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Research Paper

On the Vertical seismic Response of the Floor Mounted Motorized Non-Structural Components

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ABSTRACT

Seismic design guidelines for non-structural components typically do not account for the potential interaction between the vibrations of these elements and the deflections of the host structure, especially in the vertical direction. This paper examines critical seismic scenarios, such as the simultaneous vibrations from operating motorized devices (like chillers) and earthquake-induced movements, by considering the short-period spectral characteristics of vertical ground motion components in near-fault regions. To address this, the amplification factor of non-structural components installed in low-rise and mid-rise steel moment-resisting frame structures was assessed using nonlinear time history analysis. The evaluation showed that the amplification factor of vertical acceleration for non-structural components with vertical mode periods below 0.5 seconds ranged from 1 to 4, depending on the number of floors in the host structure and whether the motor was operational. The operation of the chiller's motor on the roof during an earthquake increased the vertical acceleration amplification factor by 10% to 50%. These findings suggest that the current seismic code approaches, which overlook the vertical mode frequency of structural and non-structural elements, need to be reconsidered, especially in near-fault areas.

Keywords:
Seismic vertical component; Non-Structural elements; Operating motorized devices; Near-field earthquakes

1. Introduction

Recently, the combined modeling of structural and non-structural elements under earthquake excitation has improved to reduce the possible losses over the lifetime of buildings located in seismic-prone areas. Non-structural components (NCSs) constitute a significant portion of the investment in existing buildings, and maintaining their functionality after potential earthquakes is of great importance both in terms of preserving capital in general buildings and service provision in emergency and essential buildings. Therefore, it is important to properly account for the anticipated non-structural damages via estimating the acceleration demands that are imposed on them on any one-floor level during an earthquake (Kazantzi et al., 2020). These components can be classified based on their behavior as components sensitive to acceleration, deformation, or to both conditions, and based on their function, as architectural components, mechanical and electrical equipment, and internal installations and equipment.

The common approach of most seismic guidelines for designing the acceleration-sensitive components, which are connected to the floor of the building, is to estimate the inertial lateral forces without modeling the non-structural elements on the floor of structure. To calculate the inertial lateral force acting on these components due to the horizontal earthquake component, three parameters are usually considered including: (i) the weight of non-structural element, (ii) the peak floor acceleration (PFA), (iii) the component amplification factor (ap) which indicates the degree of acceleration amplification at the center of non-structural element mass compared to the acceleration generated at the floor where the element is installed. According to the current seismic provisions such as ASCE7-22 (2022) and the Iranian Seismic Code (2015), this factor ranges from 1 to 2.5, depending on the classification of the component as rigid or flexible, with the criterion for classification being vibration period lesser or greater than 0.06 seconds. Furthermore, these seismic codes stipulate that the vertical component of earthquake should be applied simultaneously with the horizontal lateral force to the non-structural element. In this regard, a relationship is considered, where only the weight and importance factor of non-structural components are effective with no amplification factor for the vertical component of seismic excitation. In fact, the assumption of rigidity of the non-structural component in the vertical direction has led to considering this factor close to 1, according to the most seismic code provisions. Also, the peak floor vertical acceleration (Vertical PFA) factor over the height of structure is taken equally to 1, according to these seismic code provisions. This implies that the location of the NCSs along the height of buildings does not impact the magnitude of inertial force in the vertical direction. This assumption would be questionable for certain load-bearing structural systems that do not have complete rigidity in the vertical direction.

On the other hand, in near-fault areas, the fault-rupture propagation towards the building at a very high speed causes a significant portion of seismic energy to be transmitted to the structure, as a long-period pulse which is often observed in the velocity-time history of earthquake horizontal component. According to studies, vertical ground motion in these areas has a higher proportion of short-duration spectral content (with high frequency) in comparison with horizontal ground motion (Aghaei-Araei et al., 2019). Additionally, during short periods and in near-fault earthquakes, the ratio of peak acceleration of the vertical component to the horizontal component is higher than in far-field earthquakes and exceeds the common values have been offered in most seismic codes which is a coefficient of two-thirds or 0.6. This aspect has a significant impact on the seismic design of non-structural components which usually occur in short-time periods (i.e. periods less than 0.06 sec for rigid components). In a group of non-structural elements, such as mechanical and electrical equipment that may experience device vibration while operating, the intensification of seismic intensity in near-fault areas would be possible during an earthquake event (Karoubi, et al., 2024). It is noteworthy that this aspect of the issue has not been thoroughly investigated in previous studies.

