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EFFECT OF BUILDING ORIENTATION ON STRUCTURAL RESPONSE OF REINFORCED CONCRETE MOMENT RESISTING FRAME STRUCTURES

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by

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A Thesis
Submitted in Partial Fulfillment of the Requirements for the
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THESIS APPROVAL

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Approved by:

Dr. Jale Tezcan, Chair

Dr. Aslam Kassimali

Dr. J. Kent Hsiao

Graduate School
Southern Illinois University Carbondale
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In time history analysis of structures, the geometric mean of two orthogonal horizontal components of ground motion in the as-recorded direction of sensors, have been used as measure of ground motion intensity prior to the 2009 NEHRP provision. The 2009 NEHRP Provisions and accordingly the seismic design provisions of the ASCE/SEI 7-10, modified the definition of ground motion intensity measure from geometric mean to the maximum direction ground motion, corresponding to the direction that results in peak response of the oscillator. Maximum direction response spectra are assumed to envelope the range of maximum possible responses over all nonredundant rotation angles. Two assumptions are made in the use maximum ground motion as the intensity measure: (1) the structure's strength and stiffness properties are identical in all directions and (2) azimuth of the maximum spectral acceleration coincides with the one of the principal axes of the structure. The implications of these assumptions are examined in this study, using 3D computer models of multi-story structures having symmetric and asymmetric layouts and elastic vibration period of 0.2 second and 1.0 second subjected to a set of 25 ground-motion pairs recorded at a distance of more than 20 km from the fault. The influence of the ground-motion rotation angle on structural response (here lateral displacement and story drift) is examined to form benchmarks for evaluating the use of the maximum direction (MD) ground motions. The results of this study suggest that while MD ground motions do not always result in largest structural response, they tend to produce larger response than the as-recorded ground

motions. On the other hand, more research on non-linear seismic time history analysis is recommended, especially for asymmetric layout plan buildings.

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CHAPTER 1

INTRODUCTION

Earthquake ground motion accelerations are recorded by triaxial accelerographs with accelerations in two horizontal component and one vertical component. The seismic design of many structures requires at least two horizontal ground motion components or all three components for the time history analysis of 3-dimensional structures, in which the structural response is computed considering those two or three components. Directionality of two horizontal components of ground motion relative to the principal axes of the structure is critical for calculation of structural response. For instance, a slight change in the building orientation (alternatively rotating the ground motion components) may change the value of structural response significantly. Considering the significant effect of building orientation on the structural response, there is not enough guidance in the design codes proposing a specific direction which the two horizontal components of ground motion should be applied to the structure.

New measures of ground motion intensity in ASCE 7-10 standard, which proposes maximum direction (MD) rather than geometric mean (GM), has drawn attentions to challenges in defining intensity measures and its implications on selecting, scaling, response evaluation and interpretation of the response. As the maximum direction ground motion does not necessarily coincide with a principal axis of the structure, the suitability of maximum direction ground motion as an appropriate ground motions intensity measure has been questioned. Furthermore, the effect of maximum direction intensity measure on the design of eccentric structures (having asymmetric plan) which are subjected to torsion during earthquakes, is unclear.

This thesis aims to investigate the effect of building orientation on the structural response of reinforced concrete moment resisting frame structure. For ease of operation, the horizontal pair of ground motions has been rotated instead of rotating the building. Four different building models and a group of 25 ground motions pairs has been selected for this purpose. The building models includes symmetric and asymmetric layout plans. The group of 25 ground motions pairs are rotated through all non-redundant rotation angles and then applied to the building models in terms of seismic time history load to the building's principal directions (here X and Z axes of structure), and then the response of the structures has been recorded with respect to the rotation angle in terms of lateral displacement and story drift at center of mass of the floor level.

1.1 STATEMENT OF THE PROBLEM

The ground motions intensity measures are primarily focused on two orthogonal components of horizontal ground motion, while the component orientation is arbitrary, depending on the orientation of the sensors. The two horizontal components of ground motion are needed for the response history analysis of structures, according to seismic design codes. Most seismic design codes used geometric mean of the two orthogonal components of horizontal ground motions (Sa_{GM}) for response history analysis of structures, ahead of the Next Generation Attenuation (NGA) project (Power et. al, 2008).

The geometric mean of the two horizontal ground motion components was mostly favored because, it lowers the scattering of data and approximates the central value of casually oriented horizontal ground motion components. Geometric mean of the spectral accelerations of the two horizontal ground motion components for a fixed damping ratio, the geometric mean in 'X' and 'Y' direction (here termed as Sa_x and Sa_y) are obtained as follows:

$$Sa_{GM}(T) = \sqrt{Sa_x(T) \times Sa_y(T)} \quad (1)$$

Where T is the vibration period.

However, the amplitudes of ground motion components are not the same at all rotation angles in the geometric mean of ground motions intensity measure. It means that the actual ground motion intensity measure in the desired rotation angle could be different from the recorded orientation of ground motion components.

The NEHRP 2009 (National Earthquake Hazards Reduction Program) Seismic Provisions, modified the definition of horizontal ground motion intensity measure from the geometric mean of ground motions to the maximum direction ground motions. The maximum direction (MD) ground motion is in the direction which results in the maximum response of an oscillator considering all non-redundant rotation angles. As the maximum motion changes with the period of oscillator, the amplitude of maximum direction spectral pseudo-acceleration can vary at each period. The maximum direction ground motion at a desired period can be obtained by rotating the two given pairs of ground motion through all non-redundant rotations angles and taking out the maximum pseudo-acceleration for that period. Alternatively, we can obtain the maximum direction ground motion for a desired period graphically by plotting the pseudo-acceleration trace of a linear oscillator subjected to the pair of horizontal ground motion components and locating the point furthest away from the origin. Figure 1 illustrates an example using the 1956 El Alamo Earthquake recording from El Centro Array# 9 Station for an oscilliator with vibration period T= 1.0 second and damping ratio ζ= 5% , red line shows the direction and magnitude of the maximum pseudo-acceleration of the oscillator, defining the MD spectral ordinate at T=1 second.

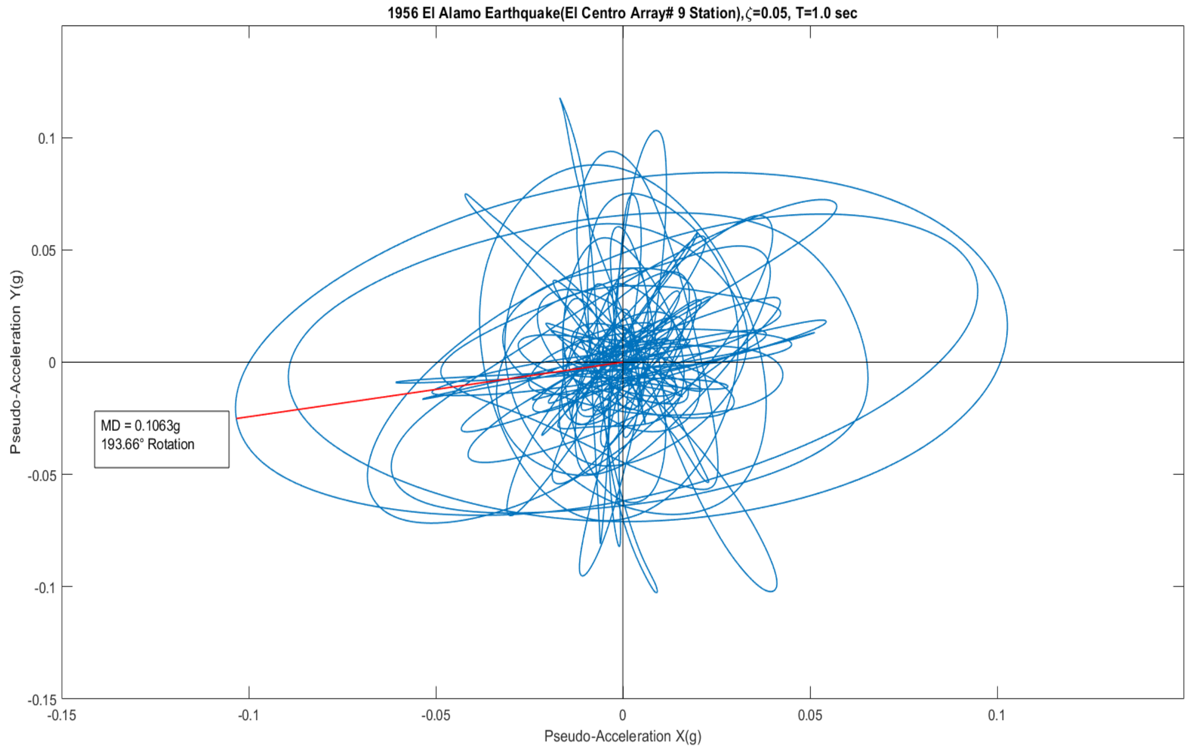


Figure 1. Trace of pseudo acceleration of a linear oscillator. The red line represents the magnitude and direction of maximum pseudo-acceleration.

As opposed to the NGA project using GMRotI50, the maximum direction is not a geometric mean measure of ground motions. Hence, the 2009 NEHRP Provision maps used the maximum direction to geometric mean ratios of 1.1 and 1.3 for short and mid-periods respectively (from Huang et al. 2008) to transform from the geometric mean maps. Accordingly, the ASCE/SEI 7-10 standards, adopted the maximum direction ground motions as the seismic intensity measure to be used in response history analysis of structures (Chapter 21 of ASCE/SEI 7-10).

The maximum direction (MD) orientation angle varies with respect to the given period T. The assumptions made in using the maximum direction ground motions are (1) the structures properties are identical in all directions (2) azimuth of the maximum spectral acceleration (MD) coincides with principal axis of the the structure.

Basically, structures are either azimuth dependent or azimuth independent. The structural dynamic properties such as stiffness and strength are identical in azimuth independent structures (e.g. bridge piers, silos and chimneys), while they are varying with respect to principal direction of structure in azimuth dependent structures (e.g. dams, bridges). The azimuth independent structures don't have a preferred direction of response, while the azimuth dependent structures have a preferred direction of response. Generally, building structures have different dynamic properties such as stiffness and strength with respect to their main axes (e.g. longitudinal and transverse axes). Somehow, for this reason, structural analysis for lateral load is performed with respect to two main axes buildings. The structural design is often governed by response in the weak axis (transverse direction) of the structure. Even azimuth dependent structures which have identical properties in all directions, have a tendency to the preferred response direction related to their vibration modes. Hence, the first assumption might be valid for structures with a symmetric layout plan. Furthermore, the second assumption is less probable to occur coinciding the maximum direction response with the principal axis of the structures. Stewart et al. (2011), wrote an article undermining use of maximum direction ground motions in the NEHRP seismic maps and likewise, defining maximum direction ground motion for response history analysis of structures in seismic provision of building design codes. The authors argued that it would cause overestimation of design ground motion level by 10 to 30 percent.

1.2 SCOPE OF THE RESEARCH

This study evaluates the effect of building orientation on the structural response of reinforced concrete moment resisting frames with regular and irregular layouts plans. For this purpose, four reinforced concrete moment resisting space frames are modeled in STAAD PRO which consist of symmetric and asymmetric layout plans while each layout is associated with two natural periods (0.2 second and 1 second period). The natural periods are selected based on ASCE/SEI 7-10 calculation of seismic design loads. Using linear time history analysis in STAAD PRO, all four structures are subjected to a group of 25 ground motion pairs rotated through all non-redundant rotation angles (in this case: 0° - 180°) with 5° increment using MATLAB software. As the direction of maximum direction ground motions in the near fault regions (R_{rup} < 3-5 km) tend to align with the strike normal direction, in this study all selected ground motions have fault distances greater than 15km to remove the alignment of maximum direction. The plans and 3D models of four computer models are shown in figure 5 through figure 8 with their descriptions in chapter 3 of this thesis.

1.3 ORGANIZATION OF THESIS

This thesis consists of six chapters. The remaining chapters of this thesis is organized as follows:

Chapter 2 is devoted to literature review. It starts with a discussion on record of ground motion acceleration and use of geometric mean of ground motion to produce response spectrum. Next the directionality and need for rotation of ground motions has been discussed, and finally introduction of maximum direction ground motions in the building design codes and its controversy has been discussed accordingly.

Chapter 3 presents the methodology and the details of research carried out in the completion of this thesis. The information for data collection, MATLAB coding for rotation of ground motions, application of rotated ground motions to the structure layouts using STAAD PRO, and generation of results after linear static analysis of the structure layouts in STAAD PRO, have been discussed in detail.

Chapter 4 presents the results of structural response obtained from 25 rotated ground motion pairs applied to all four types of reinforced concrete moment resisting space frames, after linear static time history analysis by STAAD PRO. It also includes figures showing the structure response of the two proposed layouts for different rotation angles, response corresponding to maximum direction motions. In this chapter, a discussion of results is also included.

Chapter 5 summarizes the results obtained in this thesis and ends with the recommendations for future works to be carried in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 GEOMETRIC MEAN OF GROUND MOTIONS:

Generally, the earthquake ground motion accelerations are recorded by accelerometer sensors in three directions (along x,y & z axes), one vertical direction component and two orthogonal horizontal direction components, while the building design codes require only two orthogonal horizontal components of ground motion accelerations for response history analysis of a three-dimensional building structure. The seismic design of structures to withstand lateral loads induced by the earthquake is primarily governed by horizontal ground motion components and the vertical component effects are negligible. The spectral acceleration (Sa) cannot be represented in two dimensions. So, there is a need for combining the two orthogonal horizontal components of ground motion or just considering one of the components. Several methods have been proposed in the past to compute spectral acceleration (Sa) to represent two-dimensional horizontal ground motions in a single direction. One of the commonly used method, that was acceptable among most of the researchers, is the geometric mean of the two orthogonal horizontal ground motions so-called geometric mean response spectra (Sa_{GM}). Geometric mean response spectra (Sa_{GM}), has been traditionally preferred over other methods because it was assumed that it reduces the data dispersion and estimates the central value of arbitrary oriented individual horizontal components of ground motion.

2.2 ROTATION OF GROUND MOTIONS:

On the other hand, using the geometric mean measure of as-recorded ground motions in their arbitrary orientation makes them dependent on the as-recorded orientation of the sensor instrument. Researchers have tried numerous approaches to compute orientation independent measures of ground motion intensity. Among them, Boore et al. (2006) proposed two forms of orientation independent geometric-mean response spectra for the two recorded orthogonal components. One of them is the period-dependent measure, e.g. GMRotDpp, which D indicates the period-dependency of rotation angle and pp indicates the percentile of the geometric means for sorted amplitudes of all rotation angles. For instance, GMRotD00, GMRotD50 and GMRotD100 are meant to be the maximum, median and minimum geometric mean spectra values respectively over all rotation angles. GMRotDpp is obtained by rotating a pair of ground motion components through all non-redundant rotation angles and selecting a specific percentile from sorted amplitudes of ground motions from all rotations. Another measure proposed by Boore et al. 2006, is GMRotIpp, which was developed to eliminate the unlikable period-dependency of GMRotDpp. Hence, GMRotIpp is defined as the geometric mean measure of the rotated ground motion components to minimizes the period inconsistency of GMRotDpp. GMRotIpp is obtained by defining a penalty function of rotation angles to the GMRotDpp measure, computing the angle corresponding to it, and rotating the ground motion pairs through that angle. The authors of Boore et al. (2006) have included a complete algorithmic procedure for calculation of both orientation independent geometric mean measures of ground motion (e.g. GMRotDnn and GMRotInn). The Next Generation Attenuation (NGA) Project employed GMRotI50, for Ground Motion Prediction Equations (GMPEs) which is independent of arbitrary orientation of the recorded ground motion components.

2.3 MAXIMUM DIRECTION GROUND MOTIONS:

The National Earthquake Hazards Reduction Program (NEHRP) Provisions and Commentary 2009 proposed a new measure of ground motions to be used in the seismic design of structures called Maximum Direction (MD) ground motions. Followingly, the US standard

ASCE/SEI 7-10, proposed the maximum direction ground motions to be used in the response history analysis of structures (ASCE/SEI 7-10, Chapter 21). The maximum direction (MD) ground motion is the maximum response of the oscillator regardless of the oscillator's orientation. It can be obtained by finding the maximum response spectra after rotating the ground motion pair through all non-redundant rotation angles or alternatively by plotting the trace of the ground motion pair and finding the furthest point from the origin. Maximum direction (MD) ground motion made it possible for bidirectional ground motions in the horizontal plane to be represented by the maximum spectral pseudo acceleration with a specific period and damping ratio. The maximum direction (MD) ground motion diverges from past practice in earthquake engineering, in which the design spectra were being computed by the geometric mean of the two horizontal components of ground motion. Maximum direction (MD) ground motion intensity measure drew the attention of many researchers to publish several papers on this topic. Campbell and Bozorgnia 2007 & Watson-Lamprey and Boore 2007 observed that the azimuth (orientation) of the maximum direction ground motion is arbitrary for fault distances (R_{rup}) larger than approximately 3–5 km, while at closer fault distances, the orientation of the maximum direction (MD) ground motions tends to align with the strike-normal direction. Other researchers tried to develop approximate factors to convert geometric mean ground motion intensity to maximum direction ground motion intensity. Among them, (Bommer et al. 2006, Boore et al. 2007, and Campbell et al. 2007) proposed a maximum direction to geometric mean (MD/GM) ratio of 1.2 to 1.35 depending on period T. Using different procedures, Huang et al. (2008) found modification factors of maximum direction (MD) ground motion to be 1.1 to 1.5 times the geometric mean ground motions. Moreover, (Boore et al. 2007) noticed that the standard deviation is higher for maximum-direction ground motions than for geometric mean ground motions. The ground motion hazard maps of the 2009 NEHRP Provisions utilized the factors from Huang et al., 2008, to convert from geometric mean to maximum direction ground motions by factors of 1.1 and 1.3 for short and mid periods respectively. However, (Shahi and Baker 2014) argued that the NEHRP 2009 ratio of 1.1 (short period) was inaccurate and it should be approximately 1.2 (short period).

Use of the new measures of ground motion intensity (maximum direction (MD) ground motion) instead of previously used geometric mean ground motion intensity in NEHRP 2009 provisions found out to be controversial by Stewart et al. (2011). The authors doubted about using maximum direction (MD) ground motion in the NEHRP 2009 and USGS seismic design maps to be unconservative relative to the previously used geometric mean of arbitrary components of ground motions. The authors' doubts were mainly focused on the assumptions made for using the maximum direction (MD) ground motion intensity in the NEHRP 2009 and USGS seismic design maps. Those assumptions are (1) structure's dynamic properties are the same in all directions (2) azimuth of the maximum direction ground motion aligned with the structure's principal axes. The authors argued that these assumptions might be true for some in-plane symmetric structures, but the response of most of the structures is controlled by mode shapes of structures along their specific axes, and usually, they have distinct dynamic properties along those axes. Their research findings show that maximum direction (MD) ground motions applied to structures with azimuth-dependent properties are likely to result in 10% to 30% overestimation of the ground motions depending on the natural period of the structure; this would affect the costs of construction and retrofitting if used in the building codes. In addition to concerns about construction cost, the increase of carbon-related materials in the building's footprint was another concern of authors, while efficiency in the use of materials is necessary for the sustainability of the environment. Considering all these issues, the authors recommended that for structures with azimuth independent properties, they support the use of the 2009 NEHRP Provisions and following ASCE 7-10 seismic design code, including the existing ground motion design maps. However, for structures with azimuth dependent properties, they recommended use of the 2009 NEHRP Provisions, along with existing site factors and risk factors and following ASCE 7-10 seismic design code except for the ground motion design maps; they suggested use of reduction factors of 1.1 and 1.3 for short and mid periods respectively for using NEHRP seismic design maps until new design maps are prepared by NEHRP.

