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ON THE VARIATION OF MAXIMUM ISOLATOR DISPLACEMENTS DUE TO GROUND MOTION DIRECTIONALITY

GÖKHAN ÖZDEMİR, BURAK ERŞEKER, and ÖZGÜR AVŞAR

Civil Engineering Dept, Anadolu University, Eskişehir, Turkey

In most of the cases, code specifications dictate the use of nonlinear response history analyses (NRHA) to estimate maximum isolator displacements (MIDs) of a seismically isolated structure (SIS). For this purpose, a set of ground motion records with similar characteristics needs to be selected. Then, the structure is analyzed bidirectionally by considering both orthogonal horizontal components of these records. However, there is not any provision regarding the ground motion directionality effect in the codes but simply use of as-recorded motions is encouraged. This study investigates the effect of ground motion directionality on variation of MIDs in case of bidirectional NRHA. Thus, a typical SIS, where the isolator units are composed of lead rubber bearings (LRBs), is subjected to ground motions rotated from their as-recorded original form by increments of 10^{o} up to 360^{o}. Here, LRBs are modelled by a deteriorating hysteretic representation in which the strength of the isolator reduces gradually due to the applied loading. In the analyses, first, the original as-recorded ground motion is applied to the SIS and the corresponding MID is noted. Then, the same structure is subjected to rotated versions of the same motion and again the MIDs are noted. To quantify the variation in the isolator displacement, analytically obtained MIDs are compared. Results showed that there is an amplification in MIDs due to change in ground motion direction.

Keywords: Incidence angle, Seismic isolation, Bidirectional analysis, Lead rubber bearing, Isolator displacement, Hysteretic deterioration.

1 INTRODUCTION

Maximum isolator displacement (MID) is one of the primary concerns during the design stage of a seismically isolated structure (SIS). Hence, estimation of MIDs is of crucial importance for design. Code specifications establish three methods to be used in estimating the MID of a SIS (ASCE 2010). These methods are Equivalent Lateral Force Procedure, Response Spectrum Procedure and Response History Procedure. Among these procedures, Response History Procedure is assumed to provide the so called “exact” solution and defined as the procedure that has to be followed in most of the cases. It assures the use of nonlinear force-deformation relation of isolators obtained from test results in analytical representation of isolators. In the analyses, the structural form composed of superstructure and isolation system shall be subjected to a set of ground motion records selected to represent the scenario earthquake.

Furthermore, in these analyses, the orthogonal horizontal components of the selected ground motions shall act simultaneously by means of bidirectional simulations.

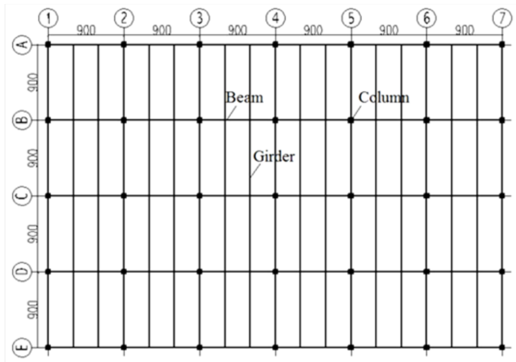
According to current code specifications, bidirectional Nonlinear Response History Analyses (NRHA) of SISs are performed using either as-recorded or synthetic ground motion records. There is not any code provision regarding the ground motion directionality effect in the simulations. However, there are several studies that have discussed the effect of ground motion directionality on the structural response (Ghersi and Rossi 2001, Athanatopoulou 2005, Rigato and Medina 2007, Moschonas and Kappos 2013, Kalkan and Reyes 2015). Research outcomes of studies mentioned here revealed that variation in ground motion direction result in amplification in structural response quantities. Furthermore, it has been stated that the critical incidence angle differentiates highly depending on the response quantity. However, all of these studies employed fixed-base structures rather than SISs. The study presented herein aims to quantify the amount of variation in MID of a typical SIS when subjected to bidirectional ground motion excitations with different incidence angles. For this purpose, bidirectional NRHA were conducted with ground motion records rotated from their as-recorded original forms by increments of 10^o up to 360^o. The isolation system of the investigated structure is composed of lead rubber bearings (LRBs). The nonlinear hysteretic behavior of LRBs is represented by a deteriorating force-deformation relation proposed by Kalpakidis and Constantinou (2009). Thus, reduction in the strength of LRBs under cyclic motion is properly considered in the analyses.