Given the above discussion, by using the recent approach of combined modeling of structural and non-structural elements, this paper aims to evaluate the seismic response of a group of mechanical devices with motors installed in steel buildings at near-fault regions.

2. Introduction to the Principles and Methods of Modeling Vibration of Non-Structural Components of the Type of Mechanical Devices with Motors

This category of non-structural components includes equipment such as air compressors, HVAC units, chillers, cooling towers, washing machines, and similar items that may be placed on the floor with or without vibration insulation. The methods for modeling devices with motor, which preserve the dynamic characteristics of the system and are easily implemented in common software programs, can be divided into two categories of concentrated and distributed one-degree-of-freedom systems. A study by Shihab et al. (2017) has offered an equation of motion for harmonic forced vibration of the rotating motor of a washing machine in the operating state.

Assuming that it is able to move in both horizontal $x(t)$ and vertical $y(t)$ directions, it is presented as equation (1). In this equation, M is the total weight, m is the rotational weight, R is the drum motor radius, ω is the rotational frequency of the motor, θ is the angle between the spring and the vertical axis, C_{ex} and C_{ey} represent the equivalent damping of the system in the horizontal and vertical directions, and K_{ex} and K_{ey} represent the equivalent stiffness of the system in the horizontal and vertical directions, as shown in Figure (1).

$$\begin{aligned} M\ddot{x} + C_{ex}\dot{x} + K_{ex}x &= mR\omega^2 \cos\omega t \\ M\ddot{y} + C_{ey}\dot{y} + K_{ey}y &= mR\omega^2 \sin\omega t \end{aligned} \tag{1}$$

Using combined models of finite element methods and mass-spring systems in order to model mechanical devices (such as chillers) is also being expanded. As an example, this approach was employed to model a cooling tower located on the roof of a five-story concrete building according to Figure (2). This was presented as a laboratory-numerical study by Marin-Artieda et al. (2014). A good agreement was observed between the results obtained from the simulation and the ones determined through the seismic response of the structure and the cooling tower in the state of non-operating and situated on a shake table under the influence of horizontal component of six seismic accelerograms. In this study, the first to the third modes of the cooling tower motion were examined in both conditions of full and empty of water, as shown in Figure (3), with the first mode in the vertical direction (having a period of 0.21 and 0.22 seconds in the filled and empty states, respectively), followed by the transverse and

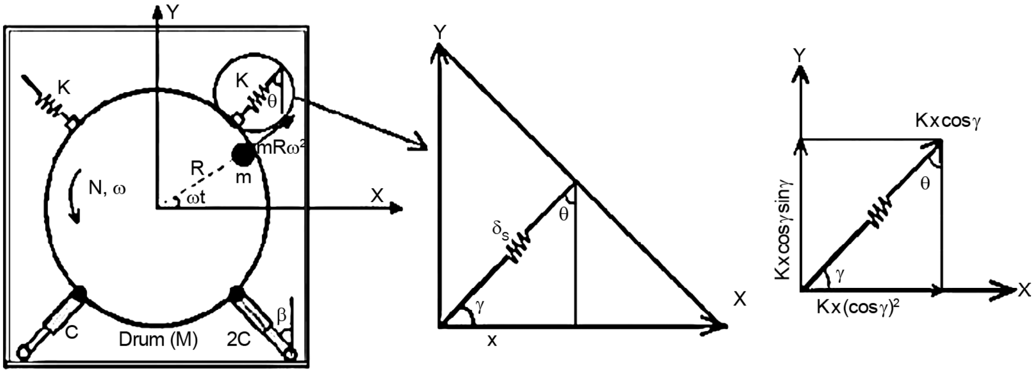


Figure 1. A physical model of a washing machine motor (Shihab et al., 2017).