Following the NEHRP and USGS seismic design maps use of maximum direction (MD) ground motion, the building codes in the United State such as the California Building Code (CBC2010) and also the International Building Code (IBC 2009) with reference to seismic design provisions of ASCE/SEI 7-10, authorized using ground motions rotated to fault normal, fault parallel and maximum direction (MD) ground motions for response history analysis of building structures. According to the mentioned building codes, for time history analysis of a building within 5 kilometers (3.1 miles) from an active fault that dominates the earthquake hazard, the orthogonal ground motion pair should be aligned to the fault normal and fault parallel directions; while for building sites away from the fault source (R_{rup} > 5 km), the maximum direction (MD) ground motions are proposed for response history analysis of buildings. It is believed that the angle corresponding to the FN/FP directions and the maximum direction would lead to the most critical structural response. Subsequently, the United States Geological Survey (USGS) published a research report (Kalkan et al. 2012) on whether to use ground motions rotated to Fault Normal/Parallel or Maximum Direction (MD) direction for response history analysis of buildings, or not. The authors of the USGS report examined the influence of rotation angle of the ground motion on several engineering demand parameters (EDPs) in linear elastic and nonlinear inelastic domains using a group of computer models of symmetric and asymmetric plan, single-story and multistory buildings subjected to 30 bidirectional near-fault ground motions (i.e. 0.1 km – 15 km), with an average earthquake magnitude of (Mw = 6.7±0.2). Considering all these criteria, the authors intended to find out whether ground motions rotated to MD or FN/FP directions would lead to the most critical estimates of engineering demand parameters (EDPs) from response history analysis. For this investigation, they have rotated all 30 ground motion pairs from 0° to 360° with a 5° increment and then applied them to all 3D computer models. As mentioned earlier, the previous studies of ground-motion directionality have shown that the azimuth of the maximum direction (MD) ground motion is arbitrary for sites away from the fault (R_{rup} > 5 km) and at near-fault sites (R_{rup} < 5 km) the azimuth of the maximum direction motion tends to align with the strike-normal direction. While findings of the USGS article indicate that the azimuth of the maximum direction motion does not necessarily align with the strike-normal direction even at closer fault distances (R_{rup} < 5 km). Moreover, their study shows that there is no unique orientation for a given structure to maximize all engineering demand parameters (EDPs) simultaneously and the critical angle (θ_{cr}) corresponding to the largest response over all possible rotation angles varies with the ground-motion pair selected, R-value used in the design process and the response quantity EDPs of interest. Finally, the authors of the USGS report conclude that as maximum direction (MD) is not unique for a given ground motion pair and changes with period and R-value of the system, as a result, the maximum direction (MD) response spectrum develops an envelope of the maximum response spectral accelerations of the ground motion pair at all possible rotation angles and periods. Although it was true for linear elastic systems, when they conducted a nonlinear response history analysis for ground motions oriented in the maximum direction (MD); it did not lead to maximum engineering demand parameters (EDPs) over all orientations in particular for asymmetric plan buildings. Therefore, they claimed that the use of MD ground motion for design is an overly conservative approach. However, the authors still support rotating the bidirectional ground motions at various angles with respect to the structural axes to cover all possible responses for performance assessment and design against worst-case scenarios; and compared to no rotation at all, their research article suggests that the use of ground motions rotated to maximum direction (MD) or fault normal and fault parallel directions is still acceptable.

CHAPTER 3

METHODOLOGY AND APPLICATION

3.1 INTRODUCTION:

This chapter describes the process of data collection and using it for analysis. It also describes the computer program that was used in this research. Then it discusses the selection of reinforced concrete frames layouts and their natural periods. Next it describes the algorithm for rotating ground motions and obtaining the maximum direction spectral accelerations.

3.2 GROUND MOTIONS SELECTED (DATA):

For this research, 25 ground motion pairs of records, listed in table 1, were selected from 20 shallow crustal earthquakes compatible with the following configuration:

- Moment magnitude: $5 \leq M_w \leq 7.62$
- Fault distance: $R_{rup} \geq 15$ km
- Site classes: A, B, C, D, E

Ground motion data was collected from PEER NGA-West2 ground motion database website(https://peer.berkeley.edu/peer-strong-ground-motion-databases). The web-based PEER NGA-West2 ground motion database consist of a very large set of ground motions records from worldwide shallow crustal earthquakes. By creating an account, a user will be able to search, select and download ground motion data from the website. The database gives choice of different distance measure, site characterizations, earthquake source data, etc. Figure 2 shows the distribution of magnitude (Mw) versus fault distance (R_{rup}) for the 25 ground motion records selected and Figure 3 shows the response spectra of 25 selected ground motion records. As shown in Figure 2, all ground motions were selected for fault distances of more than 15 km (R_{rup}>15 km) so that the maximum direction orientation would not be affected by fault normal and fault parallel directions. The maximum direction orientation is assumed to have an arbitrary orientation and will vary with respect to the period of the oscillator. The Figures 4a and 4b show the polar plots of maximum direction spectral accelerations with respect to their rotation angles (θ) for 0.2 second and 1 second natural period of vibration respectively, for 25 ground motions pairs. In these figures, the median spectral acceleration value ± σ_n (one standard deviation), is shown by red lines. The blue points indicate the maximum direction spectral acceleration with respect to their rotation angle (θ_m) for all 25 ground motion pairs. The blue half-circle lines show the maximum direction median spectral acceleration values ± σ_m (one standard deviation).

All 25 ground motion pairs were rotated using MATLAB software through all non-redundant rotation angles, in this case from 0° to 180° with a 5° increment. The following formulas from Boore et al. (2006) were used for rotation of ground motion pairs:

$$\ddot{u}_{Rot1} = \ddot{u}_1 \times \cos(\theta) + \ddot{u}_2 \times \sin(\theta) \qquad (2)$$

$$\ddot{u}_{Rot2} = -\ddot{u}_1 \times \sin(\theta) + \ddot{u}_2 \times \cos(\theta) \qquad (3)$$

where:

$\ddot{u}_{Rot1}$ & $\ddot{u}_{Rot2}$ = the new rotated acceleration ground motions.

$\ddot{u}_1$ & $\ddot{u}_2$ = The orthogonal horizontal components of ground motion accelerations.

θ = Rotation angle, here it takes the values from 0° to 180° with 5° increments.

Table 1. Selected ground motion records.

GM No	*Earthquake name*	*Year*	*Station Name*	*Earthquake magnitude (Mw)*	*Fault Mechanism*	*Fault Distance R_{rup}(km)*	*Site Shear Wave velocity Vs_{30}(m/s)*
1	Humboldt Bay	1937	Ferndale City Hall	5.8	strike slip	71.57	219.31
2	Kern County	1952	LA - Hollywood Stor FF	7.36	Reverse	117.75	316.46
3	El Alamo	1956	El Centro Array #9	6.8	strike slip	121.7	213.44
4	Parkfield	1966	San Luis Obispo	6.19	strike slip	63.34	493.5
5	Lytle Creek	1970	Cedar Springs Pump house	5.33	Reverse Oblique	22.94	477.22
6	San Fernando	1971	Carbon Canyon Dam	6.61	Reverse	61.79	235
7	San Fernando	1971	Lake Hughes #9	6.61	Reverse	22.57	670.84
8	San Fernando	1971	Cedar Springs, Allen Ranch	6.61	Reverse	89.72	813.48
9	Northern Calif-07	1975	Cape Mendocino	5.2	strike slip	34.73	567.78
10	Friuli, Italy-01	1976	Codroipo	6.5	Reverse	33.4	249.28
11	Santa Barbara	1978	Cachuma Dam Toe	5.92	Reverse Oblique	27.42	465.51
12	Tabas, Iran	1978	Sedeh	7.35	Reverse	151.16	354.37
13	Norcia, Italy	1979	Bevagna	5.9	Normal	31.45	401.34
14	Loma Prieta	1989	Point Bonita	6.93	Reverse Oblique	83.45	1315.92
15	Loma Prieta	1989	Foster City - APEEL 1	6.93	Reverse Oblique	43.94	116.35
16	Coalinga-01	1983	Parkfield - Fault Zone 1	6.36	Reverse	41.99	178.27
17	Iwate, Japan	2008	IWTH17	6.9	Reverse	72.44	1269.78
18	Chuetsu-oki, Japan	2007	TCGH17	6.8	Reverse	103.85	1432.75
19	Tottori, Japan	2000	OKYH02	6.61	strike slip	70.52	1047.01
20	Chi-Chi, Taiwan-05	1999	HWA003	6.2	Reverse	50.44	1525.85
21	Chi-Chi, Taiwan-06	1999	HWA003	6.3	Reverse	56.02	1525.85
22	Chi-Chi, Taiwan	1999	HWA003	7.62	Reverse Oblique	56.14	1525.85
23	Yountville	2000	APEEL 2 - Redwood City	5	strike slip	94.5	133.11
24	Morgan Hill	1984	Foster City - APEEL 1	6.19	strike slip	53.89	116.35
25	Niigata	2004	SIT011	6.63	Reverse	173.39	130.47

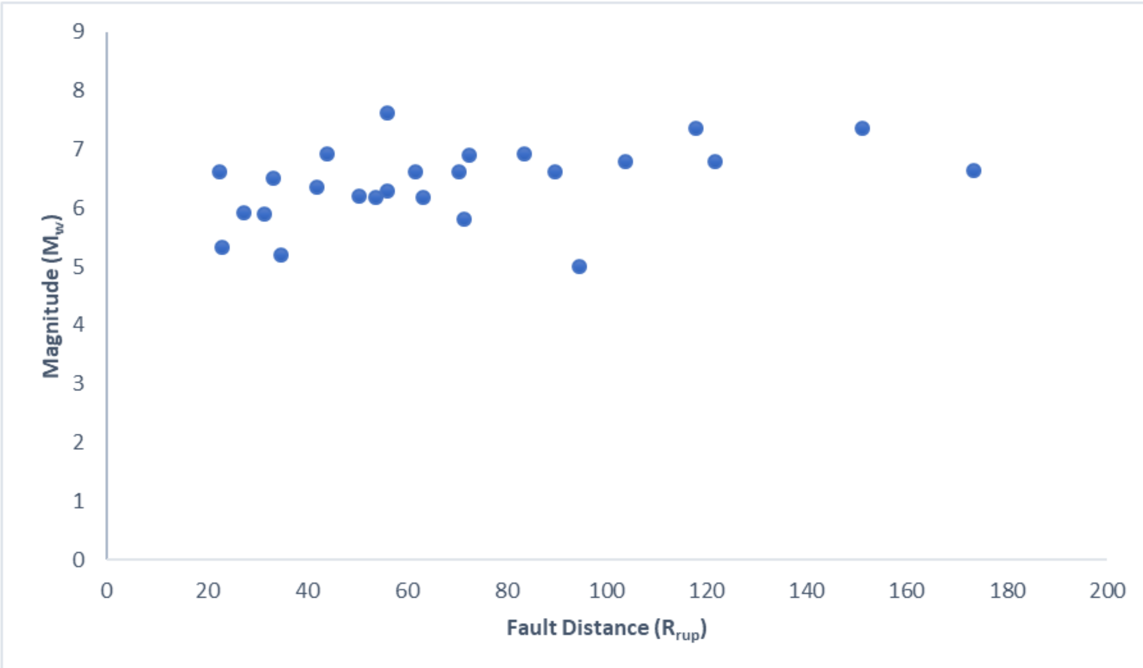


Figure 2. Distribution of magnitude (*Mw*) and fault distance (R_{rup}) for the 25 ground motion records selected.

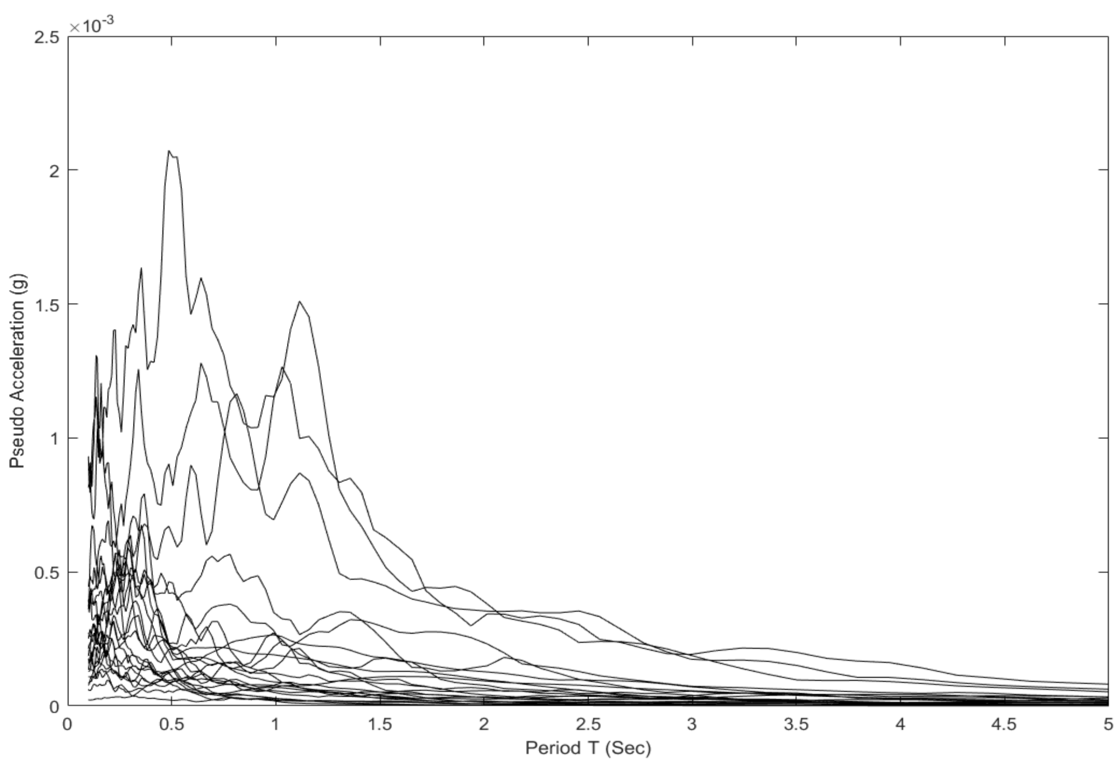
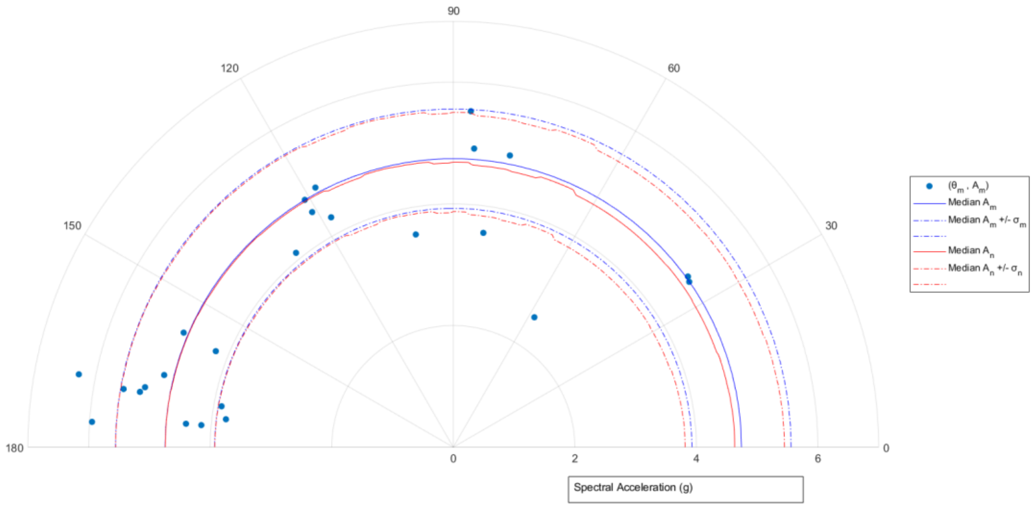
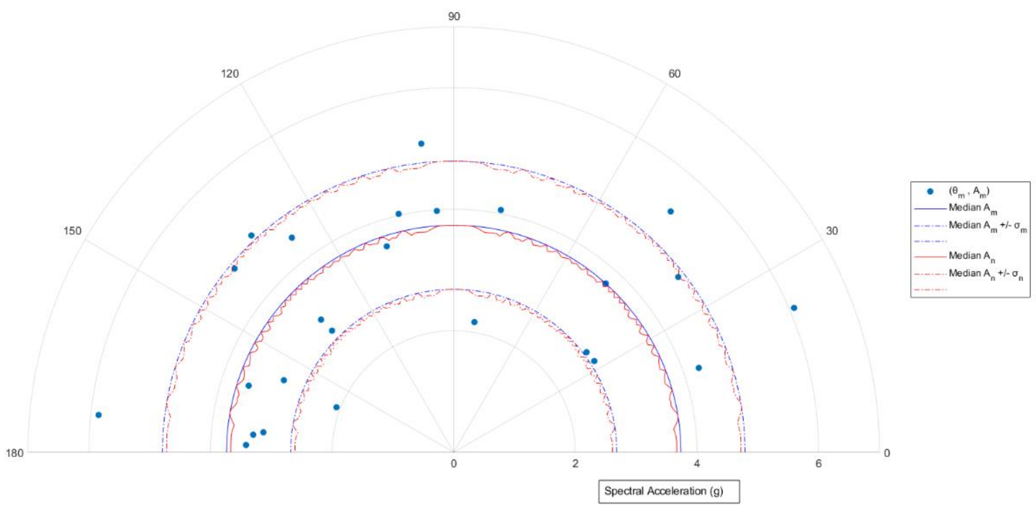


Figure 3. Response spectra of 25 ground motion records selected.



(4a)



(4b)

Figure 4. Polar plots of spectral acceleration values with respect to rotation angles (θ) for natural vibration periods of 0.2 second (Figure 4a) and 1 second (Figure 4b), for selected 25 ground motion pairs (listed in Table 1). The blue points show the spectral acceleration (A_m) with respect to its maximum direction (θ_m) for each ground motion pair. The median spectral accelerations (A_n) ± σ_n (one standard deviation) are shown by red lines, and the median spectral acceleration ± σ_m (one standard deviation) in the maximum direction, is shown by blue half-circle lines.

3.3 STAAD PRO:

STAAD PRO is a structural analysis and design software developed by Bentley Systems Inc. Most of the US and international codes of design for steel and concrete design are included in STAAD PRO. It has the ability to perform all types of linear and non-linear analysis. It has a graphical interface, which makes the structural modeling very easy for the users. In addition, it includes an editor, which enables the user to use command line for structural modeling, analysis and design.

3.4 BUILDING MODELS:

A group of four reinforced concrete moment resisting frame building models were created in STAAD PRO for this research. The building models are:

1) A two-story symmetric layout plan building with natural period of 0.2 second (BM1).
2) A two-story asymmetric layout plan building with natural period of 0.2 second (BM2).
3) A seven-story symmetric layout plan building with natural period of 1 second (BM3).
4) A six-story asymmetric layout plan building with natural period of 1 second (BM4).

The plan and 3D view of all four reinforced concrete moment resisting frame building models are shown in Figures 5 through Figure 10. The natural periods of 0.2 second period (Ss) and 1 second period (S1) were selected based on the seismic design of buildings in ASCE 7-10. All rectangular shape beam/column cross section area were selected for this research. The concrete of 28-day compressive strength of (fc' = 4000 psi) and steel reinforcements of grade 60 (fy = 60000 psi) were provided as construction materials for structural analysis. The dead load, live load, number of stories and column/beam dimensions were selected in such a way to obtain a natural period of 0.2 second and 1 second. The damping ratio of the structure was assumed to be 5% of critical damping. Fixed support was assumed for all columns.

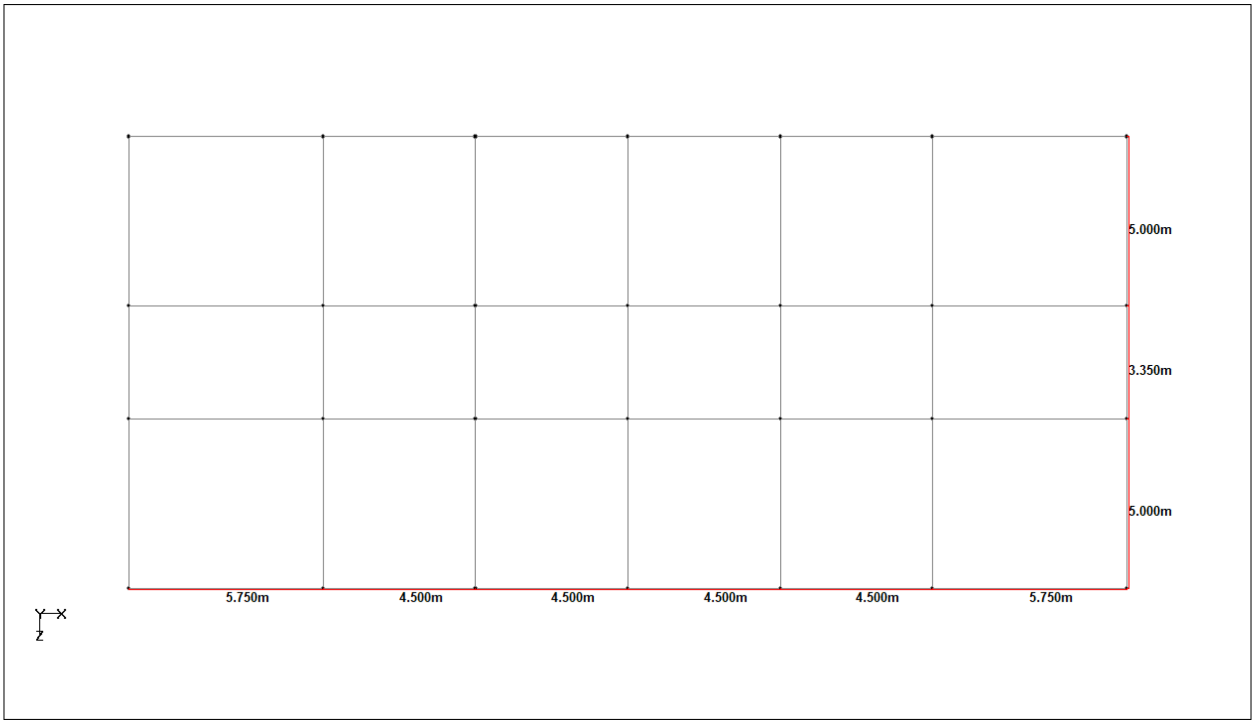


Figure 5. Plan view of BM1 and BM3.