2 STRUCTURAL MODEL

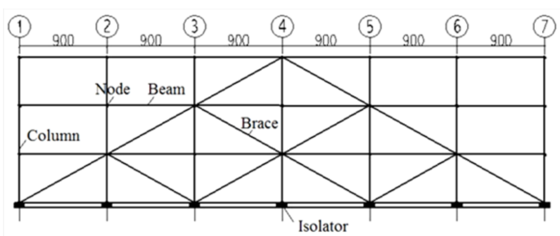
The analyzed structure is selected to be representative of a typical SIS. Accordingly, the hypothetical emergency operation center designed for National Earthquake Hazards Reduction Program (NEHRP 2006) is considered as the superstructure. The isolation system is redesigned such that all isolator units are composed of LRBs. It is a 3-story seismic isolated steel frame structure. The height of the building is 9m (each story height is 3m) with plan dimensions of 36mx54m. Span lengths in short and long directions are identical and equal to 9m. The structure is symmetric in both plan and elevation. Weight of the superstructure is 73000 kN. Figure 1 presents the geometrical features of the analyzed SIS.

3 MODELING OF LEAD RUBBER BEARINGS

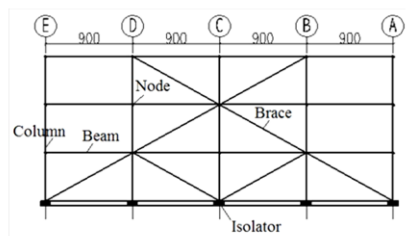
For SISs where the only nonlinearity takes place at the isolation level, modeling of nonlinear hysteretic behavior of isolator units is crucial. Experimental studies revealed that any LRB subjected to cyclic motion undergoes a deterioration in its force-deformation relation. The main reason for such deterioration is found to be the temperature rise in the lead core of LRB. On the other hand, existing design approaches refer to non-deteriorating hysteretic representations rather than the actual deteriorating one. This is basically due to the lack of ability to model the actual behavior of LRBs. Such a modeling approach aims to define envelopes for response quantities of LRBs instead of simulating the actual response. In this study, the deteriorating hysteretic behavior of LRBs is employed in the analyses. For this purpose, a coupled material model that is capable of incorporating the effect of lead core heating on the hysteretic behavior of LRBs is used in NRHA. Coupled solution is also vital because, NRHA are performed bidirectionally.



(a) Plan view



(b) Side view for B and D axes



(c) Side view for 2 and 6 axes

Figure 1. Properties of the analyzed seismically isolated structure (all units are in cm).

Effect of lead core heating on hysteretic behavior of LRBs is taken into account by means of Eq. (1)-(4) where, h_L, a, ρ_L, c_L and σ_{YL0} are the height, radius, density, specific heat and initial yield stress of the lead core, respectively; t_s is the total shim plate thickness, α_s is the thermal diffusivity of steel, k_s is the thermal conductivity of steel, t^+ is the dimensionless time, t is the time since the beginning of the motion, and E_2 is a constant that relates the temperature and yield stress. In Eq. (1), Z_x and Z_y are the hysteretic dimensionless quantities that varies between ±1, $\mathring{U}_x$ and $\mathring{U}_y$ are the relative velocities of the bearing. Once definition of hysteretic behavior of LRBs is established, the coupled solution of the isolator forces in both orthogonal horizontal directions is based on equations proposed by Park *et al.* (1986). Due to space limitations, related set of equations are not presented here.