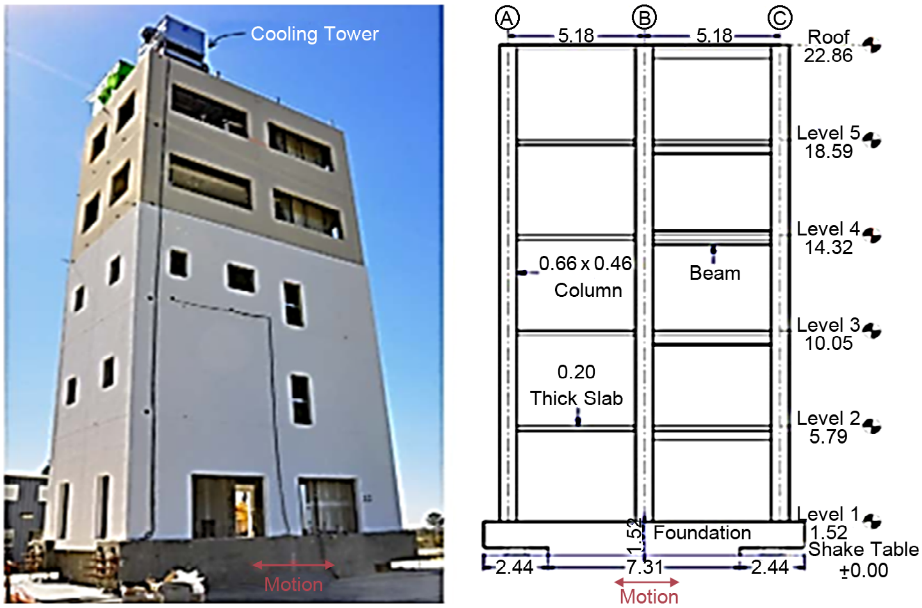


Figure 2. The full-scale test structure outfitted with a wide range of NCSs (Astroza et al., 2015)

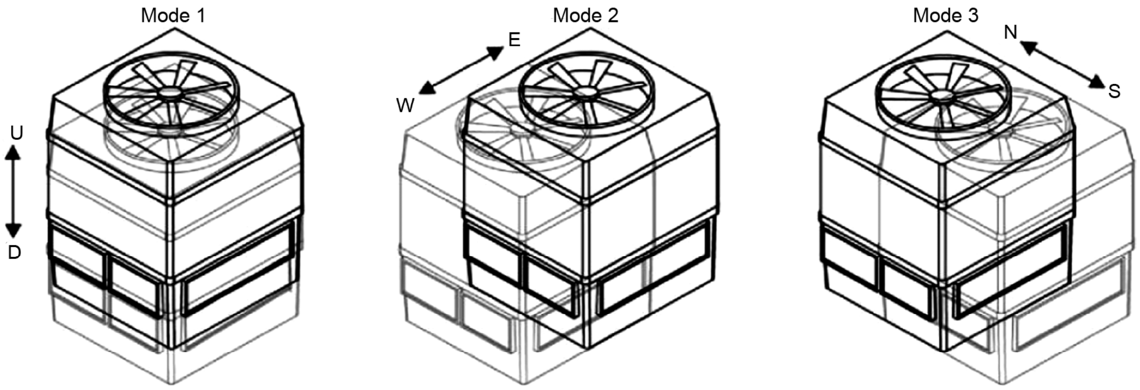


Figure 3. Modes of the cooling tower system motion (Astroza et al., 2015).

longitudinal modes. However, this study has only focused on the amplification coefficients of acceleration in the horizontal direction and has not investigated the behavior of the cooling tower motor during the vertical component of earthquakes.

Furthermore, the recent study via structural health monitoring (SHM) following the 2018 Osaka earthquake in Japan showed that the fragility functions used in current methodologies for estimating non-structural elements damage may not be entirely representative of the in- situ reality and possibly underestimate actual damage due to factors such as differences in installation conditions and loading protocols used in experimental testing, possible interaction with other elements, variability in the quality of workmanship during installation and possible wear, tear and degradation during service (O'Reilly, et al., 2023).

3. Structural and Non-Structural Components Modeling

In this study, two subgroups of mechanical and electrical non-structural elements with motors, including a chiller cooling tower and a washing machine, have been investigated. The studied structures are designed in two categories of low-rise (4-story) and mid-rise (8-story) buildings with moderate level of importance (I_S = 1), located in a high relative hazard zone (A = 0.35) in soil type II (according to the Iranian Seismic Code (2015)). The regular plan of the studied structures is shown in Figure (4a), with short (4 meters) and long (7 meters, i.e. sensitive to vertical direction motions) spans, with a story height of 3.2 meters. The floors are made up of two-sided reinforced concrete slabs with a thickness of 15 centimeters. The lateral force resisting system in the two orthogonal structural directions is the steel intermediate moment resisting frame (R_u = 5). The column sections are of the Box type and the beams are of either IPE type and plate girder, by details described in Lashgari-gehraz (2022). The fundamental period of vibration for the low-rise and mid-rise structures are 0.8 and 1.28 seconds, respectively. The maximum ratio for relative displacement in the floors is very close to the allowable value, suggested by Iranian Seismic Code (2015). To make an optimal design of the structure, the stress ratio in the members has been considered close to 1 in the critical load combinations. The inelastic behavior of beams and columns is modeled by the formation of lumped plastic hinges at their ends. The effects of axial loading on the column-bending strength are considered with P-M-M interactions.