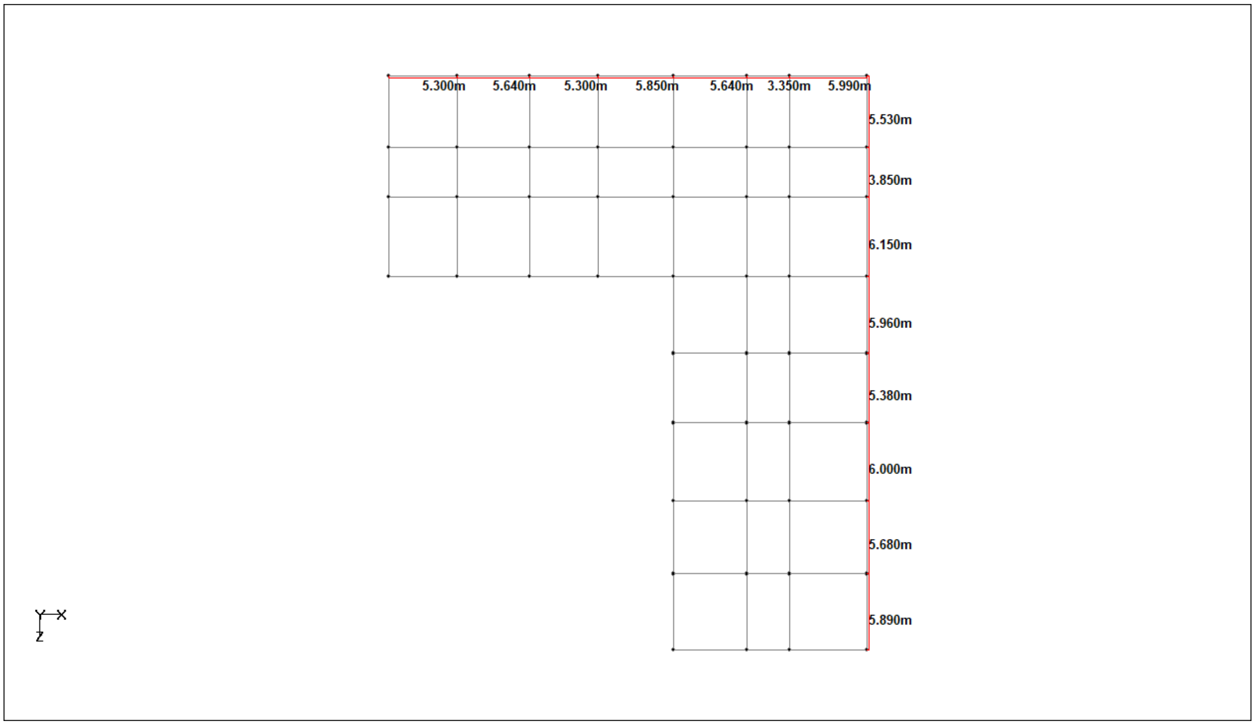


Figure 6. Plan view of BM2 and BM4.

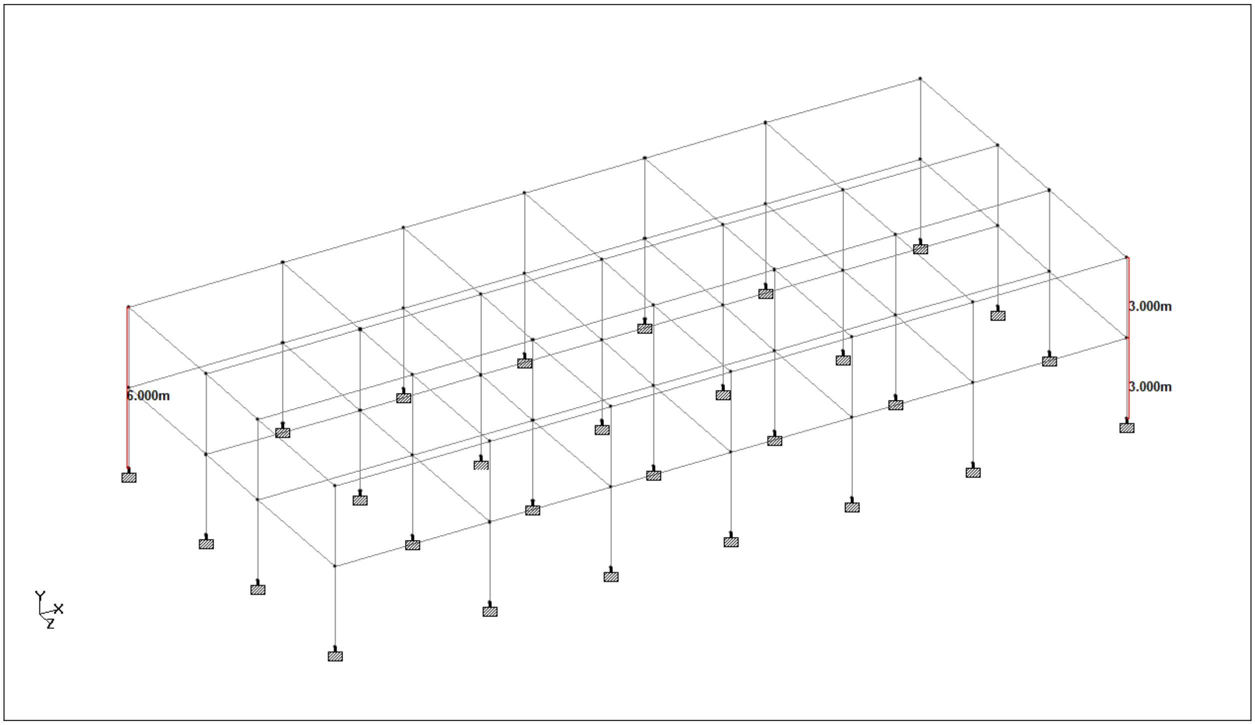


Figure 7. 3D view of BM1.

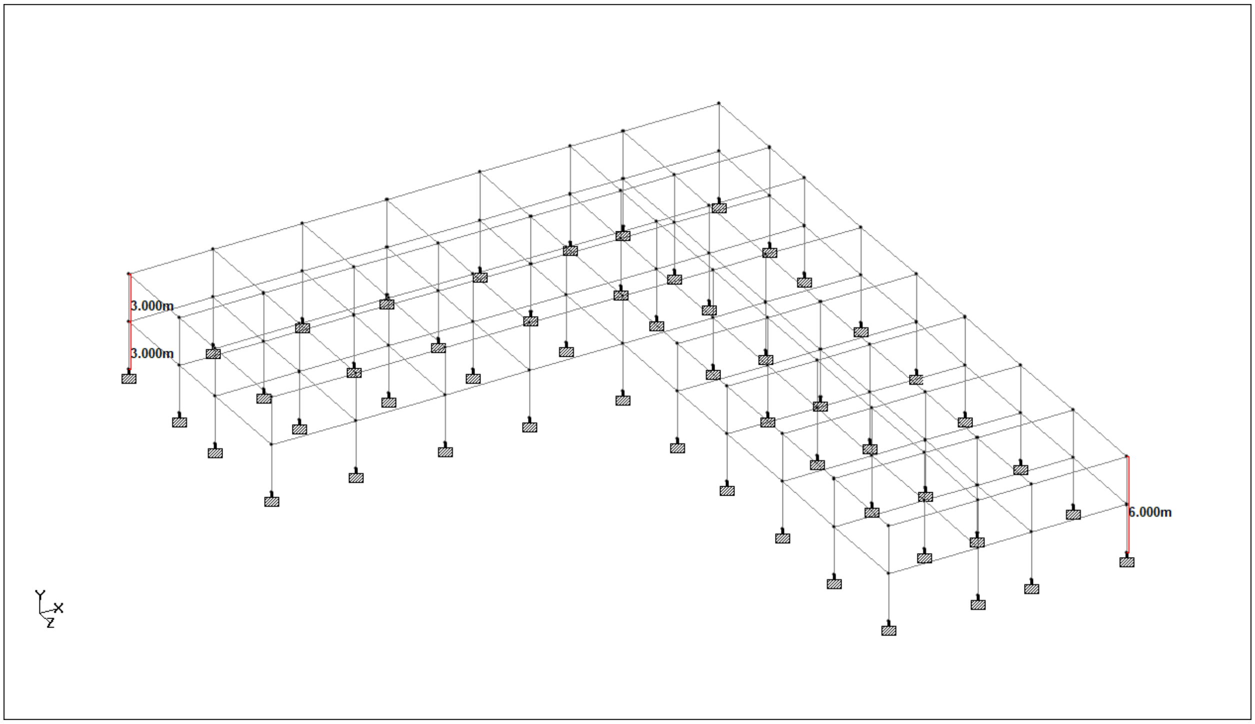


Figure 8. 3D view of BM2.

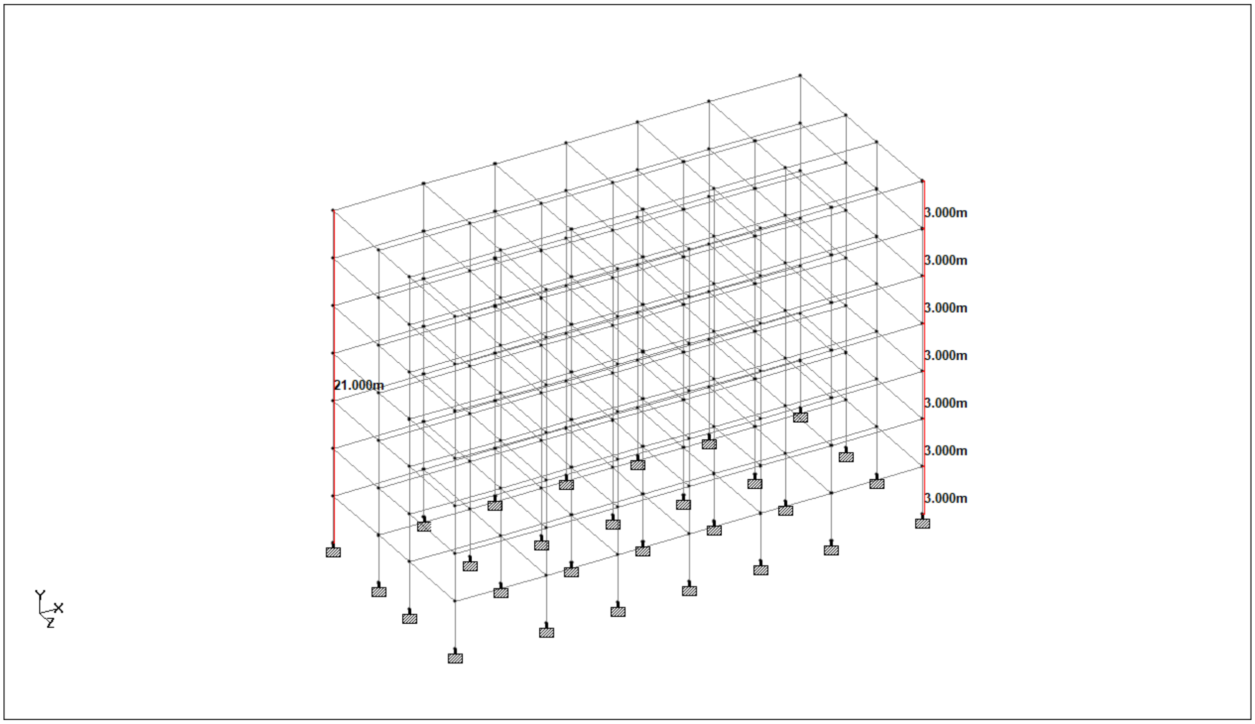


Figure 9. 3D view of BM3.

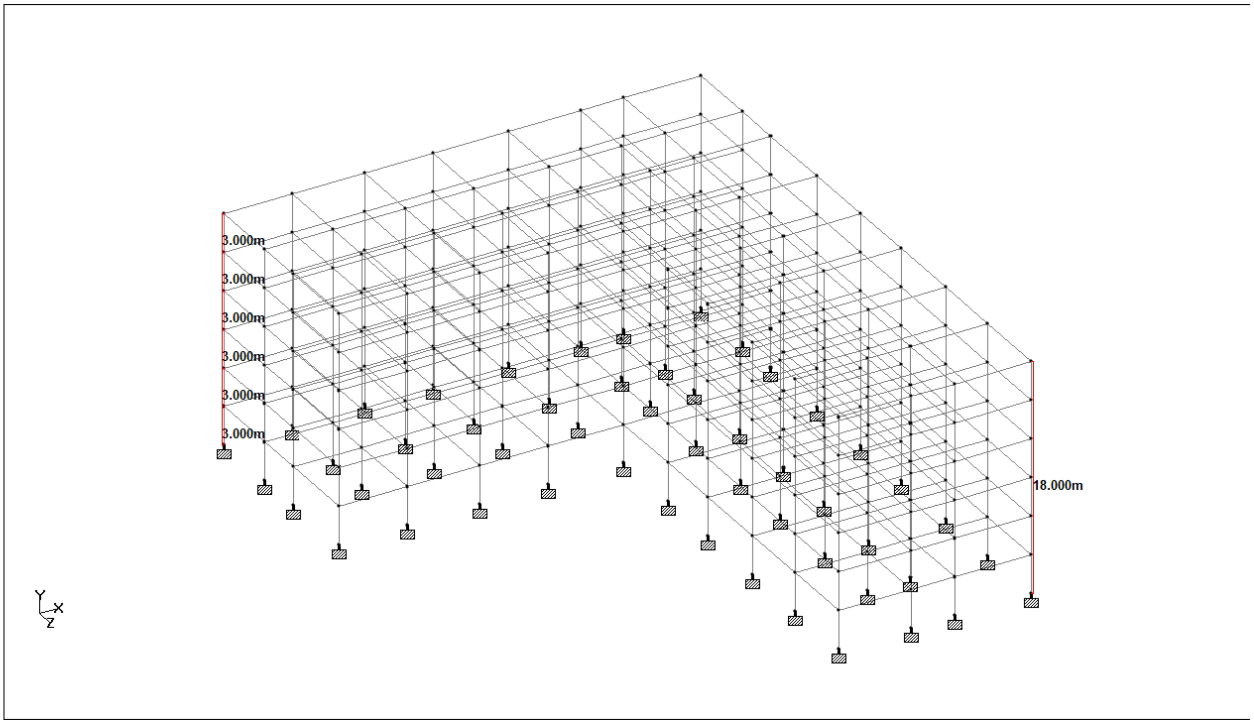


Figure 10. 3D view of BM4.

3.5 TIME HISTORY ANALYSIS:

Time history analysis is an advanced type of dynamic analysis. It has an ability to incorporate time series accelerations as forcing function. The group of 25 rotated ground motion acceleration pairs (1850 acceleration time series) were used in linear time history analysis in STAAD PRO for each one of 4 building models. The rotated ground motions acceleration time series pairs obtained from Equation 2 & 3 (e.g. $\ddot{U}_{Rot1}$& $\ddot{U}_{Rot2}$) were applied to the structures in the form of time series seismic load to “X” and “Z” directions (e.g. longitudinal and transverse directions) of the building models. After the analysis, the structural response (e.g. lateral displacement and story drift) in both directions were recorded for each story of the building models to study effect of building orientation on the structural response. A minimum of 30 mode shapes were defined for the time history analysis to obtain a minimum mass participation factor of 90%.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS:

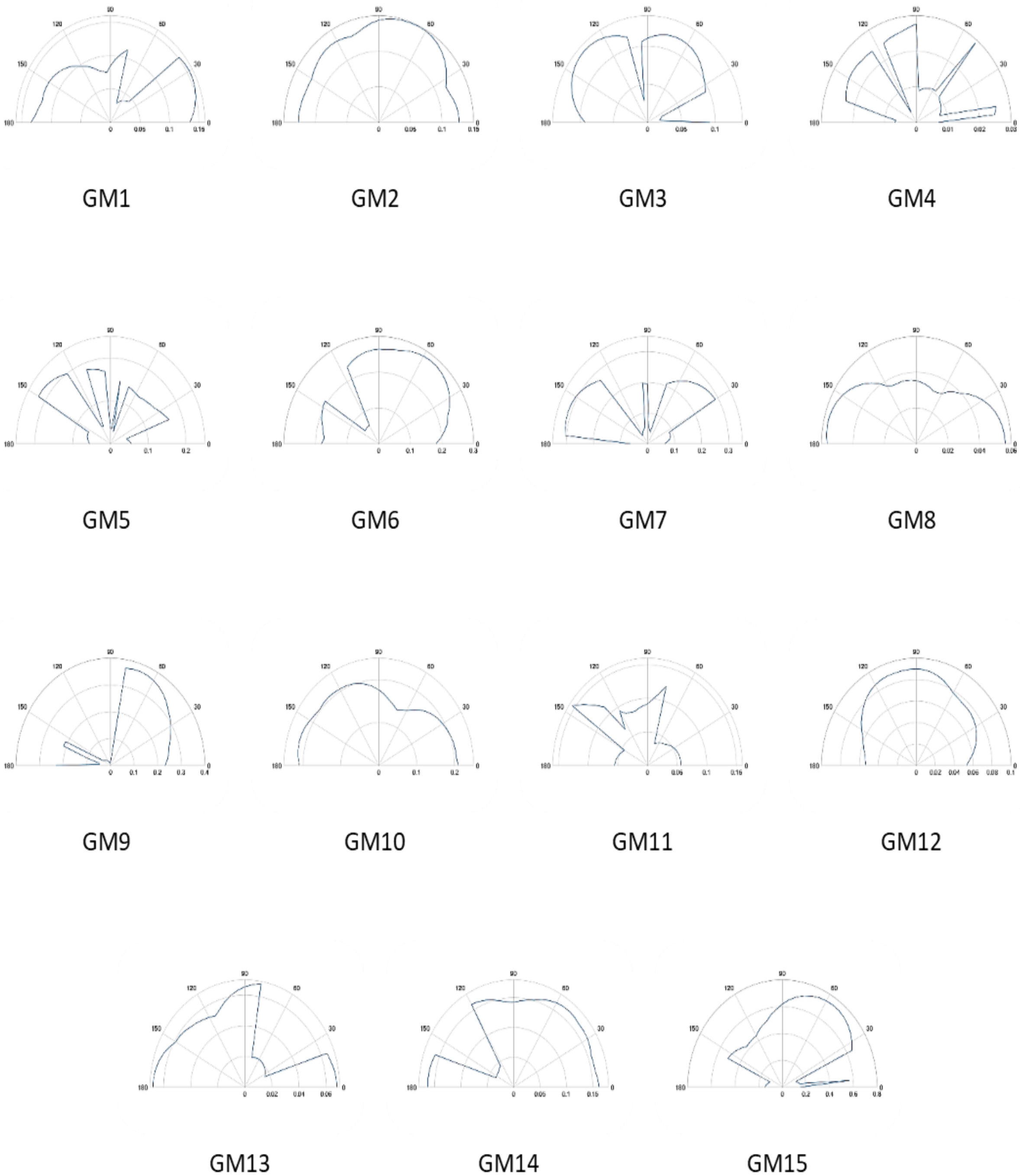
The group of 25 ground motion pairs listed in Table 1 were rotated from 0° to 180° with 5° increments, and then using those rotated ground motions pairs, linear time history analysis was performed for four computer building models. The results of time history analysis obtained, are in terms of structure's response (e.g. story drift and lateral displacement) with respect to different building orientations. For this research I have recorded the lateral displacement at center of mass of roof level, and story drifts at center of mass of each floor. These two types of structural responses were recorded for each rotated ground motion pair applied to each computer building model; the total number of structure response cases obtained were 3700. Using the results obtained from time history analysis, separate graphs have been plotted showing the variation of building story drift and lateral displacement at center of mass with respect to building orientation. A complete STAAD PRO analysis and results output for the time history analysis of seven-story rectangular shape (symmetric) building model subjected to GM2 with rotation angle 30°, is included in the Appendix A.

4.2 LATERAL DISPLACEMENT:

The group of 25 ground motion were rotated from 0° to 180° with 5° increments, then applied to all four building models in terms of time history seismic load in STAAD PRO. After time history analysis, the lateral displacement at center of mass at roof level of all four building models were recorded in X and Z direction of building models, for set of 25 rotated ground motions. Lateral displacement is defined as the displacement of structure in the horizontal direction due to applied horizontal load. The recorded lateral displacement at center of mass was then plotted with respect to the ground motion rotation angles (θx). Figures 11-18 show the variation of lateral displacement at center of mass at roof level with respect to ground motion rotation angle for all four building models subjected to 25 ground motions listed in Table 1.

