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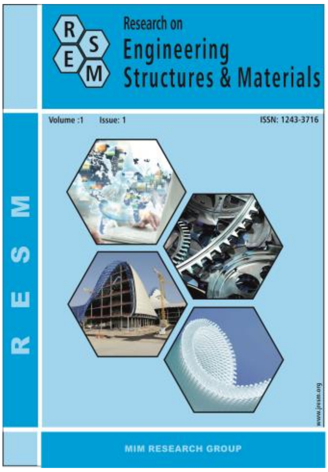

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Research Article

Response of an isolated structure with deteriorating hysteretic isolator model

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Abstract

Cyclic motion of lead rubber bearings (LRBs) leads to increasing temperature in lead core initiating the reduction in strength of LRB. This reduction results in a deteriorating bi-linear force deformation relation for LRB. In this study, response of LRBs (with deteriorating hysteresis loops due to temperature change) subjected to near-field ground motions with distinct pulse-type behavior is studied. Ground motions are applied bi-directionally and LRBs are modeled with due consideration of coupled behavior in the two orthogonal horizontal directions. Response of LRBs with deteriorating hysteresis is compared with that of non-deteriorating ones by considering bounding analyses (upper and lower bound). Thus, nonlinear response history analyses are performed for each selected ground motion record. Bounding analyses result in over predicted displacement demands for LRBs compared to results obtained by implemented deteriorating bi-linear LRB model. By means of new deteriorating model, engineers may come up with more efficient isolation system designs.

1. Introduction

As being a well-established technology now, seismic isolation has been used in many structures where isolation systems are mainly composed of two systems i.e. elastomeric bearings and sliding bearings. As an elastomeric bearing, lead rubber bearing (LRB) is the most widely used isolator type in those systems. LRBs are constructed by bonding alternate layers of rubber and steel with a center hole in which a lead core is plugged [1]. Inserted lead core improves the behavior of bearing by providing additional energy dissipation and increasing vertical load carrying capacity.

The idealized bi-linear force-deformation relations used to define hysteretic behavior of LRBs consist of two parameters: (i) post-yield stiffness and (ii) characteristic strength that is defined as the force intersect at zero displacement. Former primarily corresponds to mechanical properties of rubber whereas latter stands for the mechanical properties of lead. Experimental studies revealed that both characteristic strength and energy dissipation capacity (EDC) of LRBs reduce with increasing number of cycles [2]. That reduction emerges from reduced yield stress of lead due to temperature increase under cyclic motion [3].

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Two companion papers have been published to describe [3] and verify [4] a mathematical method to predict the reduction in both characteristic strength and EDC under cyclic motion. Proposed model is a function of displacement history of LRB and capable of updating the effective yield stress of lead due to increased temperature, instantly. Updated effective yield stress is then used to calculate the resisting force at any time instant. The interested reader is referred to related studies for further details.

The study presented herein investigates the response of an isolation system (composed of LRBs mounted under a 3-story steel frame) subjected to bi-directional excitations of near-field records with distinct pulse type behavior, in terms of maximum isolator displacements. Hence, a set of nonlinear response history analyses (NRHA) are conducted with both deteriorating and non-deteriorating idealized hysteresis for LRBs. NRHA are performed with carefully selected and scaled ground motion records compatible with the chosen target spectrum.

2. Selection and Scaling of Ground Motions

Eleven ground motion records were selected from well-known and extensively studied seismic events occurred in United States, Turkey, and Taiwan. Those records have clear pulses in their velocity traces as an indicator of the near-field characteristics. Magnitude M_w of the records are in between 6 and 7.6 and closest distance d of the records to fault rupture is less than 20 km. The average shear wave velocities of the ground motions at the upper most 30 m soil deposit are in the range of 180 m/sec and 360m/sec., and classified as soil type D as per NEHRP. Properties of the near-field records used in this study are given in Table 1 including peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD) values.