In order to model the non-structural components, such as washing machine and chiller, a single-degree-of-freedom (SDOF) model was taken into account by using mass, spring, and damper at the midspan of the longest beam of the roof, according to Figure (4b) (chiller) and the midspan of the longest beam of the first and the middle floor (washing machine).

In order to investigate the amplification effect of acceleration at the center of non-structural element mass compared to the acceleration generated at the floor, nonlinear time history analysis of the structures under the influence of horizontal and vertical components of eleven seismic ground motion records was used with the design seismic intensity level for both near-fault and far-field areas, according to Table 1.

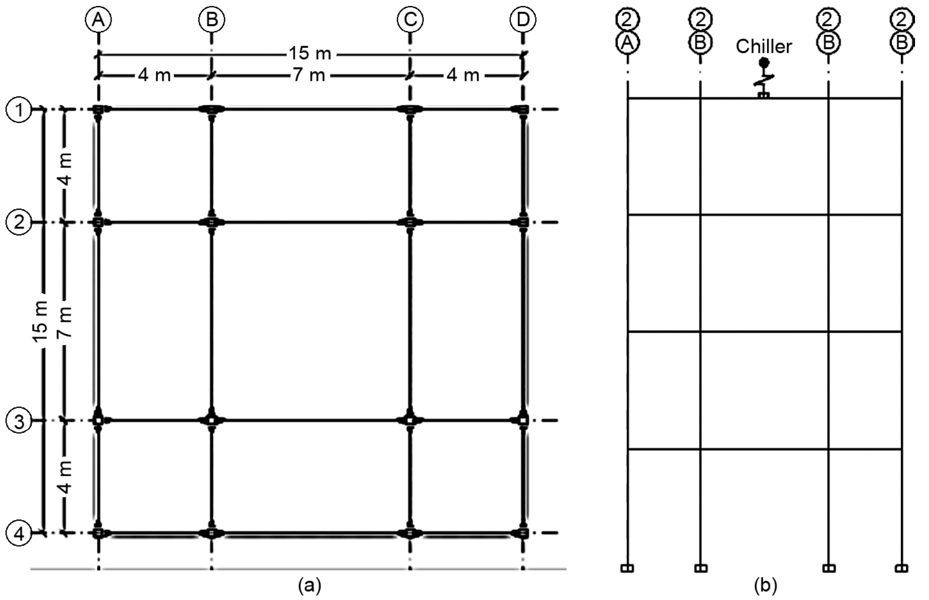


Figure 4. (a) the plan view of the structures under study and (b) a sample modeling of the cooling tower on the roof of the low-rise structure.

Table 1. The suite of 22 ground motion records.

Near Fault Category				Far Fault Category			
Event	**Magnitude**	**R (km)**[a]	**PGA(g)**[b]	**Event**	**Magnitude**	**R (km)**	**PGA(g)**
Chi-Chi Taiwan (CHY024, 1999)	M (7.6)	9.6	0.28 (II) 0.14 (V)	Chi-Chi Taiwan (HWA045, 1999)	M (7.6)	60.2	0.19 (II) 0.07 (V)
Duzce Turkey (Lamont 1061, 1999)	M (7.1)	11.5	0.13 (H) 0.05 (V)	Duzce (Mudurnu, 1999)	M (7.1)	34.3	0.12 (H) 0.06 (V)
Iwate (IWTH24, 2008)	M (6.9)	3.1	0.52 (H) 0.33 (V)	Hector Mine (Twentynine-Palms,1999)	M (7.1)	42.1	0.07 (H) 0.04 (V)
Kobe Japan (Nishi-Akashi, 1995)	M (6.9)	7.1	0.48 (H) 0.39 (V)	Kern County (Taft-Lincoln School, 1952)	M (7.4)	38.4	0.18 (H) 0.11 (V)
Kocaeli Turkey (Arcelik, 1999)	M (7.5)	10.6	0.21 (H) 0.08 (V)	Kobe Japan (Chihaya, 1995)	M (6.9)	49.9	0.11 (H) 0.08 (V)
Landers (Joshua Tree, 1992)	M (7.3)	11	0.28 (H) 0.18 (V)	Kocaeli Turkey (Mecidiyekoy, 1999)	M (7.5)	51.2	0.07 (H) 0.04 (V)
Loma Prieta (Saratoga, 1989)	M (6.9)	7.6	0.51 (H) 0.39 (V)	Landers (Twentynine Palms,1992)	M (7.3)	41.4	0.06 (H) 0.04 (V)
Montenegro Yugo (Hotel Albatros, 1979)	M (7.1)	1.5	0.23 (H) 0.13 (V)	Loma Prieta (Apeel10–Skyline, 1989)	M (6.9)	41.7	0.09 (H) 0.04 (V)
Northridge-01 (Pacoima Kagel, 1994)	M (6.7)	5.3	0.44 (H) 0.17 (V)	Morgan Hill (San Justo Dam, 1984)	M (6.2)	31.9	0.08 (H) 0.03 (V)
Parkfield-02 CA (Eades, 2004)	M (6)	1.4	0.39 (H) 0.20 (V)	Northridge-01 (Antelope Buttes, 1994)	M (6.7)	46.7	0.07 (H) 0.03 (V)
Tabas Iran (Dayhook, 1978)	M (7.3)	13.9	0.41 (H) 0.19 (V)	San Fernando (Pasadena – CIT, 1971)	M (6.6)	25.5	0.11 (H) 0.10 (V)