4.3 STORY DRIFT:

The group of 25 ground motion were rotated from 0° to 180° with 5° increments, then applied to all four building models as seismic load in STAAD PRO. After time history analysis, the story drift at center of mass of each floor for all four building models were recorded in X and Z direction, for each set of rotated ground motions. Here, the story drift is defined as the difference of the lateral displacements at the centers of mass at the top and bottom of the desired story. The recorded story drifts were then plotted with respect to the ground motion rotation angle (θx). Figure 19, 20, 22 and 23 show the variation of story drift in the X-direction for each floor level at center of mass with respect to θx for all four building models subjected to ground motions (GM21, GM16 and GM2). Figure 21 shows the variation of story drift in the X and Z direction for each floor level at center of mass with respect to their rotation angles for rectangular symmetric plan seven-story building model.


GM1
GM2
GM3
GM4
GM5
GM6
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GM9
GM10
GM11
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GM13
GM14
GM15

Figure 11 (a)

Figure 11 (b)

Figure 11. Variation of lateral displacement (cm) at roof level (Ux) in the X-direction of BM1 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).

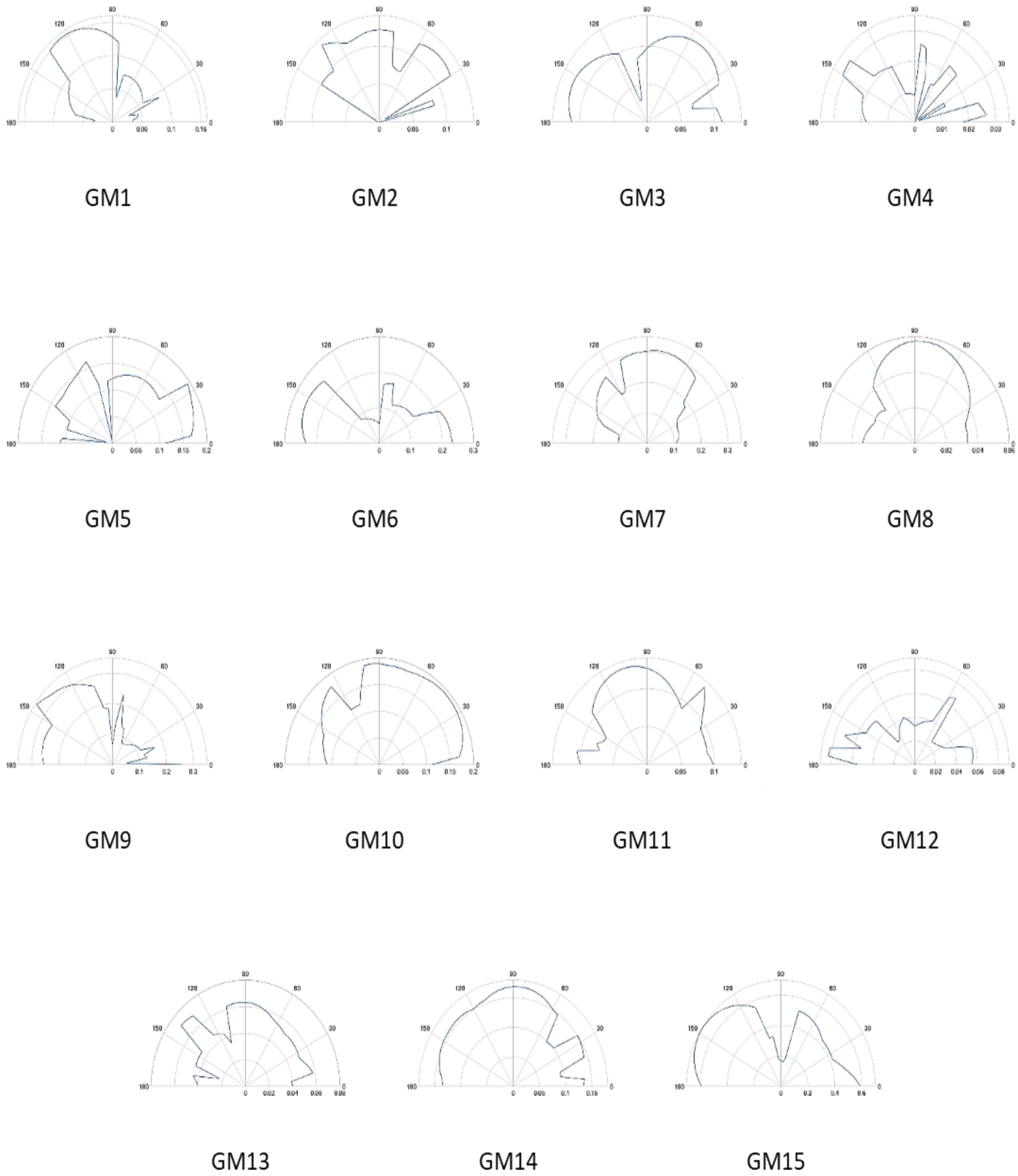

GM1
GM2
GM3
GM4
GM5
GM6
GM7
GM8
GM9
GM10
GM11
GM12
GM13
GM14
GM15

Figure 12 (a)

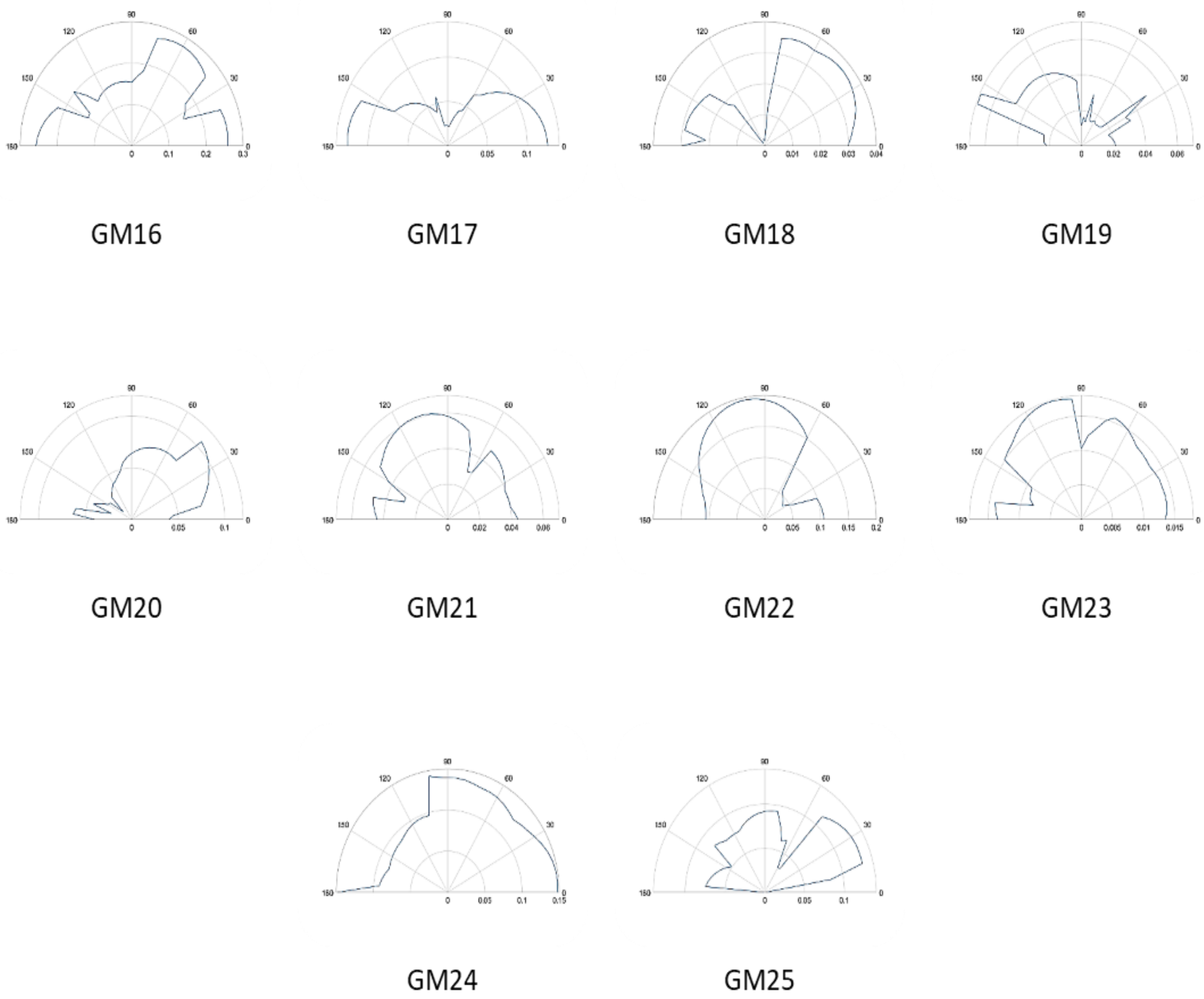
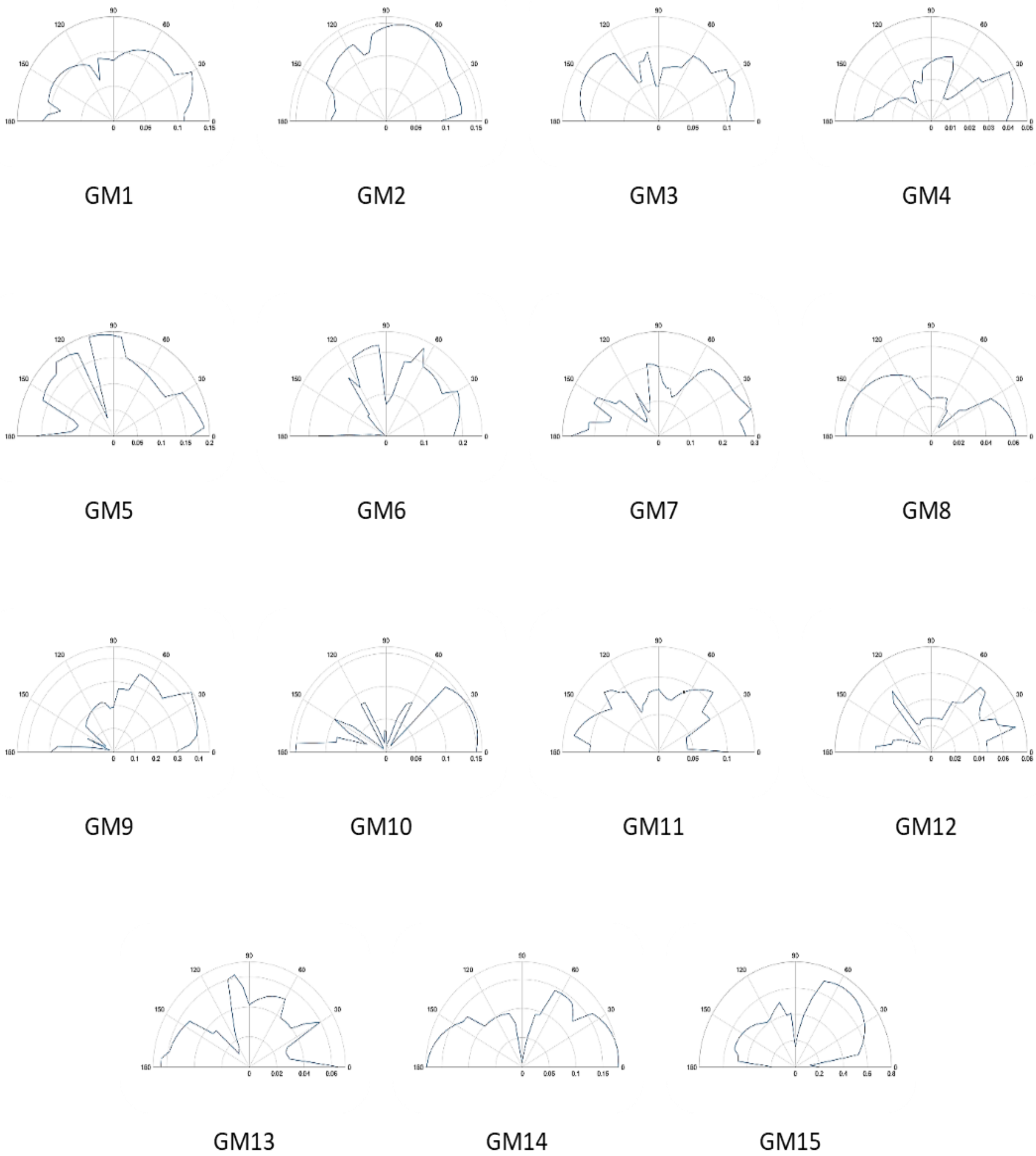


Figure 12 (b)

Figure 12. Variation of lateral displacement (cm) at roof level (Uz) in the Z-direction of BM1 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
GM2
GM3
GM4
GM5
GM6
GM7
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GM10
GM11
GM12
GM13
GM14
GM15

Figure 13 (a)

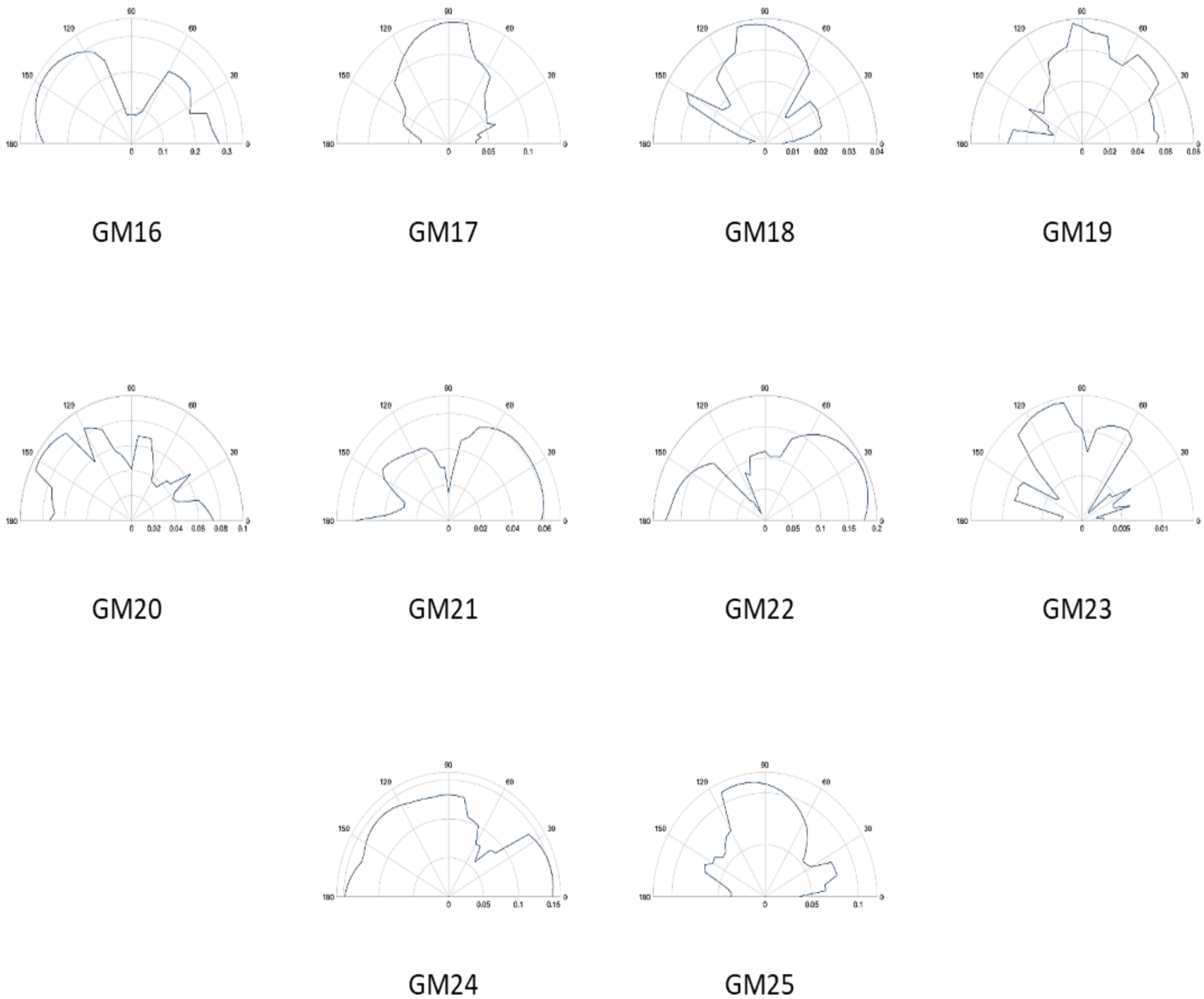
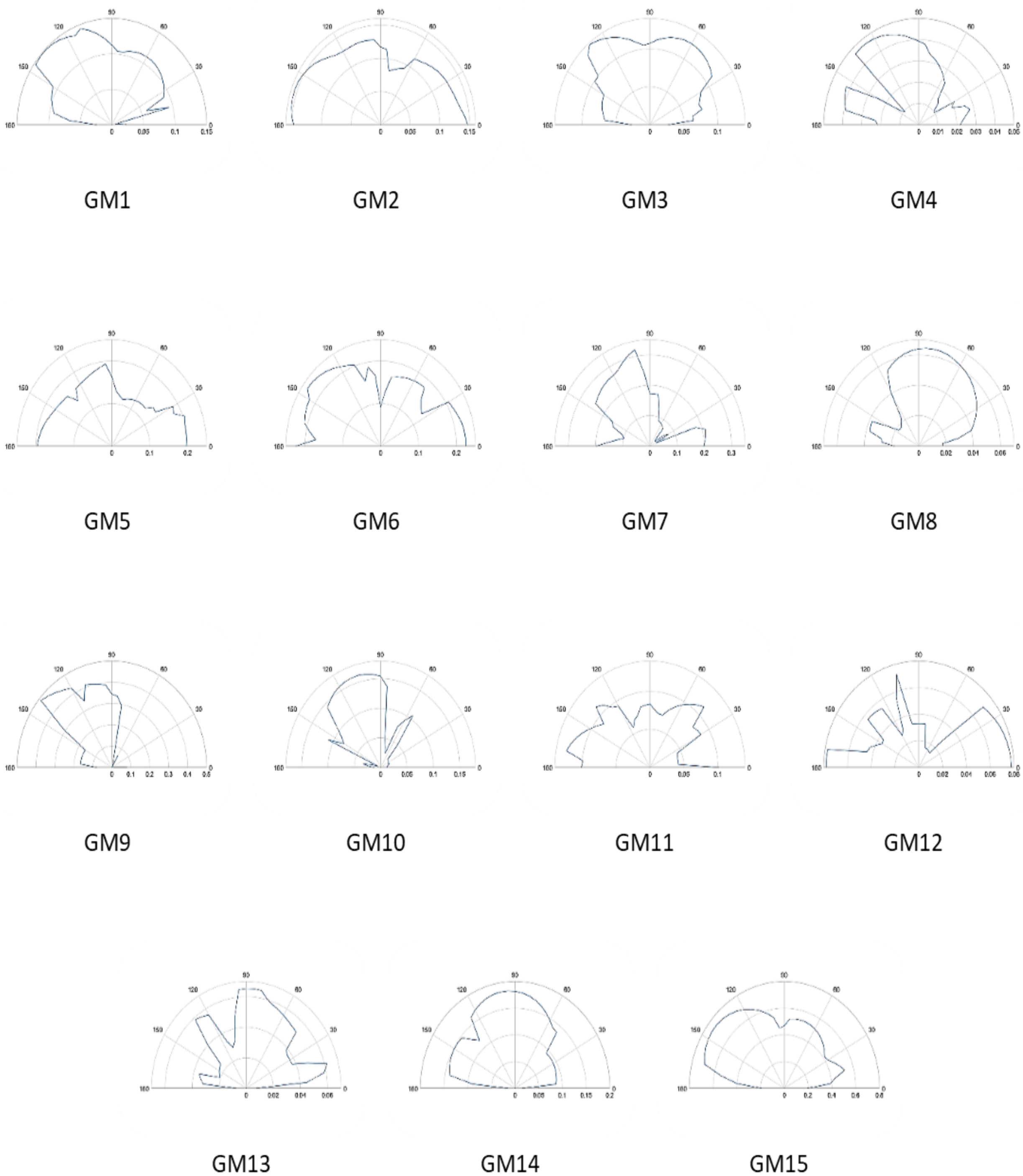


Figure 13 (b)

Figure 13. Variation of lateral displacement (cm) at roof level (Ux) in the X-direction of BM2 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
GM2
GM3
GM4
GM5
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GM8
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GM14
GM15