Scaling of the selected records were performed in two complimentary steps. The procedure followed in the first step was also utilized in Ozdemir and Constantinou [5] and seeks to minimize a sum (ε) of the weighted squared errors between the geometric mean of the two horizontal components and the target spectral values at a set of periods. Error ε is defined as:

$$\varepsilon = \sum_{i=1}^{n} b_i \left(a.\, y_i - y_{T_i}\right)^2 \qquad (1)$$

where b_i is the weighting factor for the squared error at period T_i; a is the scaling factor for the pair of ground motions of interest; y_i is the geometric mean of the spectral ordinates for the pair at period T_i; y_{Ti} is the target spectral ordinate at period T_i; and n is the number of target spectral values considered. The scaling factor (a) that results in the minimum value of ε is calculated by setting the derivative of Eqn. (1) equal to zero as given in Eqn. (2).

$$a = \frac{\sum_{i=1}^{n} b_i . y_i . y_{T_i}}{\sum_{i=1}^{n} b_i . {y_i}^2} \qquad (2)$$

This scaling was based on five target periods (T_i): 1, 2, 3, 4, and 5 sec. The weighting of factors was determined such that the scaled spectra have the most compatible shape with that of the target spectrum under consideration. To achieve this goal, a series of combinations of weight factors were tested and best combination was chosen. As a result, weight factors for the periods of concern were selected to be 0.1, 0.1, 0.2, 0.3, and 0.3, respectively. These weight factors are same for all of the ground motion records considered.

Table 1 Properties of near-field records considered in this study

Earthquake	Station	Magnitude (M_w)	*d* (km)	Component	PGA (g)	PGV (cm/sec)	PGD (cm)
Chi Chi (CC101)	TCU101	7.6	2.1	N	0.25	49.4	35.1
				W	0.20	67.9	75.4
Erzincan (EE)	Erzincan	6.7	4.4	NS	0.52	83.9	27.4
				EW	0.50	64.3	22.8
Imperial Valley (IVA4)	Array 4	6.5	7.1	140	0.49	37.4	20.2
				230	0.36	76.6	59.0
Imperial Valley (IVA5)	Array 5	6.5	4.0	140	0.52	46.9	35.4
				230	0.38	90.5	63.0
Imperial ValleY (IVA6)	Array 6	6.5	1.4	140	0.41	64.9	27.7
				230	0.44	109.8	65.9
Imperial ValleY (IVA10)	Array 10	6.5	6.2	50	0.17	47.5	31.1
				320	0.22	41.0	19.4
Kocaeli (KD)	Duzce	7.5	15.4	180	0.31	58.8	44.1
				270	0.36	46.4	17.6
Kocaeli (KY)	Yarimca	7.5	4.8	60	0.27	65.7	57.0
				330	0.35	62.1	51.0
Loma Prieta (LPCor)	Corralitos	6.9	3.9	0	0.64	55.2	10.9
				90	0.48	45.2	11.4
Loma Prieta (LPSar)	Saratoga	6.9	8.5	0	0.51	41.2	16.2
				90	0.32	42.6	27.5
Parkfield (PC)	Cholame2	6.0	14.3	90	0.60	63.3	14.1
				360	0.37	44.1	8.9

In the second step of scaling, records were further scaled so that for each period between $0.5T_D$ and $1.25T_M$, the average of square-root-of-sum-of-squares (SRSS) spectra from all ground motion pairs does not fall below 1.3 times the corresponding ordinate of the target response spectrum by more than 10%.

Target response spectrum considered in this study was taken from the Turkish Earthquake Code (TEC) [6] for the corresponding soil class and presented in Fig. 1 together with scaled average SRSS of the considered records. Here, T_D and T_M are the effective periods of the isolated structure for design earthquake (DE) and maximum considered earthquake (MCE), respectively and calculated as follows:

$$T_D = 2\pi\sqrt{\frac{W}{k_D g}} \qquad T_M = 2\pi\sqrt{\frac{W}{k_M g}} \tag{3}$$

where W is the weight acting on the isolator; k_D and k_M are the effective stiffnesses at design and maximum displacements, respectively.

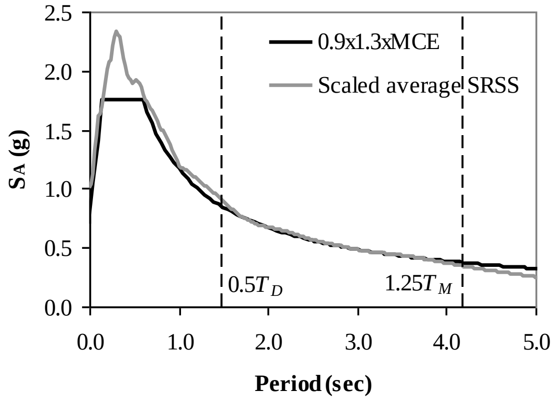

Fig. 1 Scaled average SRSS spectrum of near-field records and target spectrum.