[a] Closest distance to fault rupture

[b] H: major horizontal & V: Vertical components of the ground motion record

The criteria for selecting these earthquakes include considering shear wave velocity between 375 to 750 meters per second, earthquake magnitudes ranging from 6 to 8, and distance from the fault within 15 kilometers for the near-field area and more than 30 kilometers for the far-field area. All the seismic records for the category of near-field were chosen as pulse-like shape, with the purpose of considering the forward directivity effect. The spectrally matched acceleration histories compatible with the design response spectrum for the site according to the Iranian Seismic Code (2015) were used for nonlinear time history analyses. The spectrum matching factor of vertical components of ground motion records was taken equal to that of horizontal components.

In order to simulate that the non-structural components are operating, harmonic vibration was

Table 2. The non-structural properties using SDOF modeling.

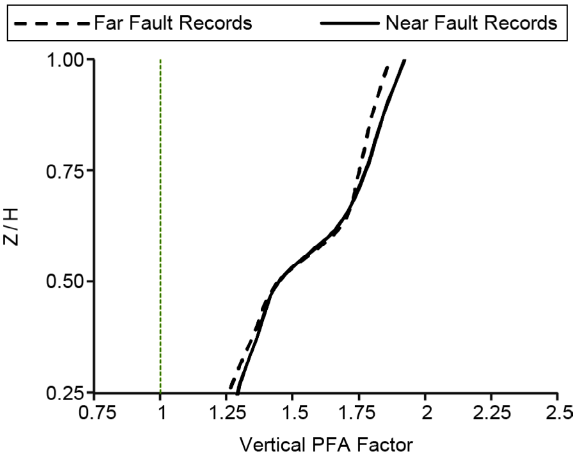
NCS Name	Weight (kg)	Period (T_p, sec)	Damping (%)	ω (rpm)
Washing Machine	50	0.06 (Horizontal) 0.06 (Vertical)	3	1200
Chiller	1560	0.18 (Horizontal) 0.21 (Vertical)	3	1200

implemented at the center of mass of the single-degree-of-freedom non-structural model simultaneously with the seismic excitation in the structural models. Specifications of mass, period, damping, and the rotational frequency of the motor for the non-structural components under study are considered based on the information presented in Astroza et al. (2015) and Shihab et al. (2017), which be shown briefly in Table (2). It is assumed that they do not have a seismic isolator at their base.

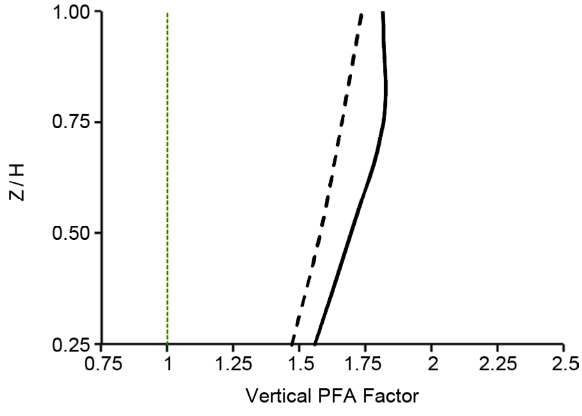
4. Evaluation of Vertical PFA Factor over the Height of the Structures under Near-Fault and Far-Fault Ground Motion Records

