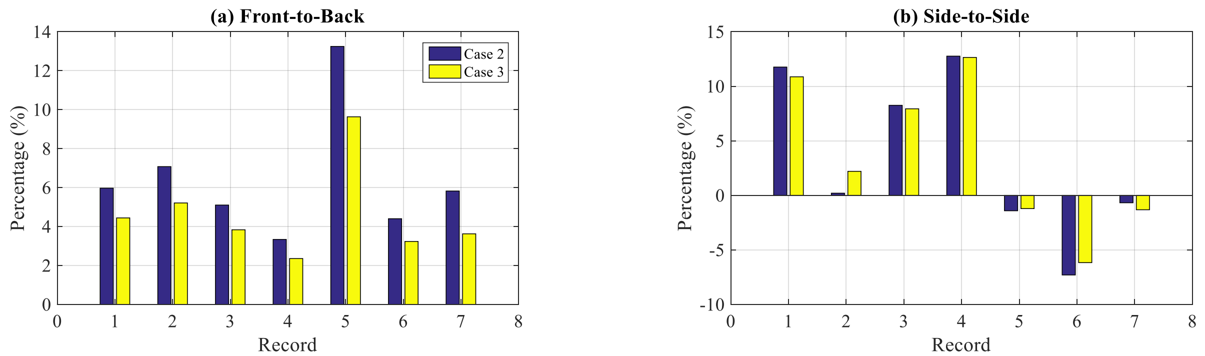


Fig. 11 Connection influence on the seismic response at the top of the cabinet for the soil 1

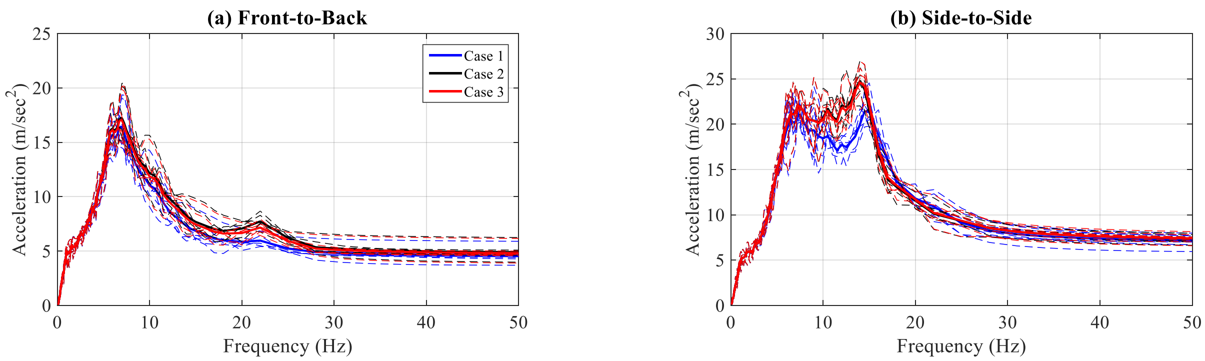


Fig. 12 Acceleration response in the frequency domain at the top in the soil 1

The analysis responses for two sites are displayed in Fig. 9, including the results of spectra acceleration and AF. All the generated results in Fig. 9 have the same earthquake input at the bedrock but different V_S profiles.

The dash lines illustrate each record, and the solid line indicates the mean value. Fig. 9(a) indicates that the acceleration peaks occur at a higher frequency when V_S increases. It is significant to note that the site characteristics will affect on the spectral periods which can denote by a simple parameter as the site period, T_S. This parameter can be calculated as follows

$$T_s = 4H / V_{s,avg} \tag{6}$$

where H is the depth of soil and $V_{s,avg}$ is the average shear wave velocity of the soil. In Eq. (6), the period is inversely proportional of V_S. For two specified sites in this study, the values of T_S are 0.16 and 0.2 (s) for soil 1 and soil 2, respectively.

The performance of site response can be assessed through an amplification factor (AF) shown in Fig. 9(b). The average amplification factors (DAFs) of 4.52 and 4.67 are adopted for soil 1 and soil 2, respectively. Another observation is that the stiffer site (site 1) has a longer frequency that can be explained in Eq. (6). Base on the obtained results, it can be concluded that the V_S profiles are one of the significant parameters that affect on AF. Additionally, the observed response spectra can differ significantly when the site characteristics are changed.