The procedure followed in scaling of records is of utmost importance for near-field records to preserve the difference between the orthogonal horizontal components [7, 8]. Especially, when bi-directional excitations are of concern where both horizontal components are applied simultaneously. It is believed that the employed scaling method is appropriate for use in bi-directional analyses.

Scale factors used for each ground motion records are given in Table 2.2. Maximum value of scale factor used in this study is 2.70. Although Hancock et al. [9] stated that it is ok up to 10, scale factors are all smaller than the normally accepted upper limit of 4 for not to introduce any bias into the results [8, 10].

Table 2 Scale factors used in this study

	Ground Motions										
	CC101	EE	IVA4	IVA5	IVA6	IVA10	KD	KY	LPCor	LPSar	P
Scale	2.43	1.24	1.75	1.48	1.24	2.70	1.74	1.39	2.20	2.41	1

3. Modeling of Superstructure

A 3-story steel superstructure was considered as shown in Fig. 2. It has 6 bays in longitudinal and 4 bays in transverse directions. The size of the bays in both longitudinal and transverse directions is 9 m each. Hence, dimensions of the floor plan are 36mx54m. The height of all floors is 3 m. There are 35 columns, 30 primary beams, and 76 secondary beams in each floor. All of the secondary beams are in the transverse direction. Total weight of the superstructure is 73000 kN. Weight of the floor at roof level is taken as 75% of the other floors and weight at the isolation level is assumed to be equal with the first and second floor weights.

Superstructure was modeled as elastic and it was assumed that all beam-column joints are fully rigid. Modulus of elasticity and Poisson ratio of steel are 200 GPa and 0.3, respectively. Floor masses were equally distributed to joints at each floor level and rigid diaphragms were assigned to joints in the same floor. Having a symmetric superstructure, any eccentric response is not addressed.

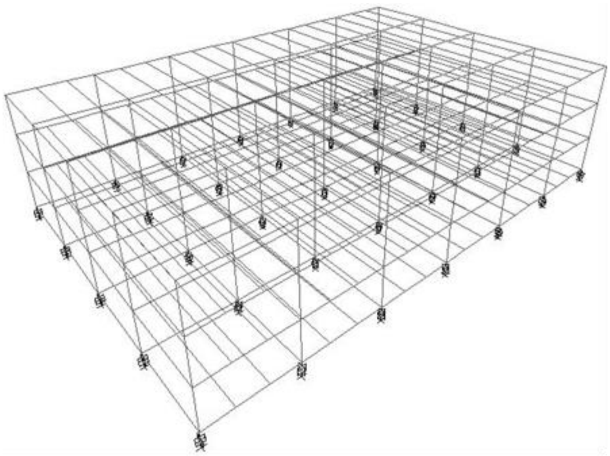

Fig. 2 3-D view of isolated steel structure.

4. Modeling of Isolators

There are basically three parameters used to construct the idealized force-deformation relation of LRBs as shown in Fig. 3: (i) post yield stiffness k_d; (ii) characteristic strength Q; (iii) yield displacement D_y. Post-yield stiffness primarily depends on the rubber characteristics and calculated by Eqn. (4) where T is the isolation period. On the other hand, characteristic strength depends on properties of lead and calculated by Eqn. (5) where σ_l and a are effective yield stress and radius of lead, respectively. It is stated that yield displacement has no significant effect on behavior of isolators [11] and it was chosen as 10 mm which is reported to be an appropriate value for LRBs [12].