Although the simple forced-based design approach for non-structural elements has been used extensively since its introduction in the 1964 edition of the Uniform Building Code (UBC, 1964) in the United States and remains the cornerstone of seismic design requirements included in current editions of design codes, it includes several questionable shortcomings (Filiatrault et al., 2021). One of these shortcomings is the establishment of reasonable estimates for the peak floor acceleration response profile along the height of buildings for the calculations of equivalent static design forces in the horizontal and/or vertical directions and applying these forces to the element's center of mass. As mentioned before, the constant distribution of floor vertical acceleration over the height of buildings adopted according to the most seismic design codes, which is examined in this section for the studied structures with steel long-span moment resisting frame load bearing systems that do not have complete rigidity in the vertical direction.

For this purpose, the time history of floor acceleration over the vertical directions has been extracted under nonlinear analysis effects of a suite of 22 seismic ground motion records in the far-field and near-field categories. In the next step, the peak floor acceleration relative to the vertical peak ground acceleration (i.e. PFA factor) is evaluated at different floor levels for each of ground motion records. The average of PFA factors for each set of far-field and near-field seismic records over the height of the structures is shown in Figure (5). In this figure, Z is the elevation of the point of attachment of the component relative to the ground and H is roof elevation of the structure relative to the ground. Z/H is used to show the normalized location of non-structural elements over the height of low-rise and mid-rise structures. According to this figure,



(a) 8-Story Structure



(b) 4-Story Structure

Figure 5. Average vertical PFAs factor over the height under the influence of ground motions.

the vertical acceleration at the different floor levels is amplified by 1.25 to 1.9 times compared to the input vertical peak ground acceleration at the basement of the building. The non-constant distribution for vertical PFA factors is observed for studied buildings, which tended from linear to nonlinear distribution as the height of the building increases. The average PFA factors from near-fault records are increased up to 10%, compared to those of far-fault records in the low-rise building. However, near-fault effects on PFA factors over the height of the mid-rise building were almost negligible. This may have been observed due to the simultaneous occurrence of the dominant vertical mode frequency of low-rise structure and short-duration spectral content of near-fault vertical earthquake components.

5. Investigation of the Vertical Acceleration Amplification Factor of Non-Structural Components with an Operating and Non-Operating Motor During Earthquakes

In the previous section, it is shown that the level of floor attachment of non-structural components over the height of the studied buildings influences on the input vertical acceleration to the base of non-structural elements. In this section, by considering the simultaneous effect of horizontal and vertical components of far-fault and near-fault earthquakes, the amplification factor of acceleration of two types motorized non-structural components has been investigated, considering the properties of operating and non-operating motor during earthquakes. For this purpose, the acceleration response spectrum under simultaneous time history analysis of ground motion records and harmonic vibration of motor at the center of non-structural element mass are obtained and plotted in component period vs. amplitude graphs, by considering the elastic behavior for the non-structural component, according to schematic representation of Figure (6). Then, the amplification factor of peak acceleration at the mass center of the non-structural component over the peak acceleration on the floor in which it is installed has been extracted under each state (i.e. ap spectrum). The averages of the spectrum graphs of ap in the vertical direction under ground motion records are shown in Figures (7) and (8) for the chiller component, by considering both conditions of operating and non-operating motor of component. According to these graphs, during the periods below 0.5 seconds (the period of non-structural component in the vertical direction), the amplification factor of acceleration in the vertical direction includes values greater than 1 in both far-fault and near-fault areas. In addition, during the periods close to the period of the chiller's vertical mode, this factor reached approximately 4,