Employed LRBs are selected so that they are representative of typical characteristics of SISs. Accordingly, characteristic strength to weight ratio (Q/W) of the analyzed LRB is 0.10 and the isolation period is 2.5s. Height of the isolator (h_L) is 290mm whereas the radius (a) and the total shim plate thickness (t_s) are 83.5mm and 84 mm, respectively.

$$\sigma_{YL}(T_L) = \sigma_{YL0} \cdot \exp(-E_2 T_L) \tag{1}$$

$$\dot{T}_L = \frac{\sigma_{YL}(T_L)\cdot\sqrt{Z_x^2+Z_y^2}\sqrt{\dot{U}_x^2+\dot{U}_y^2}}{\rho_L c_L h_L} - \frac{k_S \cdot T_L}{a\rho_L c_L h_L}\cdot\left(\frac{1}{F}+1.274\cdot\left(\frac{t_s}{a}\right)\cdot\left(t^+\right)^{-1/3}\right) \quad (2)$$

$$F = \begin{cases} 2\cdot\left(\frac{\tau}{\pi}\right)^{1/2} - \frac{\tau}{\pi}\cdot\left[2-\left(\frac{\tau}{4}\right)-\left(\frac{\tau}{4}\right)^2-\frac{15}{4}\left(\frac{\tau}{4}\right)^3\right], & \tau < 0.6 \\ \frac{8}{3\pi}-\frac{1}{2(\pi\cdot\tau)^{1/2}}\cdot\left[1-\frac{1}{3\cdot(4\tau)}+\frac{1}{6\cdot(4\tau)^2}-\frac{1}{12\cdot(4\tau)^3}\right], & \tau \geq 0.6 \end{cases} \quad (3)$$

$$\tau = \frac{\alpha_S t}{a^2} \quad (4)$$

4 GROUND MOTION RECORDS

Ground motions used in this study have very similar characteristics in terms of Magnitude (M_w), closest distance to fault rupture (R), and soil classification. Average shear wave velocities of the selected ground motions at the upper most 30 m soil profile are ranging from 180 m/s to 360 m/s (soil class D per NEHRP). Peak Ground Velocity (PGV) values of selected ground motions are also very close to each other. Avsar and Ozdemir (2013) showed that there is a high correlation between PGV and MIDs. That correlation is also not sensitive to any change in isolator characteristics. Table 1 presents the characteristics of selected ground motions. In Table 1, PGA and PGD stand for peak ground acceleration and peak ground displacement.

Table 1. Ground motion characteristics.

#	Earthquake	Station	M_w	R (km)	Component	PGA (g)	PGV (cm/s)	PGD (cm)
1	Imperial Valley	Brawley Airport	6.5	10.4	315	0.22	38.9	13.6
					225	0.16	35.8	22.3
2	Imperial Valley	El Centro Array #10	6.5	6.2	050	0.17	47.5	31.1
					320	0.22	41.2	18.0
3	Northridge	Canyon Country W	6.7	12.4	270	0.48	44.9	12.6
					000	0.41	43.0	11.8

Figure 2 shows the response spectra of the ground motions listed in Table 1. In Figure 2, orthogonal horizontal components of ground motions are identified as “strong” and “weak” according to their PGVs. The component with higher PGV is named as “strong” component. In order to mimic different incidence angles, as-recorded forms of selected records are rotated through 360^o with increments of 10^o. This is achieved by Eq. (5) where $a_x(t)$ and $a_y(t)$ are the rotated forms of original motions $a_1(t)$ and $a_2(t)$.

$$\begin{Bmatrix} a_x(t) \\ a_y(t) \end{Bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \cdot \begin{Bmatrix} a_1(t) \\ a_2(t) \end{Bmatrix} \quad (5)$$

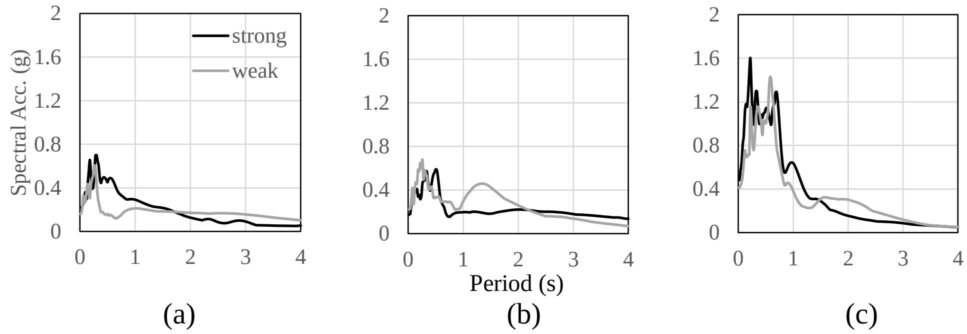


Figure 2. Response spectra for (a) EQ #1 (b) EQ #2 (c) EQ #3.