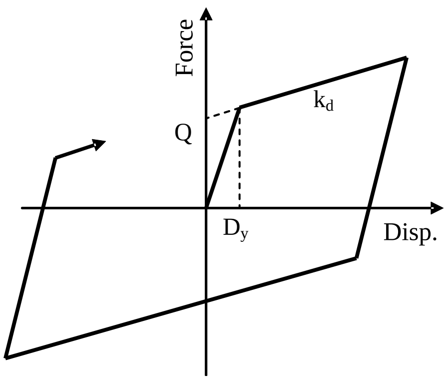

Fig. 3 Idealized force-deformation relation of LRBs.

$$T = 2\pi\sqrt{\frac{W}{k_d g}} \tag{4}$$

$$Q = \sigma_l a^2 \pi \tag{5}$$

The conventional design of LRBs consists of an iterative method to predict the maximum isolator displacement and corresponding effective damping ratio. The iteration starts with the assumptions made for isolation period, Q/W ratio and displacement. Once the assumed and iterated values are close enough, the idealized hysteresis loop for a LRB is settled. That loop does not change during the analysis and there cannot be any reduction in the EDC capacity which is equal to total area under the hysteresis loops. However, tests conducted with LRBs subjected to cyclic motion revealed that both characteristic strength and EDC reduce gradually with displacement. That variation is tried to be covered by performing bounding (upper and lower bound) analyses. Upper bound analysis is based on the effective yield stress of lead in the first cycle and used to estimate the maximum shear force (MSF) carried by LRB. On the other hand, lower bound analysis is based on the effective yield stress which is calculated by taking the average value obtained in the first three cycles and used to estimate maximum isolator displacements (MIDs). Relation between the effective yield stresses considered in upper (σ_{up}) and lower (σ_{low}) bound analyses is stated as $\sigma_{up} = 1.35\sigma_{low}$ [2].

The gradual reduction of strength and EDC is recently modeled by Kalpakidis and Constantinou [3] and implemented by Ozdemir [13] in a freeware structural analysis program namely, Open System for Earthquake Engineering Simulation [14]. According to the study of Kalpakidis and Constantinou [3] main reason of reduction in both strength and EDC is the temperature increase in lead due to cyclic motion. Hence, the effective yield stress is updated at each time step as a function of temperature rise and resisting force of LRB is calculated accordingly. That model depends on geometrical properties of LRB which is not considered in conventional analysis. Table 3.1 presents the properties of the considered LRB for all of the upper, lower, and proposed cases. In this study, the isolation period T of the considered system is 3.0 sec. and σ_{low} was chosen as 10 MPa.

Table 3 Properties of LRB considered in this study.

	Proposed	**Upper Bound**	**Lower Bound**
Effective yield stress	13.5 MPa	13.5 MPa	10.0 MPa
Q/W ratio	0.14	0.14	0.10
Total thickness of steel layers	87 mm	NA	NA
Radius of lead core	82.5 mm	NA	NA
Bonded rubber radius	711 mm	NA	NA
Height of lead core	341 mm	NA	NA
Yield force	299.4 kN	299.4 kN	223.2 kN
Yield displacement	10 mm	10 mm	10 mm
Post-yield stiffness	930 kN/m	930 kN/m	930 kN/m
Post-yield to elastic stiffness ratio	0.031	0.031	0.041

In Table 3.1, NA was used for the properties which are not considered during the analysis of the corresponding cases. With the given properties, thirty five LRBs were located under every column of the superstructure (Fig. 2). Isolators were connected to superstructure by means of *ZeroLength* elements in OpenSees with due consideration of coupled hysteretic behavior in the orthogonal horizontal directions. Coupled behavior of isolators implemented in OpenSees was tested and verified in Ozdemir [13] and based on the equations derived by Park et al. [15].

5. Analyses Conducted

To compare the response of LRBs (in terms of MSF and MID) obtained from bounding analysis and from analysis where proposed model is used, a set of nonlinear response history analyses (NRHA) were conducted. Considered 3-story isolated steel frame was subjected to bi-directional excitations of selected near-field records as shown in Fig. 4. Since, both the superstructure and isolation system are symmetric, response of isolated structure are the same for loadings shown in Fig. 4a and 4b. Hence, only one of those loadings is considered.