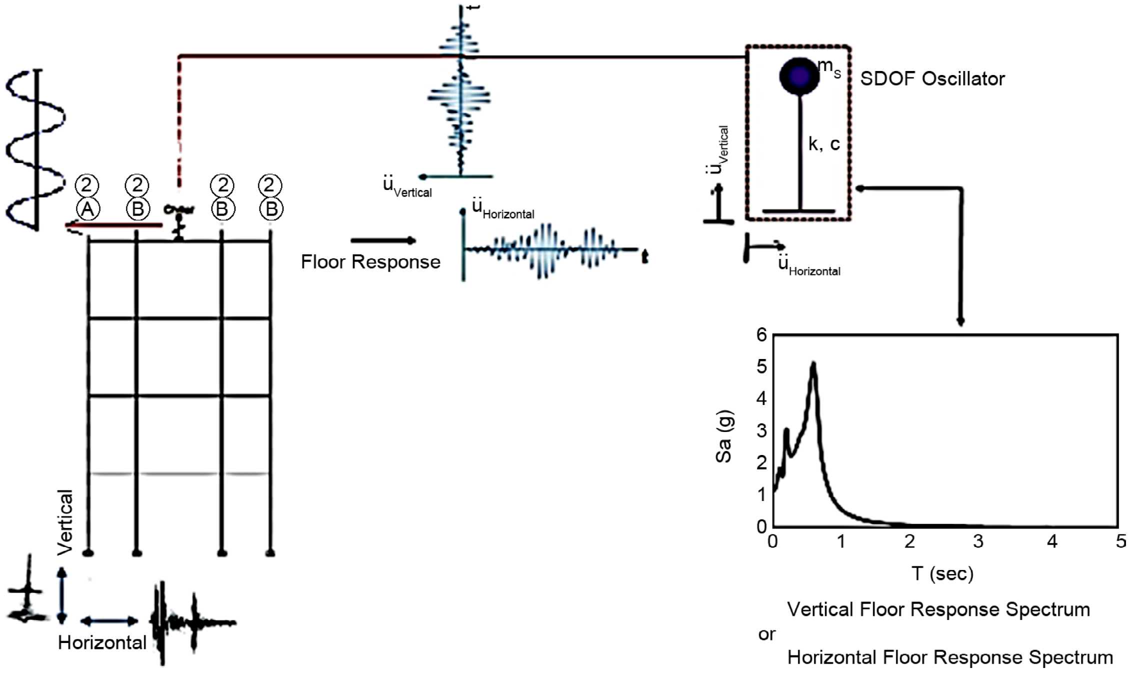
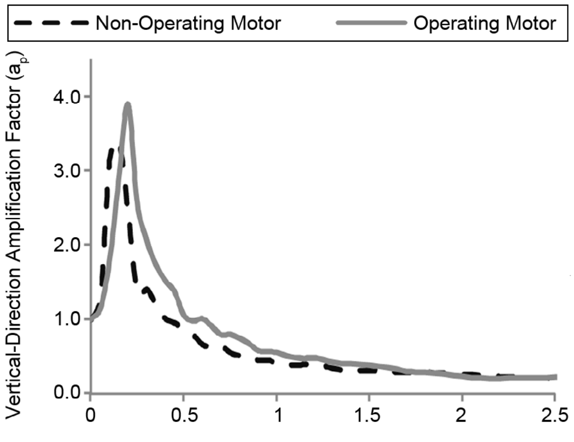
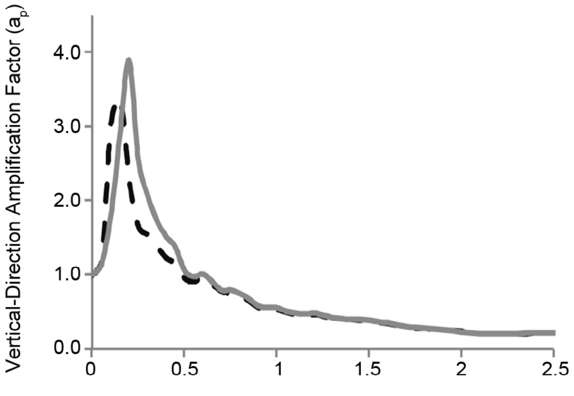


Figure 6. The schematic view for extracting the non-structural component acceleration response spectrum.