Figure 14 (a)

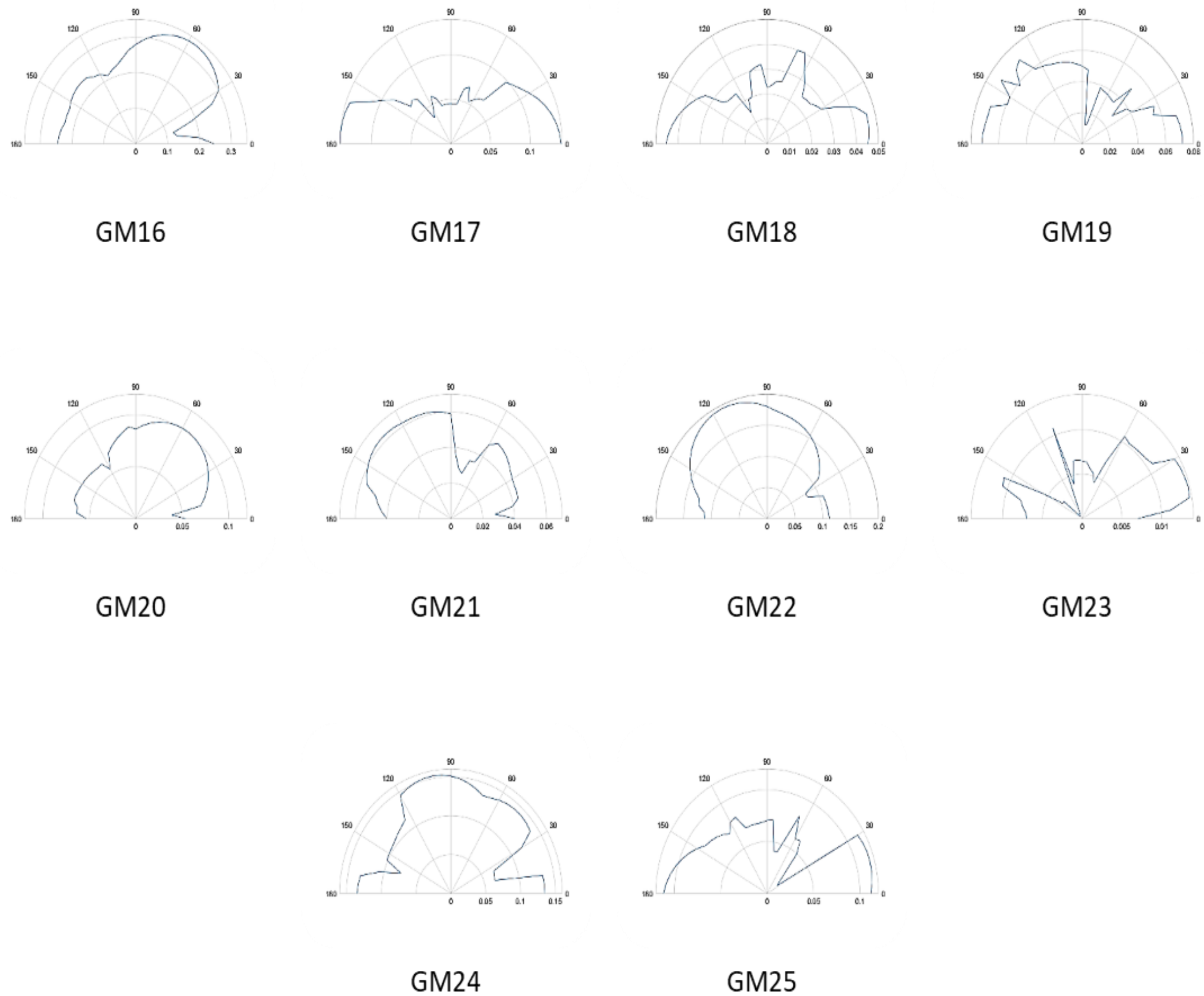
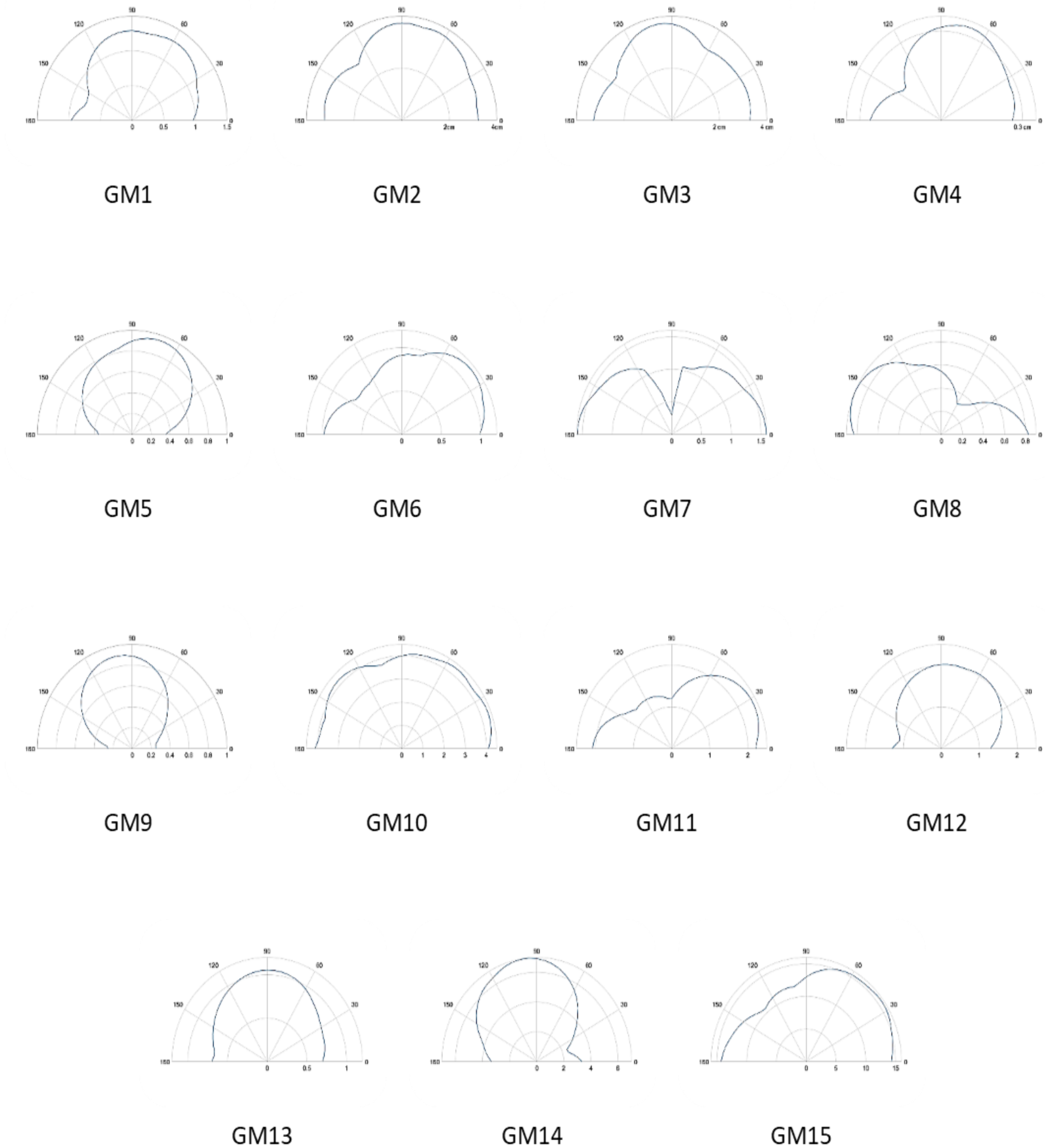


Figure 14 (b)

Figure 14. Variation of lateral displacement (cm) at roof level (Uz) in the Z-direction of BM2 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
GM2
GM3
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GM5
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GM8
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GM12
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GM14
GM15

Figure 15 (a)

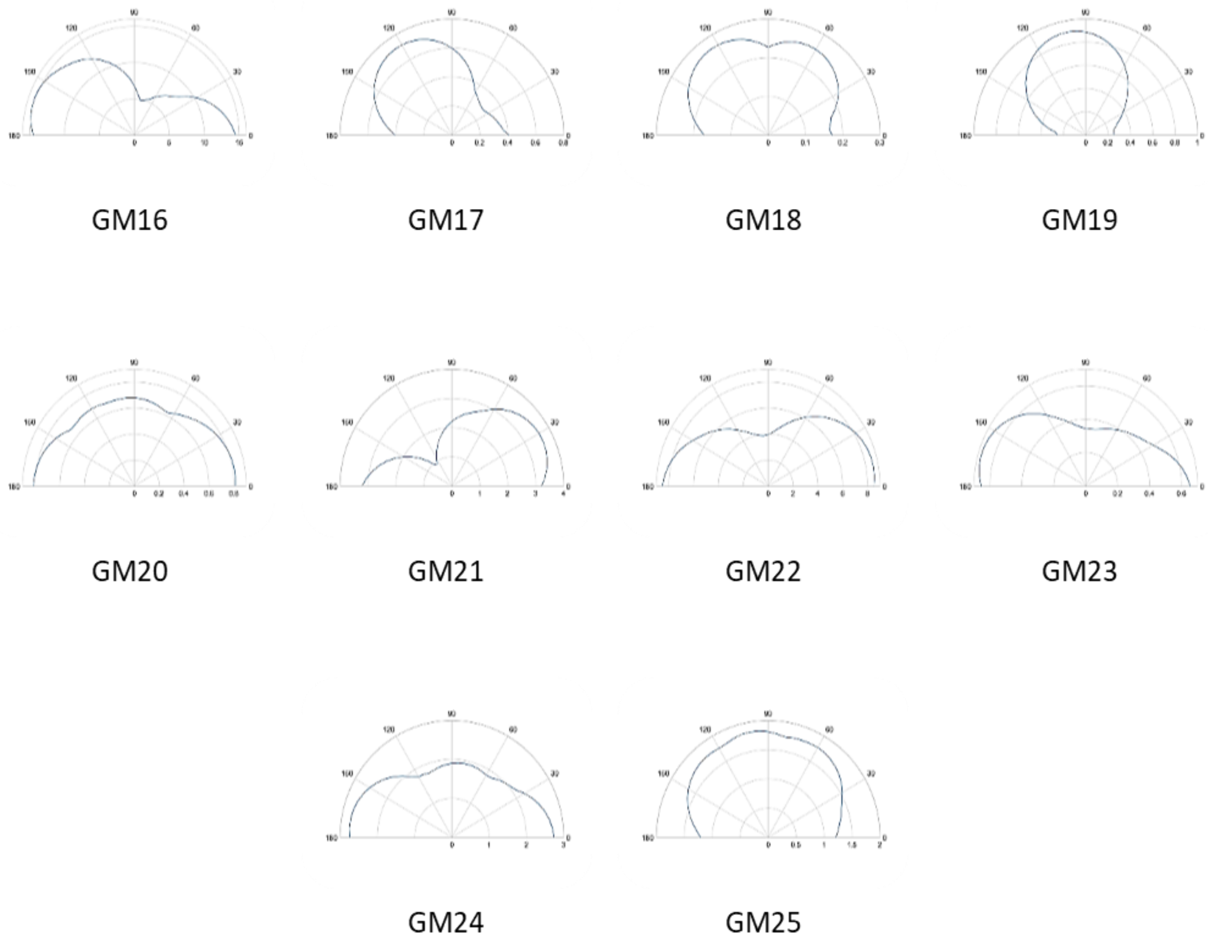
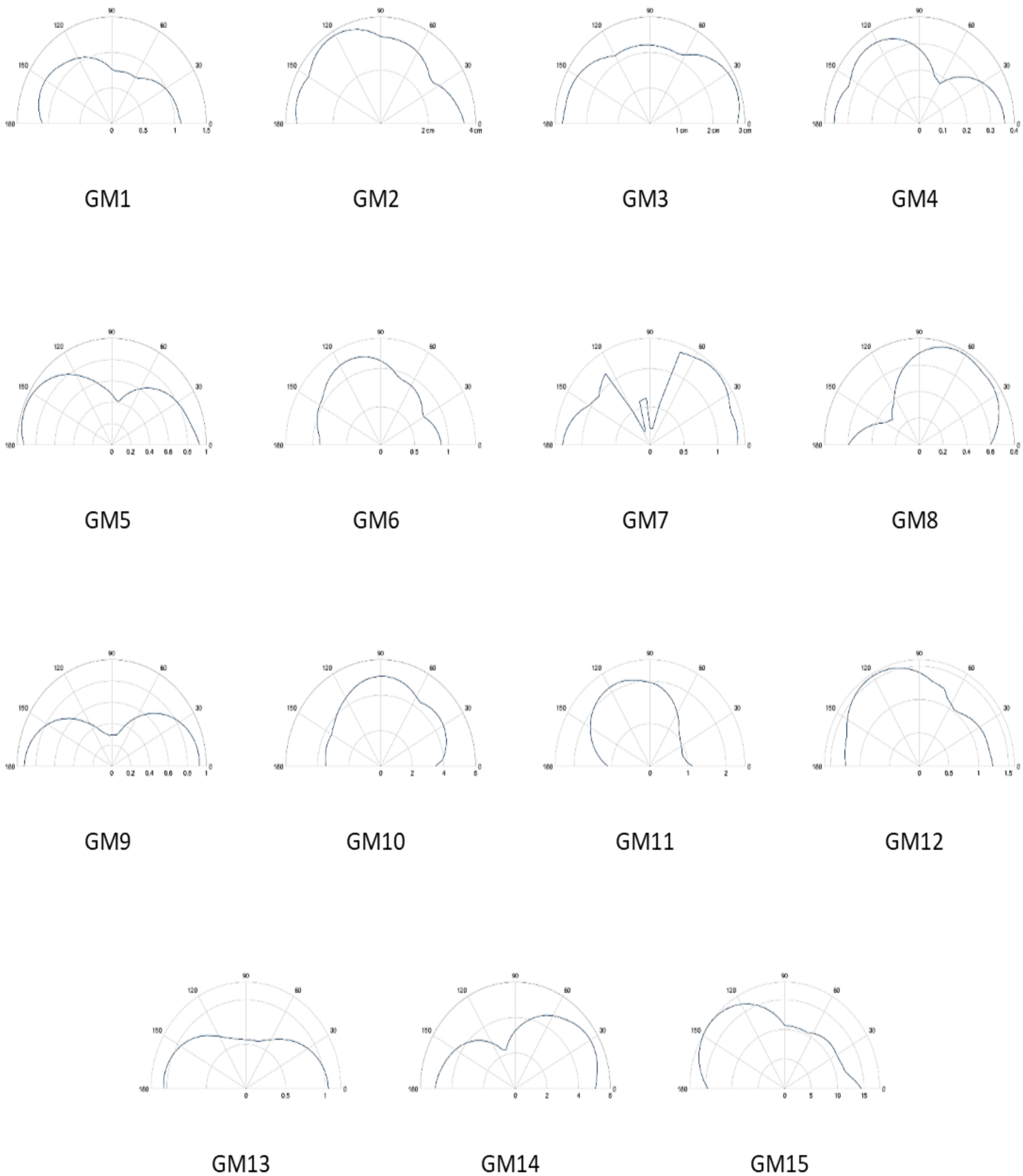


Figure 15 (b)

Figure 15. Variation of lateral displacement (cm) at roof level (Ux) in the X-direction of BM3 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
GM2
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GM4
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GM13
GM14
GM15

Figure 16 (a)

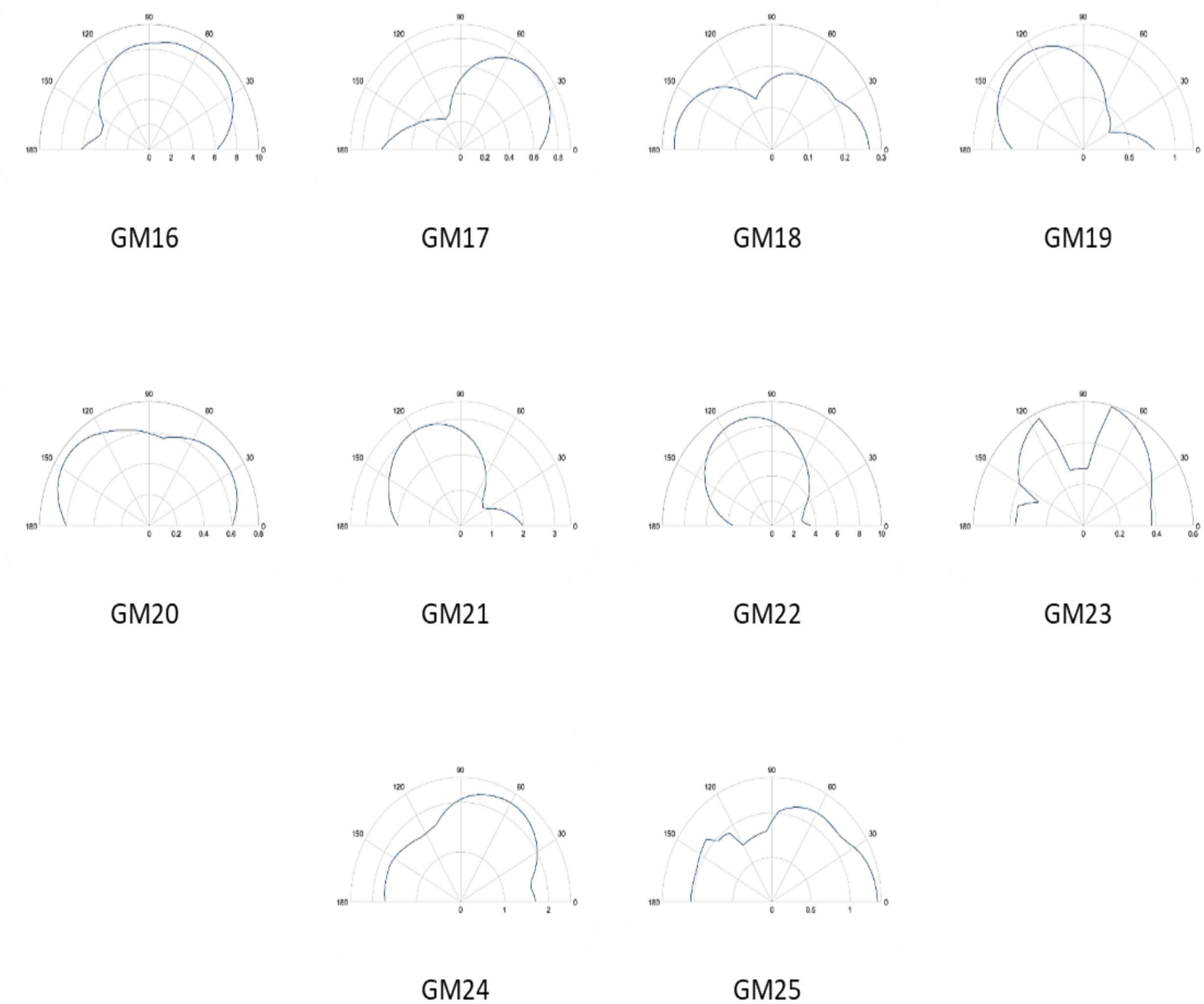
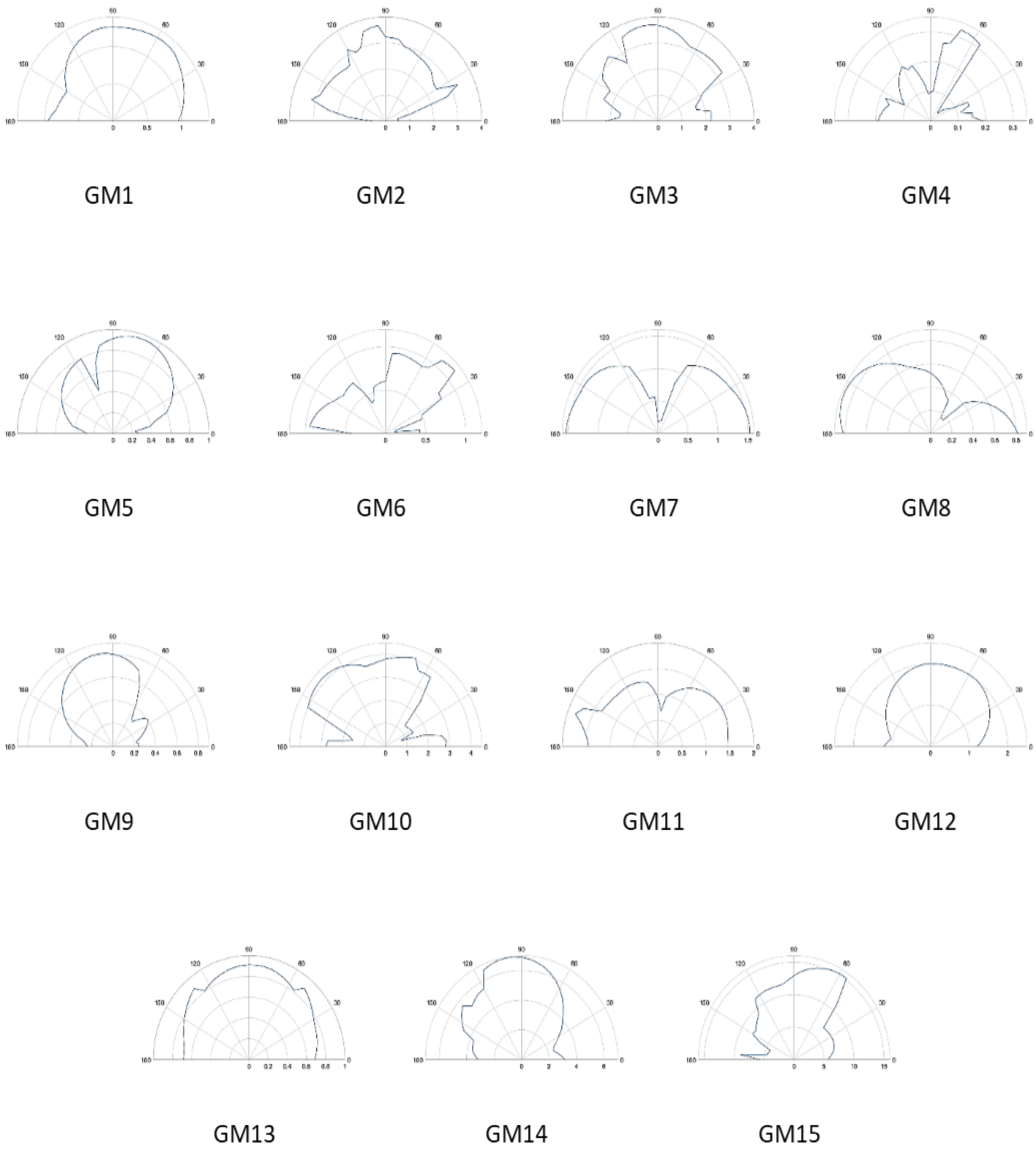