5 ANALYSES RESULTS

To identify the amount of amplification in MID of a SIS due to variation in incidence angle of ground motion records, as-recorded and the rotated versions of selected motions are subjected to model structure. Thus, a total of 108 NRHA have been performed and the corresponding MIDs were noted. MIDs obtained from analyses in which as-recorded motions were used, are called as MID_O. On the other hand, MIDs obtained from analyses conducted with rotated versions of original records are represented by MID_R. Figure 3 depicts the variation of MID_R's as a function of incidence angle. Corresponding MID_R/MID_O ratios are presented in Figure 4.

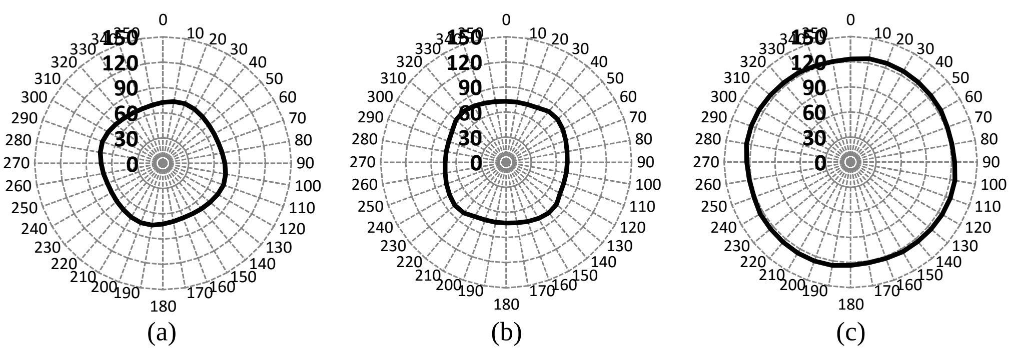


Figure 3. MID_R versus incidence angles for (a) EQ #1 (b) EQ #2 (c) EQ #3.

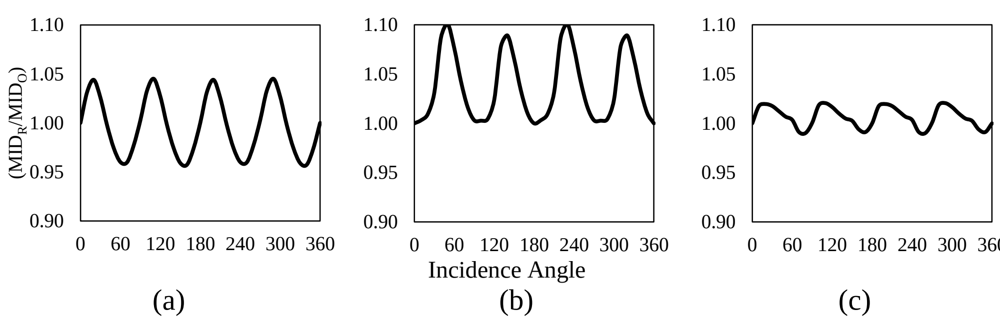


Figure 4. MID_R/MID_O ratios versus incidence angles for (a) EQ #1 (b) EQ #2 (c) EQ #3.

As can be seen from Figure 4, the amount of amplification in MIDs due to change in incidence angle is not constant and dependent of the ground motion characteristics. Specifically, for the selected ground motion records, calculated maximum amplifications are 5%, 10% and 3% for EQ #1, EQ #2 and EQ #3, respectively.

6 CONCLUSIONS

This study focused on the amplification in MIDs of a typical SIS due to variation in incidence angle of ground motions. For this purpose, bidirectional NRHA were conducted by considering both orthogonal horizontal components of ground motion records. Isolation units of the analyzed structure was composed of LRBs. Nonlinear hysteretic representation of LRBs were achieved by a deteriorating force-deformation relation. Hence, the gradual reduction in strength of LRBs under cyclic motion was taken into consideration. Analyses results showed that the amount of amplification in MIDs is not constant and depends on the ground motion characteristics.

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