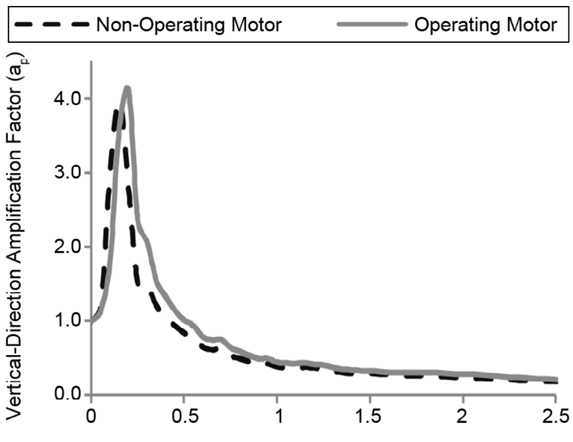


(a) Near Fault Average

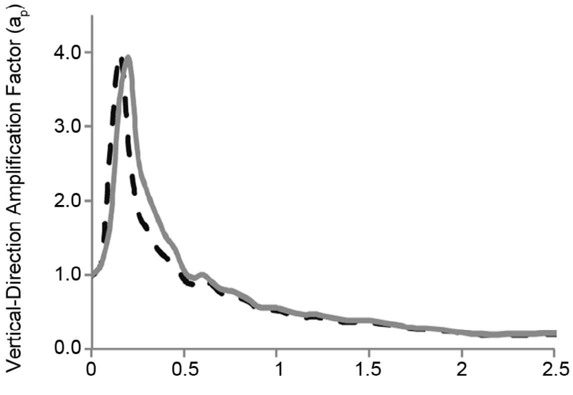


(b) Far Fault Average

Figure 7. Average ap curve for the vertical direction of the chiller on the roof of 4-story structure under the influence of ground motions.



(a) Near Fault Average



(b) Far Fault Average

Figure 8. Average ap curve for the vertical direction of the chiller on the roof of 8-story structure under the influence of ground motions.

depending on the number of floors in the hosting structure and whether the motor was operating. This is while that the assumption of rigidity of a non-structural component in the vertical direction in most seismic codes has led to considering a coefficient close to 1, which may be unconservative in some cases. The operating motor in every one of the examined cases and its simultaneity with the occurrence of an earthquake has caused the displacement of the graph towards the right (longer periods) and upward (higher coefficients in periods longer than 0.15 seconds). The range and magnitude of this have been more significant in the near-field area compared to the far-field. In the cases in which the non-structural component was of the type of a washing machine, the amplification obtained from the simultaneous situation of the operating motor with the occurrence of an earthquake was very small and negligible. The details of these cases can be observed in Lashgari gehraz (2022). It is also noteworthy that the interaction between the soil and the structure when it is built on soft soil may amplify the results of this study (Challagulla et al., 2023), which will be investigated in future research.

6. Conclusion

In this research, some questionable aspects of the vertical response of non-structural elements are investigated by considering the combined interaction between structural and non-structural elements under nonlinear time history analysis of the host buildings. For this purpose, structural models of buildings in two categories low-rise (4-story) and mid-rise (8-story), were subjected to the simultaneous application of horizontal and vertical components of seismic accelerograms in the near-field and far-field areas (11 records for each category) at the design seismic intensity level. Then, the effects of the vertical earthquake components on the amplification factor of non-structural components with electric motors located on the floor of steel intermediate moment resisting frame structures supported by relatively stiff soil type are evaluated by using the SDOF model for non-structural elements. It should be pointed out that the effects of seismic isolator at the base of studied non-structural components was not assessed in this study. According to the results obtained, the following main conclusions were derived:

1. The peak vertical acceleration factor values at the different floor levels of studied long-span SMRF structures have been obtained greater than one, which is between 1.25 to 1.9 depending on the level of floor attachment of non-structural components. Therefore, the common approach of seismic guidelines for assuming the one value for vertical PFA factors may be unconservative for some types of load-bearing structural systems that do not have complete rigidity in the vertical direction.
2. The non-constant distribution for vertical PFA factors is observed for studied buildings, which tend from linear to nonlinear patterns as the height of the building increases. The average PFA factors from near-fault records are increased up to 10%, compared to those of far-fault records in the low-rise building. However, near-fault effects on PFA factors over the height of the mid-rise building was almost negligible.
3. The evaluation of the amplification factor of non-structural component vertical acceleration showed values greater than 1 up to 4 for the non-structural components with vertical mode periods below 0.5 seconds under the simultaneous effect of horizontal and vertical earthquake components. The peak point of ap curves has occurred close to the chiller's vertical mode period under both near-fault and far-fault seismic records. Therefore, assuming rigidity in the vertical direction of non-structural elements, which is commonly used in seismic design codes to calculate inertial forces on non-structural components under the vertical earthquake component, may not be reliable for some types of more flexible non-structural elements.
4. The investigation of the amplification factor of acceleration for non-structural components with the operating motor showed that the simultaneous operation of the chiller during an earthquake leads to an increase of 10% to 50% in the amplification factor for the vertical acceleration on the roof. Therefore, neglecting the effect of the operating motor on certain types of non-structural components during an earthquake contradicts the principle of conservatism, especially for structures with high and very high importance levels.

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