Figure 16 (b)

Figure 16. Variation of lateral displacement (cm) at roof level (Uz) in the Z-direction of BM3 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
GM2
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GM12
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GM14
GM15

Figure 17 (a)

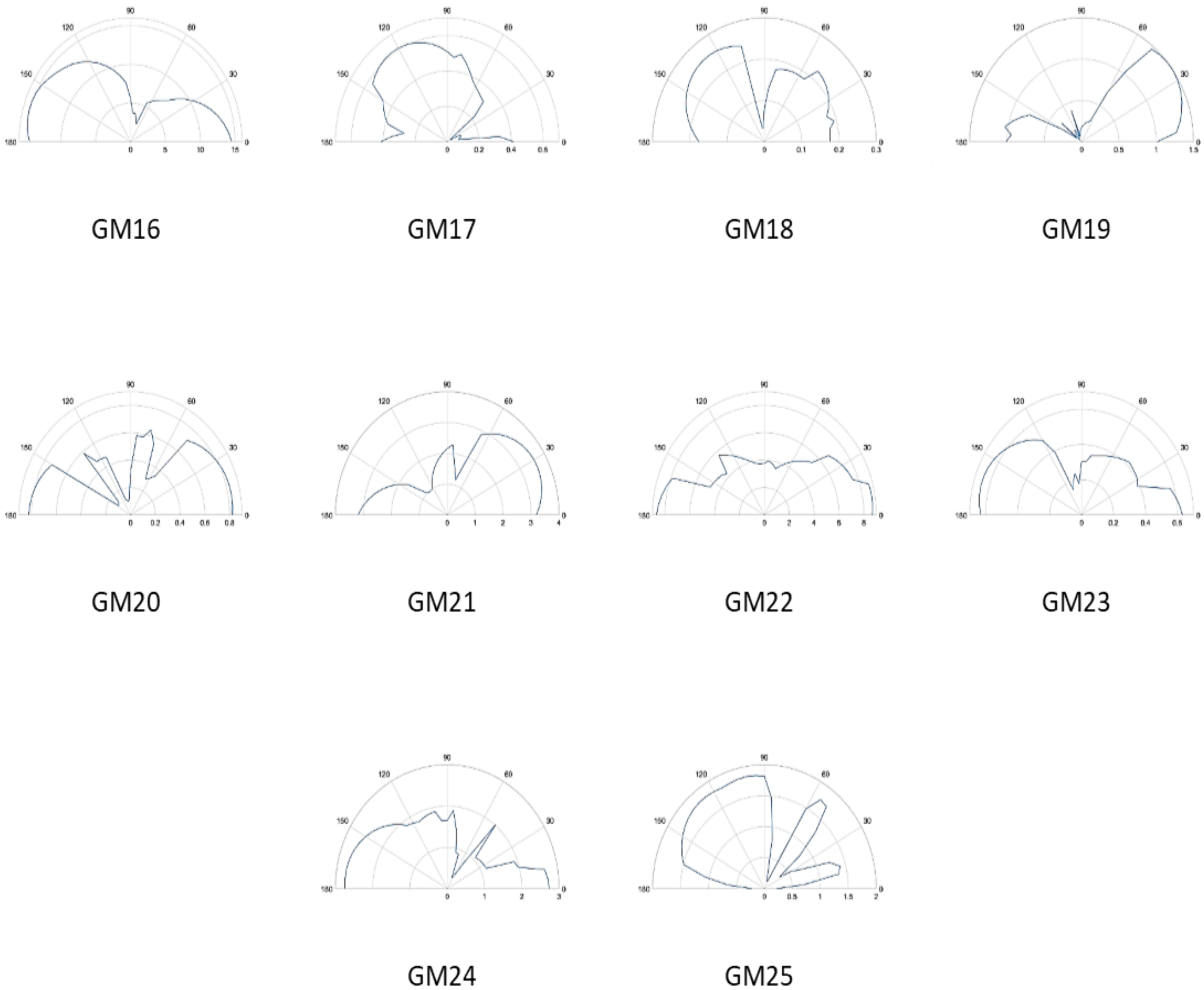
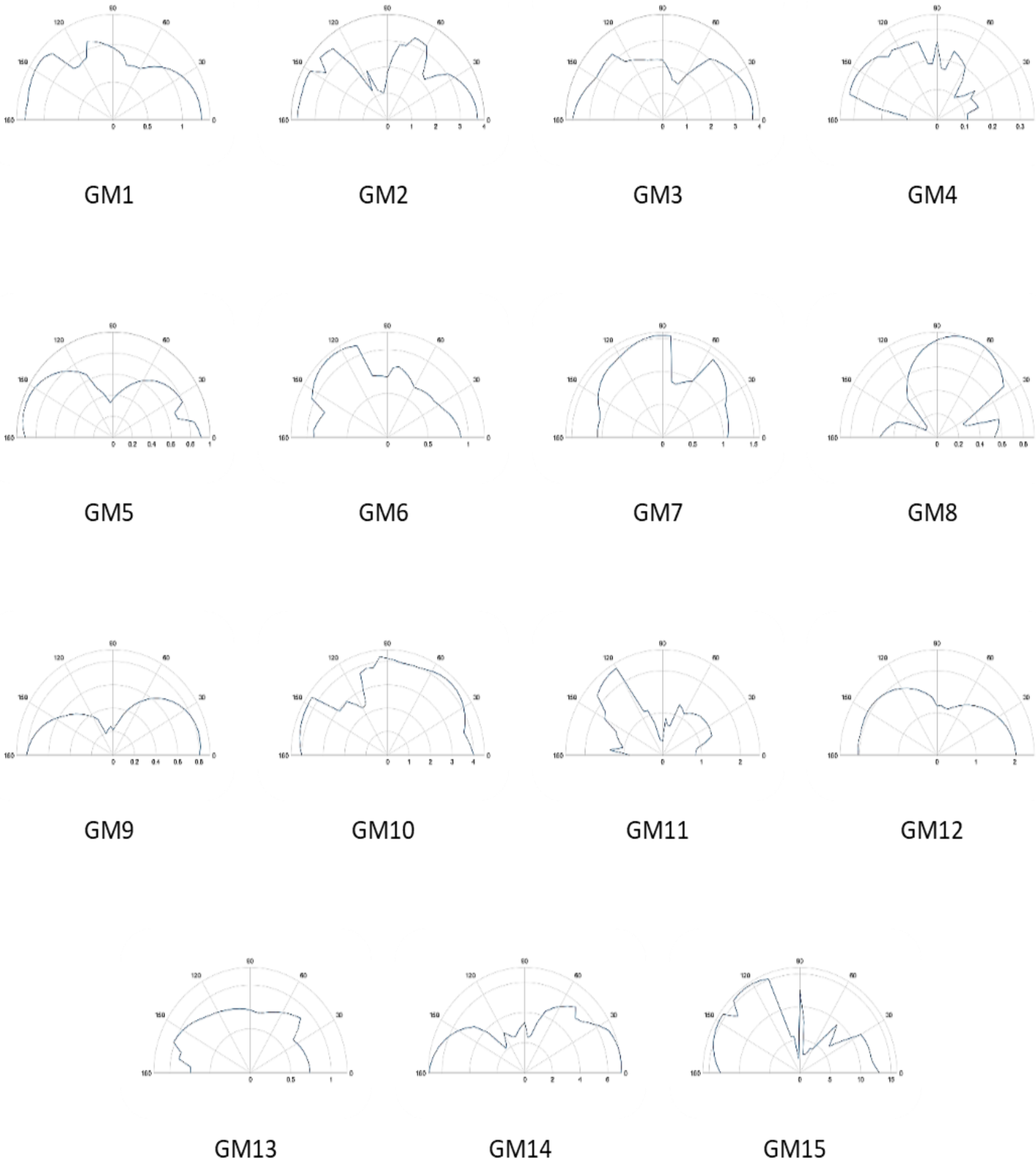


Figure 17 (b)

Figure 17. Variation of lateral displacement (cm) at roof level (Ux) in the X-direction of BM4 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).


GM1
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GM14
GM15

Figure 18 (a)

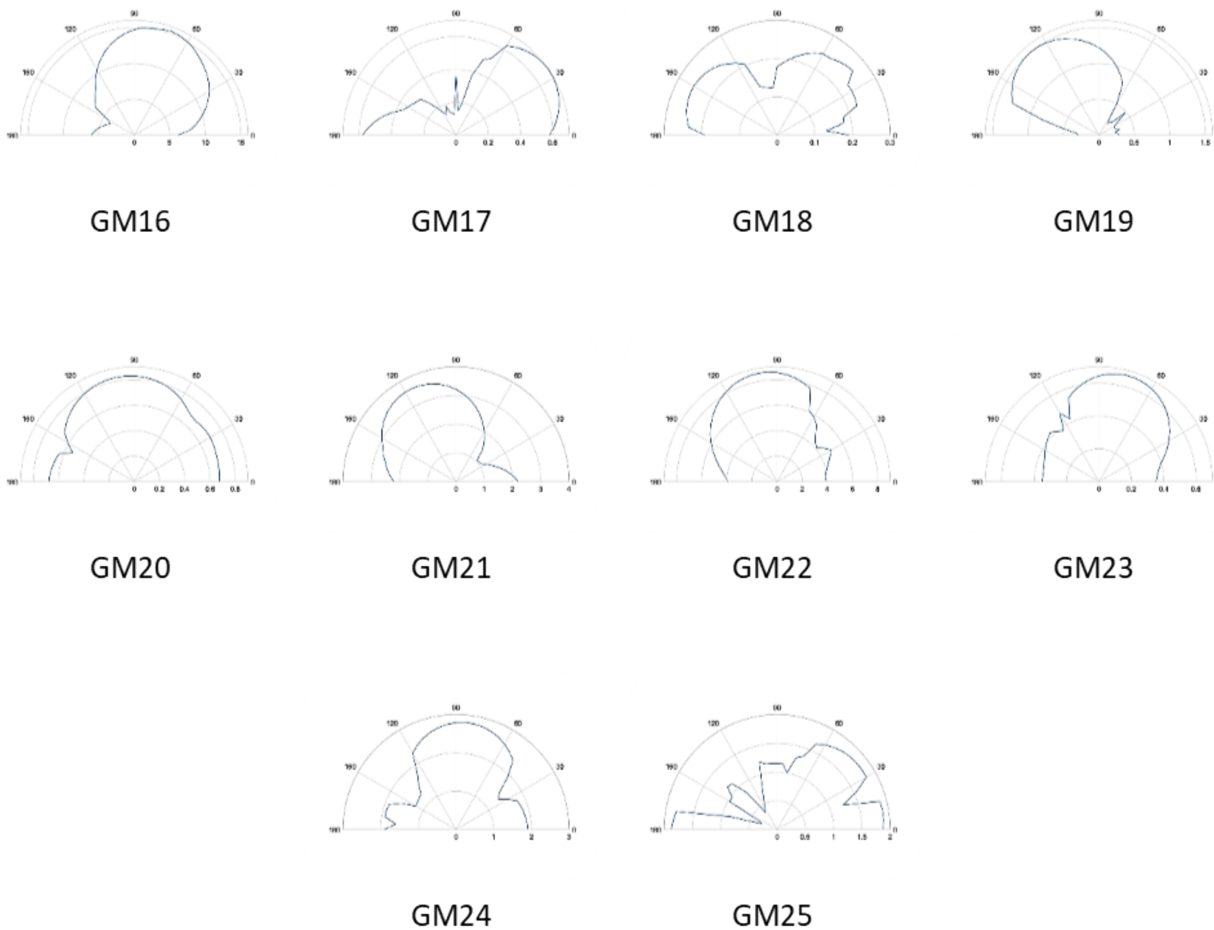

Figure 18 (b)

Figure 18. Variation of lateral displacement (cm) at roof level (Uz) in the Z-direction of BM4 at the center of mass (blue line) as a function of the rotation angle, θ_x, subjected to 25 ground motions (GM).

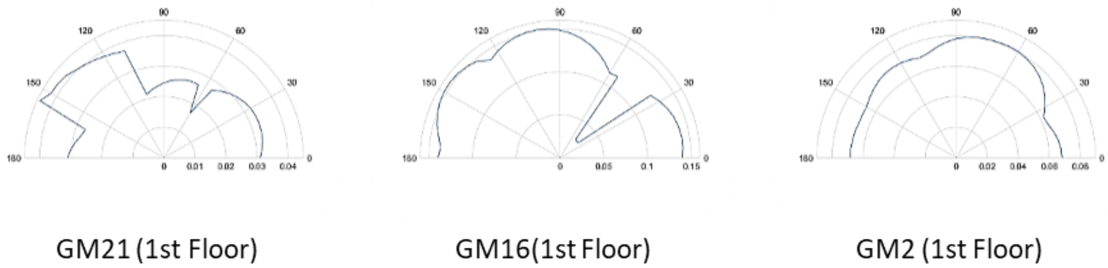

Figure 19. Story drifts in the X-direction at center of mass (cm) as a function of rotation angle θ_x, for BM1 subjected to ground-motions (GM21, GM16, GM2)

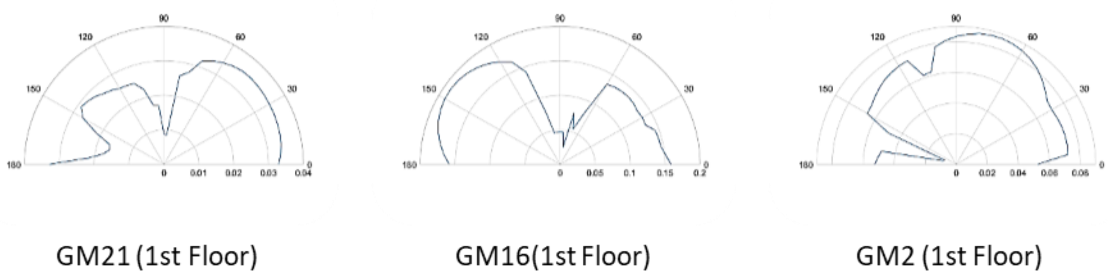

Figure 20. Story drifts in the X-direction at center of mass (cm) as a function of rotation angle θ_x, for BM2 subjected to ground-motions (GM21, GM16, GM2)

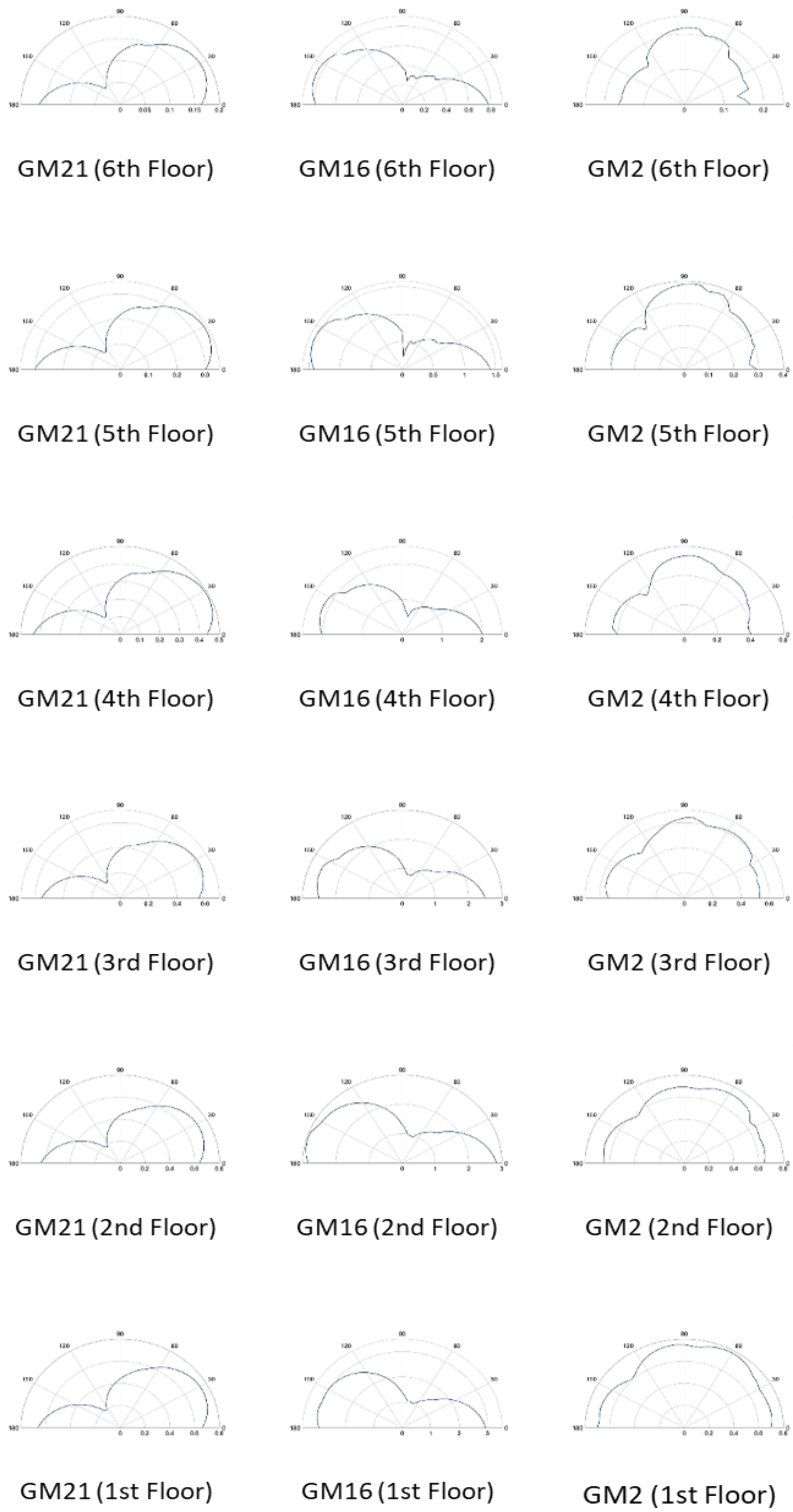

Figure 21. Story drifts in the X-direction at center of mass (cm) as a function of rotation angle θ_x, for BM3 subjected to ground-motions (GM21, GM16, GM2).