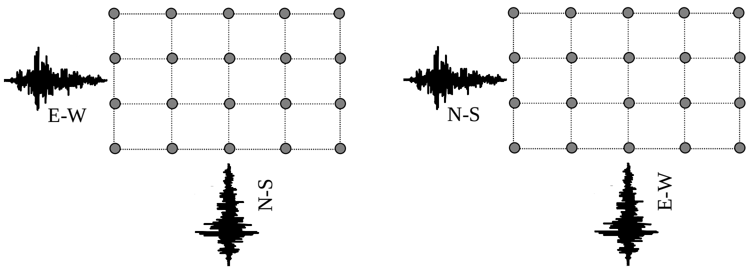

Fig. 4 Application of bi-directional ground motion excitations

6. Analyses Results

33 NRHA were conducted (11 for each cases – upper bound, lower bound, proposed method) in OpenSees. MSF and MID obtained from analyses considering proposed model are compared with those of upper and lower bound analyses, respectively. Comparisons are done for the average of response values under consideration obtained for all of the 11 ground motions (Table 5.1). MIDs are the maximum of the SRSS of displacements obtained in the two orthogonal horizontal directions at each time step. On the other hand, MSFs are simply equal to maximum value obtained in any of the horizontal directions. Comparison of MSFs is presented in terms of normalized base shears where normalization is done by dividing the MSFs with the weight of the superstructure.

In Table 4, it is clear that the average of normalized MSFs obtained from upper bound analysis and the proposed model are identical. On the other hand, average of MIDs obtained from lower bound analysis is higher (about 13%) than that of the proposed model. It is because, the effective yield stress of lead considered in lower bound analysis is based on the average of first three cycles. This assumption may be valid when there is a high seismicity with at least three cycles of large amplitude motion but, when the motion have smaller number of cycles as in the case of near-field motions with high velocity pulses, lower bound analysis result in conservative estimation of MIDs.

Due to space limitation, Fig. 5 shows hysteresis loops obtained from NRHA under excitations of only IVA4 and LPSar records for all of the three cases. Presented force-deformation histories correspond to "*dominant*" direction defined as the direction where isolator displacement is higher than the other orthogonal one. As it is seen in Fig.5, with the initiation of motion, proposed model first follows almost the same path with that of upper bound analysis, but then coincides with the path corresponding to lower bound analysis.

Table 4 Average of the results obtained from NRHA performed for all of the cases considered.

MID (cm)		MSF/*W*	
Lower Bound	Proposed	Upper	Proposed
53	47	0.29	0.29

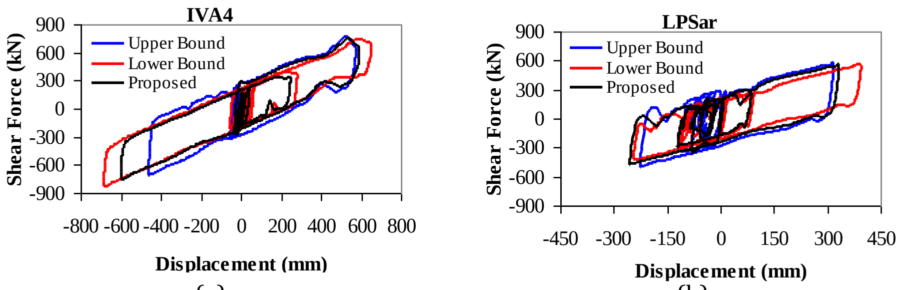

Fig. 5 Hysteresis loops after NRHA for (a) IVA4 and (b) LPSar records

7. Conclusion

The study presented herein focused on the response of an isolated 3-story steel frame under bi-directional excitations of near-field ground motions with clear pulses in their velocity traces. Isolation system was composed of LRBs with due consideration of temperature dependent behavior of lead core under cyclic motion. A set of NRHA were conducted in OpenSees in which the temperature dependent behavior was implemented. Results are then compared with results obtained by bounding analyses where conventional idealized force-deformation relation is used for modeling of LRBs.

Results of this study revealed that bounding analyses yield conservative estimations for MIDs under near-field conditions. The MSFs estimated by both upper bound analysis and proposed model are the same. Those results indicate that engineers may come up with more efficient isolation system designs by using implemented model. It is also clear that using the implemented model for LRB behavior is more practical and time saving instead of performing bounding analysis where engineers have to do same analyses twice.

However, further efforts are needed to clarify the response of LRBs presented in this study. Future efforts should be directed on behavior of temperature dependent LRB model by considering a wide range of parameters such as isolation period, Q/W ratios, and ground motion records with different characteristics.

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