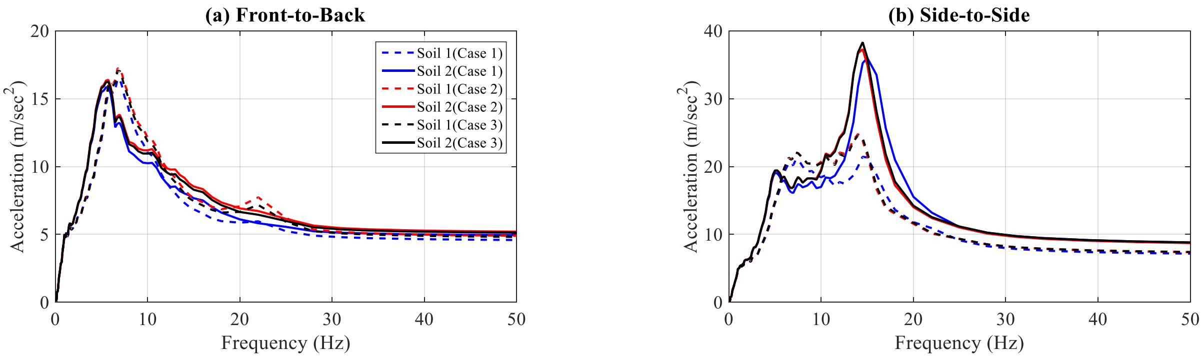


Fig. 13 Median acceleration response in the frequency domain at the top

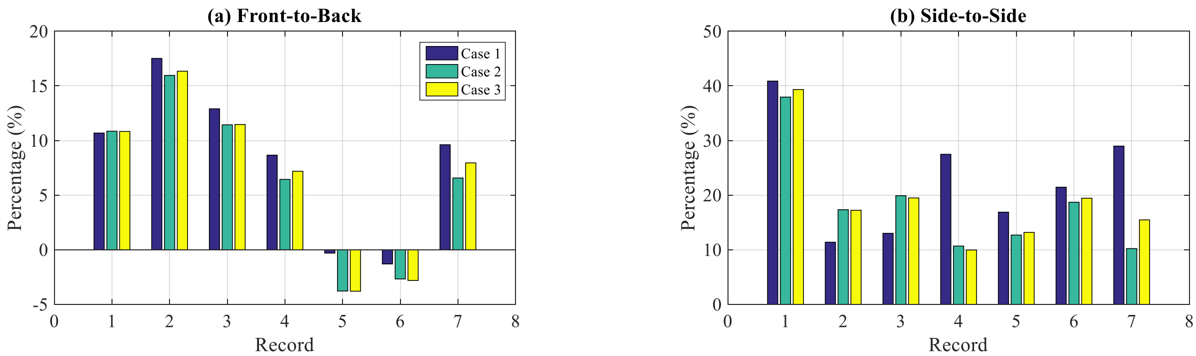


Fig. 14 Site influence on the seismic response of the cabinet in the SS direction

5. Analysis results and discussions

Three FE models with various connections between elements are presented and verified in section 3. Then, a suite of ground motions is matched to the RRS, and site response analysis is performed for two specified sites (section 4). In this section, a series of nonlinear time history analysis is performed, and ground motions recorded at the surface are used as input excitations. The acceleration response is selected as an effective indicator since the electric cabinet is the sensitive equipment having many attached devices (Cho and Kim 2011, Rustogi and Gupta 2004, Tran *et al.* 2019).

5.1 Effects of the nonlinearity interaction of plates and frames

The maximum acceleration responses at the top of the cabinet for various models in two directions are shown in Fig. 10. The results indicate that the peak cabinet accelerations (PCAs) have the same trend with a higher response when the screw fasteners are considered. The major observation is that the PCA in the SS direction is more important than the FB direction for all cases. This causes the configuration of the cabinet, which can be explained as follows:

- The diagram of the cabinet: the cabinet is assembled by plate and frame members, as shown in Fig. 4(a). The sub-frames with several horizontal and vertical members on both sides are installed; thus, the stiffness of the structure in the FB direction will increase.
- Boundary conditions: the FE model of the cabinet is modelled in such a way that it can obtain the behavior accurately. Therefore, the total of connections between the base frame and floor equal with the prototype, with 6 points at front and back sides, and two points at the left and right sides (Fig. 4(a)). This leads to the increament of the stiffness in FB direction.