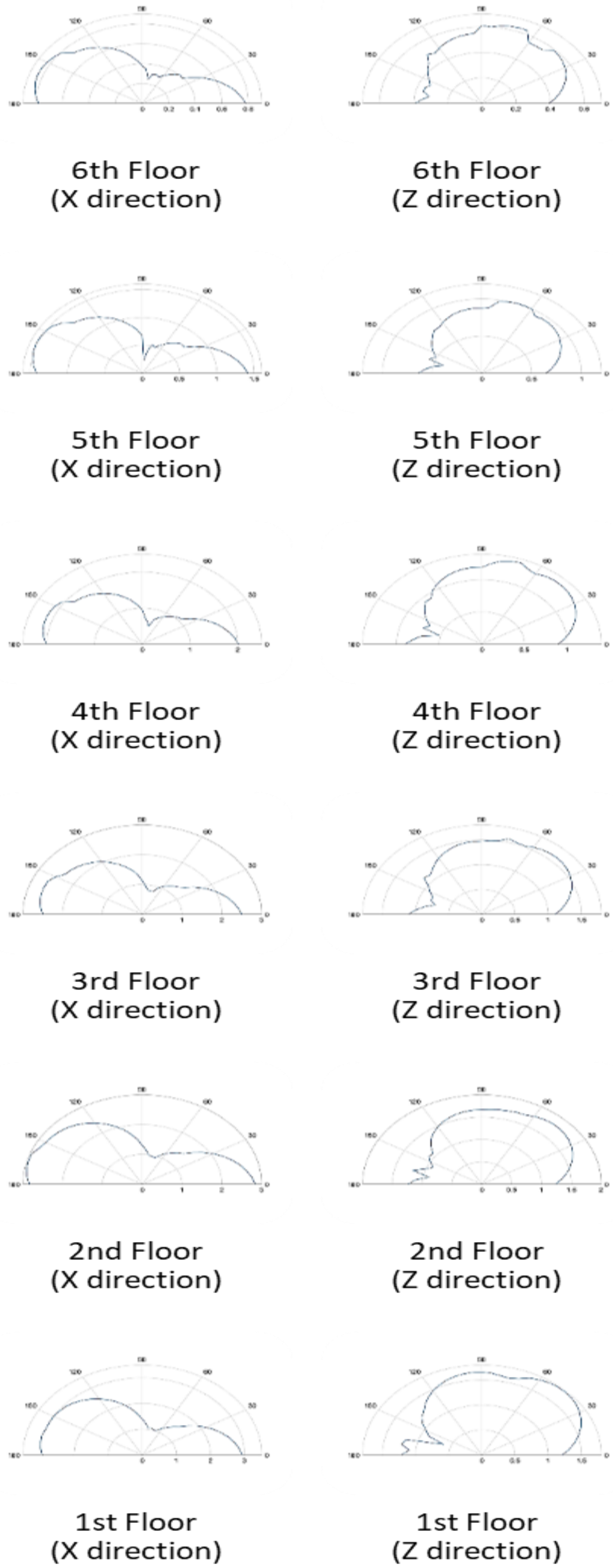

Figure 22. Story drifts in the X and Z direction at center of mass (cm) as a function of rotation angle θ_x, for BM3 subjected to ground-motion (GM16)

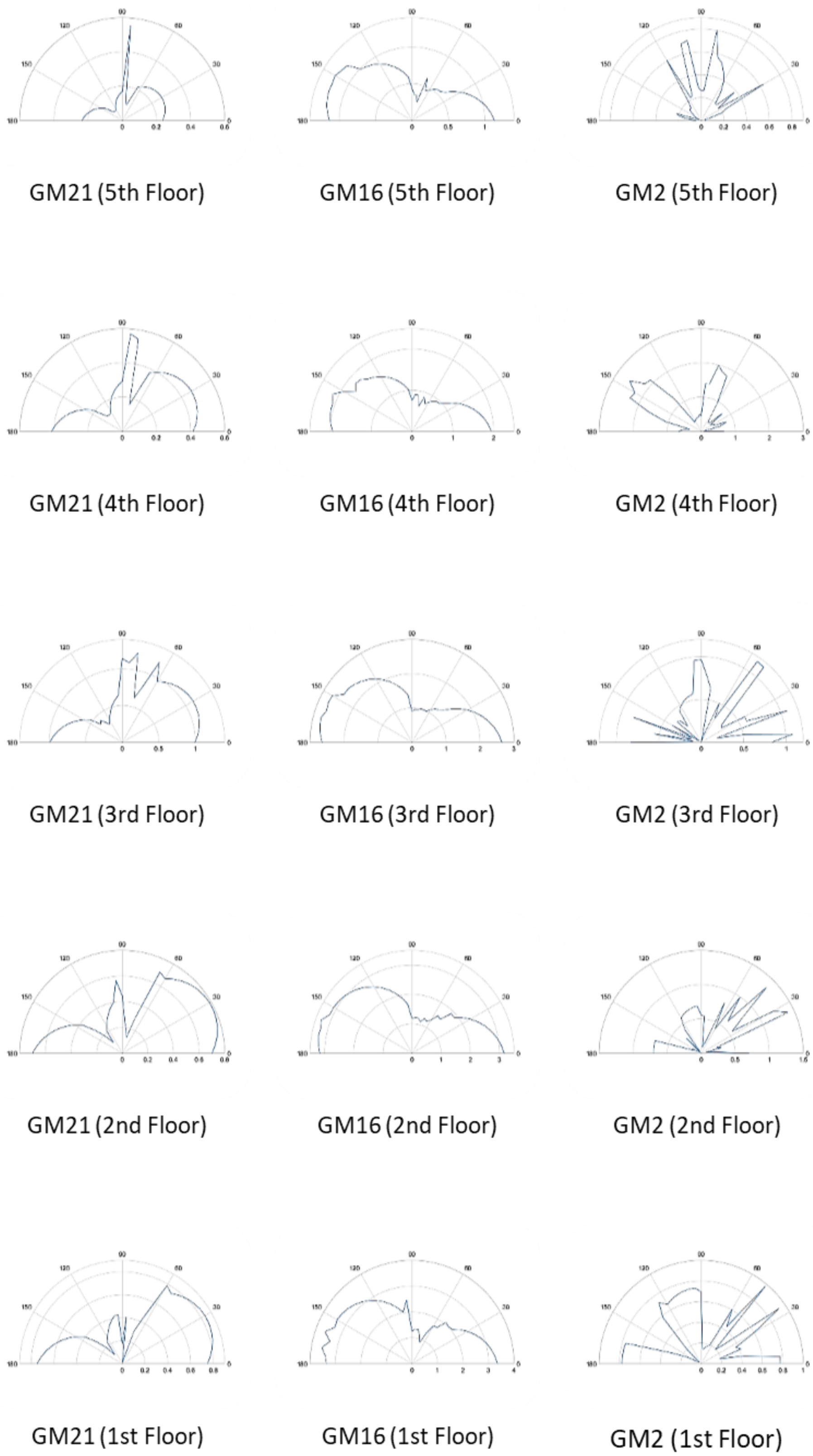

Figure 23. Story drifts in the X-direction at center of mass (cm) as a function of rotation angle θ_x, for BM4 subjected to ground-motion (GM21, GM16, GM2)

4.4 DISCUSSION:

The results obtained from linear time history analysis of all four reinforced concrete moment resisting frame building models subjected to group of 25 rotated ground motions, shows that the maximum response almost always occurs in an orientation other than the as-recorded orientation of the ground motions. Only in 4.5% of cases (9 out of 200 cases illustrated in figure 11 to 18) the maximum response occurred in as-recorded orientation of the ground motions. This result indicates the significance of the building orientation relative to the direction of application of ground motion in seismic time history analysis of structures. The results obtained from Table 2 in Appendix B (The maximum lateral displacement versus lateral displacement in the as recorded direction of ground motions), the average ratio of maximum response (lateral displacement at roof level) in maximum direction to the response (lateral displacement at roof level) in the as-recorded orientation of ground motions obtained from 25 rotated ground motions applied to 4 reinforced concrete structure building models are as follows:

1- Two story symmetric layout plan (BM1) = 3.08
2- Two story asymmetric layout plan (BM2) = 2.59
3- Seven story symmetric layout plan (BM3) = 1.51
4- Six story asymmetric layout plan (BM4) = 1.78

Here, the direction of the maximum structural response is referred to maximum direction, and the as-recorded orientation of the ground motions is referred to the arbitrary orientation.

The plots of lateral displacements at center of mass variation with respect to their rotation angle (figure 11 to 18), indicates that for ground motion with closer fault distances the variation of lateral displacement is polarized to the maximum direction, while for other ground motions away from the fault, there is no sign of polarization. The ratio of maximum response to minimum response is more in the polarized cases than unpolarized cases. This result is true for story drifts too. These plots indicates that the variation of lateral displacements with respect to their rotation angle, are smooth curves with no rapid changes in structure response in the symmetric layout plan computer models, while for asymmetric layout plan computer models the plots shows a discontinuous and broken variation with scattered patterns of rapid change in structure's response of the structure response with respect to their rotation angles.

In time history analysis, the X and Z components of the ground motion were applied to X and Z axes of the building models respectively. The response in the axes of building layout plan (here, X and Z axes), shows different response as the dynamic properties are different along those axes. In this case the vertical loads and stiffness controls the dynamic properties of the structural models, while other properties such as modulus of elasticity, damping ratio and R-value are same for all structural members.

The story drifts at center of mass variation with respect to their rotation angles plots for a given reinforced concrete moment resisting frame model subjected to a ground motion pair rotated through all non-redundant rotation angles indicates that, for symmetric layout plans the story drift plots have almost similar variation in all stories for all non-redundant rotation angles and a unique maximum direction of response, while for asymmetric plans, the story drift plots for different stories shows more variation and scattering values and maximum direction of response varies with the floor level. Therefore, the orientation of maximum response not only changes with the natural period of the structure but, it depends on the structure's layout plan.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Current seismic design codes of practice in the United States (e.g. ASCE 7-10) requires the ground motion pair to be rotated to Maximum Direction (MD) (The direction which results in the maximum response of the structure) before using them for time history analysis of structures. while it has found out to be controversial by (Stewart et al. 2011). Currently, there has not been enough researche conducted to address the effects of ground motion directionality (alternatively building orientation) on nonlinear bidirectional response of structures. In this study, a group of 25 ground motion pairs (listed in table 1) with different fault distances and magnitudes were rotated through all non-redundant rotation angles (e.g. 0° to 180° with 5° increments). Each pair of rotated ground motion were applied through X and Z axes of the computer building models for time history analysis in STAAD PRO. Four computer building models with symmetric and asymmetric plan and first mode of vibration periods of 0.2 second and 1 second were considered for this research. The results obtained from time history analysis of computer building models are in terms of lateral displacement and story drift of structure. The results obtained plotted with respect to their rotation angle using MATLAB. The conclusion of the research carried out in this thesis are as follows:

1. In 95.5% of the analysis cases considered, maximum response occurred in a direction different from the as-recorded directions.
2. The results obtained from symmetric layout plan building models show smooth curves of structural response. The orientation of maximum response in terms of story drift are same for all floors, and orientation of maximum story drift and maximum lateral displacements coincides in all cases.

3. The results obtained from asymmetric layout plan buildings show rapid changes in the structural responses with respect to their rotation angles and the orientation of maximum story drift changes for each floor. In addition, the orientation of maximum story drift and maximum lateral displacement doesn't necessarily coincide.
4. The average ratio of response in the maximum direction to response in the as recorded direction is larger for structures with 0.2 second vibration period than the ones with 1 second period.

5.1 RECOMMENDATIONS:

The recommendations for future studies are as follows:

1. Current research was conducted using linear time history analysis, a non-linear time history analysis needs to be conducted for structures with layout plans and different vibration periods.
2. The effect of building orientation on different types of structural models and materials like steel structures, steel truss, wood structures and concrete shear wall structures needs to be investigated.
3. Seismic behavior of near-fault structures should be investigated separately, as it is known that near-fault records may contain velocity pulses which typically do not coincide with the maximum direction.

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APPENDIX A

TIME HISTORY ANALYSIS RESULT

A complete STAAD PRO analysis and results output for the time history analysis of seven-story rectangular shape (symmetric) building model subjected to GM2 with rotation angle 30°, is included here.

PAGE NO.   1

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 *                                                *
 *           STAAD.Pro CONNECT Edition            *
 *           Version  22.02.00.26                 *
 *           Proprietary Program of               *
 *           Bentley Systems, Inc.                *
 *           Date=    APR  2, 2020                *
 *           Time=    19:12:50                    *
 *                                                *
 *  Licensed to: Student Design Competition site  *
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     3. ENGINEER DATE 03-SEP-19
     4. END JOB INFORMATION
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     6. UNIT METER KN
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     9. 7 29.5 0 0; 8 0 3 0; 9 5.75 3 0; 10 10.25 3 0; 11 14.75 3 0; 12 19.25 3 0
    10. 13 23.75 3 0; 14 29.5 3 0; 22 0 0 5; 23 5.75 0 5; 24 10.25 0 5; 25 14.75 0 5
    11. 26 19.25 0 5; 27 23.75 0 5; 28 29.5 0 5; 29 0 3 5; 30 5.75 3 5; 31 10.25 3 5
    12. 32 14.75 3 5; 33 19.25 3 5; 34 23.75 3 5; 35 29.5 3 5; 43 0 0 8.35
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    19. 76 23.75 3 13.35; 77 29.5 3 13.35; 78 0 6 0; 79 5.75 6 0; 80 10.25 6 0
    20. 81 14.75 6 0; 82 19.25 6 0; 83 23.75 6 0; 84 29.5 6 0; 85 0 6 5; 86 5.75 6 5
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    36. 155 0 12 13.35; 156 5.75 12 13.35; 157 10.25 12 13.35; 158 14.75 12 13.35
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56. 244 23.75 21 13.35; 245 29.5 21 13.35
57. MEMBER INCIDENCES
58. 1 8 9; 2 9 10; 3 10 11; 4 11 12; 5 12 13; 6 13 14; 13 1 8; 14 2 9; 15 3 10
59. 16 4 11; 17 5 12; 18 6 13; 19 7 14; 27 29 30; 28 30 31; 29 31 32; 30 32 33
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94. 307 115 143; 308 116 144; 309 117 145; 310 118 146; 311 119 147; 312 148 149
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114. 427 178 185; 428 179 186; 429 180 187; 430 181 188; 431 182 189; 432 190 191
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131. 529 202 230; 530 203 231; 531 232 233; 532 233 234; 533 234 235; 534 235 236
132. 535 236 237; 536 237 238; 537 204 232; 538 205 233; 539 206 234; 540 207 235
133. 541 208 236; 542 209 237; 543 210 238; 544 239 240; 545 240 241; 546 241 242
134. 547 242 243; 548 243 244; 549 244 245; 550 211 239; 551 212 240; 552 213 241
135. 553 214 242; 554 215 243; 555 216 244; 556 217 245; 557 218 225; 558 219 226
136. 559 220 227; 560 221 228; 561 222 229; 562 223 230; 563 224 231; 564 225 232
137. 565 226 233; 566 227 234; 567 228 235; 568 229 236; 569 230 237; 570 231 238
138. 571 232 239; 572 233 240; 573 234 241; 574 235 242; 575 236 243; 576 237 244
139. 577 238 245
140. DEFINE MATERIAL START
141. ISOTROPIC CONCRETE
142. E 2.17185E+07
143. POISSON 0.17
144. DENSITY 23.5616
145. ALPHA 1E-05
146. DAMP 0.05
147. TYPE CONCRETE
148. STRENGTH FCU 27579
149. END DEFINE MATERIAL
150. MEMBER PROPERTY AMERICAN
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 STAAD SPACE                                              -- PAGE NO.    4

151. 13 TO 19 39 TO 45 65 TO 71 91 TO 97 146 TO 152 159 TO 165 172 TO 178 -
152. 185 TO 191 219 TO 225 232 TO 238 245 TO 251 258 TO 264 292 TO 298 -
153. 305 TO 311 318 TO 324 331 TO 337 365 TO 371 378 TO 384 391 TO 397 -
154. 404 TO 410 438 TO 444 451 TO 457 464 TO 470 477 TO 483 511 TO 517 -
155. 524 TO 530 537 TO 543 550 TO 556 PRIS YD 0.5 ZD 0.7
156. 1 TO 6 27 TO 32 53 TO 58 79 TO 84 105 TO 111 119 TO 125 133 TO 145 -
157. 153 TO 158 166 TO 171 179 TO 184 192 TO 218 226 TO 231 239 TO 244 -
158. 252 TO 257 265 TO 291 299 TO 304 312 TO 317 325 TO 330 338 TO 364 -
159. 372 TO 377 385 TO 390 398 TO 403 411 TO 437 445 TO 450 458 TO 463 -
160. 471 TO 476 484 TO 510 518 TO 523 531 TO 536 544 TO 549 557 TO 576 -
161. 577 PRIS YD 0.6 ZD 0.4
162. CONSTANTS
163. MATERIAL CONCRETE ALL
164. SUPPORTS
165. 1 TO 7 22 TO 28 43 TO 49 64 TO 70 FIXED
166. DEFINE TIME HISTORY
167. TYPE 1 ACCELERATION
168. READ KERN_PEL_X30.TXT
169. TYPE 2 ACCELERATION
170. READ KERN_PEL_Z30.TXT
171. ARRIVAL TIME
172. 0
173. DAMPING 0.05
174. CUT OFF MODE SHAPE 30
175. LOAD 1 LOADTYPE DEAD  TITLE DL
176. SELFWEIGHT Y -1
177. MEMBER LOAD
178. 27 TO 32 53 TO 58 106 TO 110 134 TO 138 153 TO 158 166 TO 171 193 TO 197 207 -
179. 208 TO 211 226 TO 231 239 TO 244 266 TO 270 280 TO 284 299 TO 304 312 TO 317 -
180. 339 TO 343 353 TO 357 372 TO 377 385 TO 390 412 TO 416 426 TO 430 -
181. 445 TO 450 458 TO 463 485 TO 489 499 TO 503 518 TO 523 531 TO 536 -
182. 558 TO 562 572 TO 576 UNI GY -4.9
183. 1 TO 6 68 71 79 TO 84 105 111 119 125 133 139 TO 145 175 178 TO 184 192 198 -
184. 199 205 206 212 TO 218 248 251 TO 257 265 271 272 278 279 285 TO 291 321 -
185. 324 TO 330 338 344 345 351 352 358 TO 364 394 397 TO 403 411 417 418 424 -
186. 425 431 TO 437 467 470 TO 476 484 490 491 497 498 504 TO 510 540 543 TO 549 -
187. 557 563 564 570 571 577 UNI GY -15.12
188. FLOOR LOAD
189. YRANGE 0 21 FLOAD -5.8 XRANGE 0 29.5  ZRANGE 0 13.35  GY
**NOTE** about Floor/OneWay Loads/Weights.
  Please note that depending on the shape of the floor you may
  have to break up the FLOOR/ONEWAY LOAD into multiple commands.
  For details please refer to Technical Reference Manual
  Section 5.32.4.2 Note d and/or "5.32.4.3 Note f.

190. LOAD 2 LOADTYPE LIVE  TITLE LL
191. FLOOR LOAD
192. YRANGE 0 21 FLOAD -4 XRANGE 0 29.5  ZRANGE 0 13.35  GY
193. LOAD 3 LOADTYPE SEISMIC  TITLE DYNAMIC LOAD
194. SELFWEIGHT X 1
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 STAAD SPACE                                                 -- PAGE NO.    5

195. SELFWEIGHT Y 1
196. SELFWEIGHT Z 1
197. MEMBER LOAD
198. 27 TO 32 53 TO 58 106 TO 110 134 TO 138 153 TO 158 166 TO 171 193 TO 197 207 -
199. 208 TO 211 226 TO 231 239 TO 244 266 TO 270 280 TO 284 299 TO 304 312 TO 317 -
200. 339 TO 343 353 TO 357 372 TO 377 385 TO 390 412 TO 416 426 TO 430 -
201. 445 TO 450 458 TO 463 485 TO 489 499 TO 503 518 TO 523 531 TO 536 -
202. 558 TO 562 572 TO 576 UNI GX 4.9
203. 27 TO 32 53 TO 58 106 TO 110 134 TO 138 153 TO 158 166 TO 171 193 TO 197 207 -
204. 208 TO 211 226 TO 231 239 TO 244 266 TO 270 280 TO 284 299 TO 304 312 TO 317 -
205. 339 TO 343 353 TO 357 372 TO 377 385 TO 390 412 TO 416 426 TO 430 -
206. 445 TO 450 458 TO 463 485 TO 489 499 TO 503 518 TO 523 531 TO 536 -
207. 558 TO 562 572 TO 576 UNI GY 4.9
208. 27 TO 32 53 TO 58 106 TO 110 134 TO 138 153 TO 158 166 TO 171 193 TO 197 207 -
209. 208 TO 211 226 TO 231 239 TO 244 266 TO 270 280 TO 284 299 TO 304 312 TO 317 -
210. 339 TO 343 353 TO 357 372 TO 377 385 TO 390 412 TO 416 426 TO 430 -
211. 445 TO 450 458 TO 463 485 TO 489 499 TO 503 518 TO 523 531 TO 536 -
212. 558 TO 562 572 TO 576 UNI GZ 4.9
213. 1 TO 6 68 71 79 TO 84 105 111 119 125 133 139 TO 145 175 178 TO 184 192 198 -
214. 199 205 206 212 TO 218 248 251 TO 257 265 271 272 278 279 285 TO 291 321 -
215. 324 TO 330 338 344 345 351 352 358 TO 364 394 397 TO 403 411 417 418 424 -
216. 425 431 TO 437 467 470 TO 476 484 490 491 497 498 504 TO 510 540 543 TO 549 -
217. 557 563 564 570 571 577 UNI GX 15.12
218. 1 TO 6 68 71 79 TO 84 105 111 119 125 133 139 TO 145 175 178 TO 184 192 198 -
219. 199 205 206 212 TO 218 248 251 TO 257 265 271 272 278 279 285 TO 291 321 -
220. 324 TO 330 338 344 345 351 352 358 TO 364 394 397 TO 403 411 417 418 424 -
221. 425 431 TO 437 467 470 TO 476 484 490 491 497 498 504 TO 510 540 543 TO 549 -
222. 557 563 564 570 571 577 UNI GY 15.12
223. 1 TO 6 68 71 79 TO 84 105 111 119 125 133 139 TO 145 175 178 TO 184 192 198 -
224. 199 205 206 212 TO 218 248 251 TO 257 265 271 272 278 279 285 TO 291 321 -
225. 324 TO 330 338 344 345 351 352 358 TO 364 394 397 TO 403 411 417 418 424 -
226. 425 431 TO 437 467 470 TO 476 484 490 491 497 498 504 TO 510 540 543 TO 549 -
227. 557 563 564 570 571 577 UNI GZ 15.12
228. FLOOR LOAD
229. YRANGE 0 21 FLOAD 5.8 XRANGE 0 29.5  ZRANGE 0 13.35  GX
230. YRANGE 0 21 FLOAD 5.8 XRANGE 0 29.5  ZRANGE 0 13.35  GY
231. YRANGE 0 21 FLOAD 5.8 XRANGE 0 29.5  ZRANGE 0 13.35  GZ
232. YRANGE 0 21 FLOAD 4 XRANGE 0 29.5  ZRANGE 0 13.35  GX
233. YRANGE 0 21 FLOAD 4 XRANGE 0 29.5  ZRANGE 0 13.35  GY
234. YRANGE 0 21 FLOAD 4 XRANGE 0 29.5  ZRANGE 0 13.35  GZ
235. GROUND MOTION X 1 1 9.806000
236. GROUND MOTION Z 2 1 9.806000
237. *LOAD COMB 11 (STATIC + POSITIVE OF DYNAMIC)
238. *1 1.0 2 1.0 3 1.0
239. *LOAD COMB 12 (STATIC + NEGATIVE OF DYNAMIC)
240. *1 1.0 2 1.0 3 -1.0
241. PERFORM ANALYSIS
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   STAAD SPACE                                                -- PAGE NO.    6


           P R O B L E M   S T A T I S T I C S
           -----------------------------------

    NUMBER OF JOINTS        224  NUMBER OF MEMBERS     511
    NUMBER OF PLATES          0  NUMBER OF SOLIDS        0
    NUMBER OF SURFACES        0  NUMBER OF SUPPORTS     28

          Using 64-bit analysis engine.

          SOLVER USED IS THE OUT-OF-CORE BASIC SOLVER

    ORIGINAL/FINAL BAND-WIDTH=    49/    28/    168 DOF
  TOTAL      PRIMARY LOAD CASES =     3, TOTAL DEGREES OF FREEDOM =    1176
  TOTAL LOAD COMBINATION  CASES =     0  SO FAR.
    SIZE OF STIFFNESS MATRIX =      198 DOUBLE  KILO-WORDS
    REQRD/AVAIL. DISK SPACE  =     16.1/  48861.3 MB


  ***NOTE: MASSES DEFINED UNDER LOAD#       3 WILL FORM
           THE FINAL MASS MATRIX FOR DYNAMIC ANALYSIS.

 EIGEN METHOD   : SUBSPACE
 -------------------------
 NUMBER OF MODES REQUESTED             =    30
 NUMBER OF EXISTING MASSES IN THE MODEL =   588
 NUMBER OF MODES THAT WILL BE USED      =    30

   *** EIGENSOLUTION: SUBSPACE METHOD ***
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CALCULATED FREQUENCIES FOR LOAD CASE 3

MODE	FREQUENCY(CYCLES/SEC)	PERIOD(SEC)	ACCURACY
1	1.002	0.99757	1.791E-16
2	1.087	0.91971	3.045E-16
3	1.131	0.88455	0.000E+00
4	1.924	0.51977	1.945E-16
5	2.057	0.48620	0.000E+00
6	2.563	0.39020	0.000E+00
7	2.995	0.33385	1.123E-15
8	3.076	0.32512	1.522E-16
9	3.278	0.30510	4.021E-16
10	3.422	0.29221	0.000E+00
11	3.502	0.28557	3.523E-16
12	3.746	0.26696	0.000E+00
13	3.965	0.25220	1.832E-16
14	4.298	0.23267	1.559E-16
15	4.314	0.23183	3.095E-16
16	4.377	0.22845	2.855E-15
17	4.718	0.21193	6.467E-16
18	5.333	0.18750	2.025E-16
19	5.380	0.18588	3.184E-14
20	5.566	0.17968	1.485E-12
21	5.832	0.17146	1.673E-13
22	5.927	0.16873	6.675E-13
23	6.231	0.16048	2.258E-10
24	6.326	0.15808	2.140E-13
25	6.363	0.15717	3.709E-10
26	6.397	0.15632	1.115E-09
27	6.593	0.15167	1.207E-11
28	6.755	0.14804	7.586E-09
29	7.099	0.14086	4.489E-07
30	7.280	0.13736	1.205E-07

The following Frequencies are estimates that were calculated. These are for information only and will not be used. Remaining values are either above the cut off mode/freq values or are of low accuracy. To use these frequencies, rerun with a higher cutoff mode (or mode + freq) value.

CALCULATED FREQUENCIES FOR LOAD CASE 3

MODE	FREQUENCY(CYCLES/SEC)	PERIOD(SEC)	ACCURACY
31	7.770	0.12871	5.877E-10

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CALCULATED FREQUENCIES FOR LOAD CASE 3

MODE	FREQUENCY(CYCLES/SEC)	PERIOD(SEC)	ACCURACY
32	7.781	0.12851	2.835E-06
33	7.994	0.12510	3.314E-08

MODE	MODAL WEIGHT (MODAL MASS TIMES g) IN KN X	Y	Z	GENERALIZED WEIGHT
1	4.393456E+04	4.477788E-04	2.823909E-03	2.624881E+04
2	2.616651E-02	1.696310E-03	4.253945E+04	2.196378E+04
3	1.694206E+00	4.216307E-04	2.940022E+02	1.207898E+04
4	1.080277E-05	5.419254E-05	3.502036E+01	1.061509E+04
5	2.231742E-02	1.154544E-04	2.163288E-02	1.890521E+04
6	2.895323E-04	8.333211E-04	4.950516E-02	1.288106E+04
7	5.009322E-03	1.922264E-04	6.303897E-07	2.117603E+04
8	5.226242E+03	4.624638E-03	3.921081E-06	2.276884E+04
9	5.997593E-05	1.518010E-03	8.401051E+00	1.435068E+04
10	2.019594E-03	1.114409E-02	5.518197E+03	2.148180E+04
11	4.043703E-01	1.454398E-03	2.674286E+01	2.614605E+04
12	2.272588E-01	1.859533E-03	2.392859E-02	2.243453E+04
13	1.180115E-05	5.987275E-04	1.402657E+02	1.060579E+04
14	4.572139E+01	2.624980E-03	7.184260E-03	2.033325E+04
15	1.694784E-01	8.861174E-03	1.332095E+00	9.826257E+03
16	1.749756E-05	8.439970E-05	6.067123E-03	1.408948E+04
17	8.749197E-07	1.682885E-02	3.992391E+01	1.653278E+04
18	1.908484E+03	4.348200E-03	3.548795E-07	1.999455E+04
19	5.506569E-06	7.782125E-04	3.155777E-01	1.185981E+04
20	1.876481E-04	7.041190E-04	1.058043E-02	1.324976E+04
21	2.659550E-01	4.394354E-04	7.808603E-07	1.753161E+04
22	1.207666E+00	6.707230E-05	9.280289E-02	1.421897E+04
23	3.819683E-04	7.988295E-03	2.026691E+03	1.858921E+04
24	1.074773E+02	9.565444E-04	4.150215E-03	1.679893E+04
25	1.996438E-02	1.691186E-03	1.178653E+00	1.267786E+04
26	2.492584E-07	8.976651E-03	7.217180E+00	1.124337E+04
27	2.051554E-01	5.071978E-03	3.886647E-05	1.563781E+04
28	2.575671E-06	4.743532E-04	4.123751E+01	1.231606E+04
29	1.782793E-04	2.731431E-02	8.285352E+00	6.594661E+03
30	3.337866E-12	1.534310E-02	1.379742E+02	6.101120E+03

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MASS PARTICIPATION FACTORS

MASS PARTICIPATION FACTORS IN PERCENT

MODE	X	Y	Z	SUMM-X	SUMM-Y	SUMM-Z
1	82.45	0.00	0.00	82.448	0.000	0.000
2	0.00	0.00	79.83	82.448	0.000	79.830
3	0.00	0.00	0.55	82.451	0.000	80.381
4	0.00	0.00	0.07	82.451	0.000	80.447
5	0.00	0.00	0.00	82.451	0.000	80.447
6	0.00	0.00	0.00	82.451	0.000	80.447
7	0.00	0.00	0.00	82.451	0.000	80.447
8	9.81	0.00	0.00	92.258	0.000	80.447
9	0.00	0.00	0.02	92.258	0.000	80.463
10	0.00	0.00	10.36	92.258	0.000	90.818
11	0.00	0.00	0.05	92.259	0.000	90.869
12	0.00	0.00	0.00	92.260	0.000	90.869
13	0.00	0.00	0.26	92.260	0.000	91.132
14	0.09	0.00	0.00	92.345	0.000	91.132
15	0.00	0.00	0.00	92.346	0.000	91.134
16	0.00	0.00	0.00	92.346	0.000	91.134
17	0.00	0.00	0.07	92.346	0.000	91.209
18	3.58	0.00	0.00	95.927	0.000	91.209
19	0.00	0.00	0.00	95.927	0.000	91.210
20	0.00	0.00	0.00	95.927	0.000	91.210
21	0.00	0.00	0.00	95.928	0.000	91.210
22	0.00	0.00	0.00	95.930	0.000	91.210
23	0.00	0.00	3.80	95.930	0.000	95.013
24	0.20	0.00	0.00	96.132	0.000	95.013
25	0.00	0.00	0.00	96.132	0.000	95.016
26	0.00	0.00	0.01	96.132	0.000	95.029
27	0.00	0.00	0.00	96.132	0.000	95.029
28	0.00	0.00	0.08	96.132	0.000	95.106
29	0.00	0.00	0.02	96.132	0.000	95.122
30	0.00	0.00	0.26	96.132	0.000	95.381

A C T U A L MODAL D A M P I N G USED IN ANALYSIS

MODE	DAMPING
1	0.05000000
2	0.05000000
3	0.05000000
4	0.05000000
5	0.05000000
6	0.05000000
7	0.05000000
8	0.05000000
9	0.05000000
10	0.05000000
11	0.05000000
12	0.05000000
13	0.05000000

```
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 MODE       DAMPING

   17      0.05000000
   18      0.05000000
   19      0.05000000
   20      0.05000000
   21      0.05000000
   22      0.05000000
   23      0.05000000
   24      0.05000000
   25      0.05000000
   26      0.05000000
   27      0.05000000
   28      0.05000000
   29      0.05000000
   30      0.05000000

TIME STEP USED IN TIME HISTORY ANALYSIS = 0.00139 SECONDS
NUMBER OF MODES WHOSE CONTRIBUTION IS CONSIDERED =   30
TIME DURATION OF TIME HISTORY ANALYSIS =     69.994 SECONDS
NUMBER OF TIME STEPS IN THE SOLUTION PROCESS =    50396

242. PRINT STORY DRIFT


BASE SHEAR UNITS ARE -- KN   METE

MAXIMUM BASE SHEAR  X=   4.864331E+03  Y=  -1.576599E+00  Z=  -5.053513E+03
    AT TIMES             19.531944          15.454167          14.105556

STORY    DRIFT
```

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STORY	HEIGHT (METE)	LOAD	DRIFT(CM) X	DRIFT(CM) Z	ECCENTRICITY (METE)	RATIO
BASE=	0.00					
1	0.00	1	0.0000	0.0000	0.0000	L /999999
		2	0.0000	0.0000	0.0000	L /999999
		3	0.0000	0.0000	0.0000	L /999999
2	3.00	1	0.0001	0.0002	0.0000	L /999999
		2	-0.0000	-0.0000	0.0000	L /999999
		3	-0.4834	0.3603	0.0000	L / 620
3	6.00	1	0.0005	0.0007	0.0000	L /999999
		2	-0.0000	-0.0000	0.0000	L /999999
		3	-1.1806	0.9485	0.0000	L / 508
4	9.00	1	0.0010	0.0016	0.0000	L /571652
		2	-0.0000	-0.0000	0.0000	L /999999
		3	-1.8316	1.5212	0.0000	L / 491
5	12.00	1	0.0016	0.0026	0.0000	L /454889
		2	-0.0000	-0.0000	0.0000	L /999999
		3	-2.3811	2.0100	0.0000	L / 504
6	15.00	1	0.0024	0.0039	0.0000	L /388280
		2	-0.0000	-0.0000	0.0000	L /999999

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 STAAD SPACE                                            -- PAGE NO.   12

                   3      2.8193      2.3958       0.0000       L /   532

  7      18.00     1      0.0033      0.0052       0.0000       L /347159
                   2     -0.0000     -0.0000       0.0000       L /999999
                   3      3.1291      2.6733       0.0000       L /   575

  8      21.00     1      0.0042      0.0065       0.0000       L /324632
                   2     -0.0000     -0.0000       0.0000       L /999999
                   3      3.2961      2.8461       0.0000       L /   637
243. FINISH

          *********** END OF THE STAAD.Pro RUN ***********

            **** DATE= APR  2,2020   TIME= 19:13: 3 ****
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STAAD SPACE                                              -- PAGE NO.   13

     ************************************************************
     *   For technical assistance on STAAD.Pro, please visit    *
     *   http://www.bentley.com/en/support/                     *
     *                                                          *
     *   Details about additional assistance from               *
     *   Bentley and Partners can be found at program menu      *
     *   Help->Technical Support                                *
     *                                                          *
     *      Copyright (c) 1997-2017 Bentley Systems, Inc.       *
     *                http://www.bentley.com                    *
     ************************************************************
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APPENDIX B

MAXIMUM ROOF DISPLACEMENT UNDER AS-RECORDED AND MD GROUND MOTIONS

The numerical values of the maximum response (lateral displacement) and response (lateral displacement) in the as-recorded orientation of ground motions at center of mass of roof level for all four building models is shown here. Chapter 4 describes these values as Maximum direction and as-recorded. All values are in centimeters.

Table 2. Maximum roof displacement under as-recorded and MD ground motions.

GM No.	(BM1)				(BM2)			
	X		Z		X		Z	
	As-recorded	Maximum Direction	As-recorded	Maximum Direction	As-recorded	Maximum Direction	As-recorded	Maximum Direction
1	0.0637	0.1538	0.1347	0.1544	0.1109	0.1406	0.0235	0.1487
2	0.1275	0.149	0.0025	0.1326	0.092	0.1513	0.1471	0.1544
3	0.0923	0.1326	0.1118	0.1286	0.1067	0.1225	0.0264	0.1379
4	0.0069	0.0291	0.0179	0.0315	0.039	0.0469	0.0217	0.0473
5	0.0554	0.2205	0.1119	0.1946	0.1612	0.1967	0.1966	0.2048
6	0.1816	0.2844	0.2331	0.2589	0.1764	0.2325	0.2241	0.236
7	0.0629	0.3113	0.1084	0.3072	0.272	0.298	0.1978	0.322
8	0.0565	0.0573	0.0332	0.0577	0.0619	0.0624	0.0178	0.0647
9	0.2313	0.3723	0.2558	0.3438	0.2933	0.4442	0.0791	0.4885
10	0.2096	0.217	0.1111	0.1932	0.1505	0.1563	0.0117	0.1613
11	0.0557	0.1554	0.0986	0.1326	0.1012	0.125	0.0943	0.1434
12	0.053	0.0901	0.0403	0.083	0.0466	0.0729	0.0779	0.078
13	0.0679	0.0686	0.0403	0.0714	0.0644	0.0645	0.032	0.0654
14	0.1624	0.1654	0.1337	0.1692	0.1787	0.1799	0.0893	0.1829
15	0.149	0.7459	0.5899	0.6974	0.196	0.7231	0.1911	0.7429
16	0.2653	0.286	0.2576	0.2773	0.2755	0.3305	0.2459	0.3351
17	0.0614	0.1321	0.1256	0.1262	0.0343	0.1366	0.1387	0.1394
18	0.0342	0.0357	0.0298	0.037	0.006	0.0386	0.454	0.0462
19	0.0104	0.0741	0.0216	0.0693	0.0534	0.0772	0.0721	0.0721
20	0.0907	0.0941	0.0401	0.1064	0.0736	0.0958	0.0535	0.1007
21	0.0595	0.627	0.0442	0.061	0.0582	0.0614	0.0403	0.0628
22	0.2083	0.2093	0.1062	0.1959	0.1776	0.1924	0.1122	0.1946
23	0.019	0.0196	0.0135	0.0178	0.0027	0.0135	0.0007	0.0138
24	0.1506	0.1635	0.1479	0.1484	0.1486	0.1508	0.1349	0.1508
25	0.0874	0.1287	0.0722	0.1269	0.0366	0.112	0.1117	0.115

Table 2. Maximum roof displacement under as-recorded and MD ground motions. (continued)

GM No.	(BM3)				(BM4)			
	X		Z		X		Z	
	As-recorded	Maximum Direction	As-recorded	Maximum Direction	As-recorded	Maximum Direction	As-recorded	Maximum Direction
1	0.9632	1.3147	1.1028	1.2194	0.9536	1.2975	1.2769	1.3095
2	3.2269	3.7369	3.5245	3.8429	0.5606	3.6857	3.7287	3.7287
3	3.2858	3.7354	2.8137	2.8957	2.1976	3.707	3.7075	3.7413
4	0.2625	0.3292	0.3592	0.3592	0.1916	0.3254	0.1086	0.3284
5	0.3539	0.948	0.928	0.98	0.27	0.9571	0.9118	0.9569
6	0.9845	1.1507	0.8934	1.209	0.4229	1.1269	0.9119	1.1583
7	1.5874	1.5874	1.3717	1.3717	1.5366	1.5366	1.0733	1.556
8	0.8291	0.8973	0.7789	0.7789	0.8159	0.8793	0.5303	0.8961
9	0.2526	0.9022	0.9261	0.9265	0.2377	0.8154	0.8064	0.8202
10	4.1036	4.3656	3.5084	5.0648	2.7934	4.188	4.0028	4.313
11	1.9338	2.4013	1.1187	2.1334	0.5301	1.8371	1.3685	2.3819
12	1.2942	2.0457	1.2396	1.5656	1.225	2.0078	2.0375	2.0659
13	0.6986	1.054	1.043	1.0448	0.6865	0.912	0.7419	1.0153
14	3.3377	6.9696	5.0619	5.48	3.1679	6.9331	6.9483	6.9995
15	14.0468	15.6969	14.5335	17.9831	5.662	15.2505	13.101	15.6833
16	14.4732	15.1693	6.2151	9.1014	14.5226	15.1213	6.1107	15.3672
17	0.4081	0.7185	0.6466	0.8201	0.4169	0.6118	0.5795	0.6989
18	0.1718	0.2699	0.2669	0.268	0.1756	0.2564	0.1917	0.2617
19	1.2066	1.482	0.7749	1.1164	1.0145	1.4986	0.2914	1.5051
20	0.8137	0.816	0.2793	0.7445	0.8232	0.8279	0.6759	0.8297
21	3.2176	3.6043	1.9862	3.0391	3.1901	3.5829	2.2036	3.5985
22	8.5132	8.6029	3.5529	9.0019	8.6731	8.7443	3.929	8.6232
23	0.6546	0.6798	0.3708	0.5948	0.6311	0.6516	0.3513	0.6697
24	2.7445	2.7609	1.711	2.2941	2.7373	2.7495	1.91	2.8017
25	1.2139	1.8323	0.1754	1.4035	0.6484	1.8373	1.8739	1.8936

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Osmania University
Bachelor of Engineering, Civil Engineering, May 2015

Thesis Paper Title:

EFFECT OF BUILDING ORIENTATION ON STRUCTURAL RESPONSE OF REINFORCED CONCRETE MOMENT RESISTING FRAME STRUCTURES

Major Professor: Dr. Jale Tezcan