Fig. 11 displays the results of the observed PCA of nonlinear models (case 2 and case 3) for the soil 1. Each bar indicates the percentage of variation (increment or decrement) that is normalized by the observed PCA of case 1 (rigid connections). The increasing values of responses can be obtained when considering the nonlinear behavior of connections; the differences are for the records in the SS direction with less than 5% for decreasing values. When comparing the responses of case 3 (increasing the number of screw fasteners) with case 2, the decreasing percentages are found since the welded fasteners are much stiffer than the screw fasteners. Note that, a larger incremental percentage is found in the FB direction for case 3 because the screw fasteners reduce the influence of side plates of structure.

Fig. 12 shows a comparison of the median surface response spectra in three cases for the soil 1. Dash lines illustrate the response for each record, and the solid line is median values. When compared to the first case, the maximum median spectra are larger than 1.28 and 1.27 times for case 2 and case 3, respectively for the SS direction. While in the FB direction, the factors are 1.30 and

1.20 for case 2 and case 3, respectively. It is also observed from Fig. 12, the median values of the FB direction are smaller than those of the SS direction. Based on the observation, it is worth noting that the bilinear force-deformation relationship proposed for screw connections will distribute the nonlinear behavior of the structure. Therefore, it can capture a realistic response under earthquakes.

5.2 Effects of site conditions on the behavior of the cabinet

In order to evaluate the influence of site conditions on the seismic response of the cabinet, the predicted accelerations at the top of cabinet models are plotted in Fig. 13. The figure shows the responses of the cabinet with different fasteners and resting on different soil types. It is expected that the acceleration response in both directions can differ since the structure is installed at different sites. The response of the soil 1 underestimates comparing with the rest one for the SS direction. While for the FB direction, the response of the soil 1 is overestimated at the first frequency. In general, the spectra accelerations increase due to the decreases in soil stiffness. This leads to conclude that the soft soil condition produces higher spectral acceleration.

Similar to Fig. 11, the PCAs are considered to evaluate the site effects on the seismic response of the cabinet, as presented in Fig. 14. Each bar indicates the percentage of variation (increment or reduction) of soil 2 that are normalized by the observed PCA of the soil 1. It is founded that for the SS direction, the increased percentage of the PCA by considering soil 2 is about 20% when compared with soil 1. However, for the FB direction, the percentage reductions of around 15% are also founded for some records. This observation highlights that the soil effect plays a crucial role in estimating the structural response due to seismic ground motion records.

6. Conclusions

The influence of nonlinearity of steel plate and frame connections on the dynamic response of the cabinet facility is investigated in this work. This approach is applied to three finite element models with varieties of type and number connections. The connections between the steel plate and frame members using the bilinear relationship for the displacement-force curve are implemented to consider the nonlinear behavior of the structure. Dynamic characteristics of FE models from the modal analysis are compared with experimental work. Additionally, the effects of site characteristics on the structural seismic response are investigated for two specific soils in Macedonia. Based on the observed results, the major conclusions can be drawn as follows:

- The comparison between experimental and numerical results shows good agreements in dynamic characteristics for all cases, confirming the reliability of the proposed FE models. Consequently, the improved FE models can be used for seismic assessment of the cabinet facility.
- Once the nonlinearity of connections is considered, a slight change in natural frequencies is achieved. The replacement with screw connections decreases the natural frequencies due to the decrease in the stiffness of the structure. The decreased values of 2.82% and 4.87% in front-to-back and side-to-side directions, respectively, are found when comparing to the welding. With the increment of the number of screw connections, the frequencies have slight increases compared with the second case due to the increment of the structural stiffness.
- Local mode shapes and frequencies of panels are sensitive to the stiffness of screw fasteners. When comparing with the linear case, the frequencies of the nonlinear model decrease about 4 and 2 Hz for the first and second modes, respectively. It is also noticeable that the modeling of the screw connection increases the response at the cabinet top in both directions compared to the rigid one.
- Spatial varying characteristics of soil conditions in terms of V_s and layering should be considered in the realistic seismic analysis of the cabinet. The combination of site-effects and the nonlinear behavior of connections has a significant influence on the seismic response of the structure.
- The acceleration response at the top of the cabinet depends on the flexibility of the soil. The response increases with the decrease of the soil stiffness.

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