Seismic performance of steel frames accompanied to bearing with perforated yielding shear devices

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Research Article

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Seismic performance of steel frames accompanied to bearing with perforated yielding shear devices

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Abstract:

Perforated Yielding Shear Device-Rubber Bearing (PYSDRB) recently proposed by the author is a new base Isolation to reduce the seismic vibration. This paper tried to evaluate the seismic behavior of the steel moment frame with PYSDRB. The First 3, 8, and 12 story frames were designed with Lead Rubber Bearing (LRB), and then because of the restriction on the PYSDRB displacement, by removing the lead core of the LRB, a suitable pattern is proposed for the design of the shear plates. The base shear and the story drift in the fixed-base frames, frames with LRB-1 (high target displacement), LRB-2 (low target displacement), and PYSDRB under 7 earthquakes were compared. The base shear reduction rate of the 3, 8, and 12-story frames with PYSDRB were about 39%, 37%, and 35% respectively. This base shear reduction rate was acceptable compared to the base shear reduction rate of frames with LRB-2. In terms of story drift, the performance of the 8 and 12-story frames with the PYSDRB were not suitable to compare with the LRB, but the performance of the 3-story frame was acceptable. Considering low target displacement in bearings design, the PYSDRB performance was better than the LRB in low frame height.

Keywords: Perforated yielding shear devices, Lead Rubber Bearing, Story drift, Base shear

1. Introduction

The most important purpose of applying seismic isolation is to shift the natural frequency of the building below the frequencies of the ground motion results in the base shear reduction of the structure. The LRB is one of the most common systems of varying height buildings. Although the use of the LRB has resulted in a significant base shear reduction, due to the high displacement of these LRBs during strong earthquakes, it is important to maintain distance with adjacent structures. Many studies have been conducted recently on the replacement of lead core in rubber bearings. These include the use of steel cantilever damper [1] and torsional steel dampers [2] with rubber bearings. U-shaped steel dampers are another type of dampers used in rubber bearings that form a stable cycle behavior with significant displacement in the bearing [3-5]. In this regard, the behavior of rubber bearing with shear plates is assessed by the researchers [6]. Also, the effect of isolators on the behavior of frames has been examined in another set of studies. For example, nonlinear time-history analyses under near-fault and far-fault motions were performed to study the influence of isolation damping on base and superstructure drift [7]. In the following, the performance of an 8-story frame with the SSRB was compared with the same frame equipped with LRB [8]. Also, the seismic response of a five-story frame with LRB subjected to near-fault ground motions was investigated by some other researchers [9]. And in line with the continuation of such research the effect of displacement restraint in seismic isolation systems on the collapse performance of seismically isolated buildings was assessed by Kitayama and Constantinou [10]. In addition, by other researchers , the seismic behavior of superelastic SMA spring in the isolation system of the multi-story steel frame was examined [11]. The advantages of using SMA spring in the isolation system mainly include the good control of the peak and residual deformations for the superstructure. Two base isolation systems, the High Damping Rubber Bearing (HDRB) actuated in parallel with a Friction Slider (FS) and the Lead Rubber Bearing (LRB) also actuated in parallel with a Friction Slider (FS), are analyzed and their seismic behavior was compared regarding a multi-story reinforced concrete building [12]. Further in this direction, the nonlinear response of fix base (FB) and base isolation (BI) asymmetric variants with various positions of the center of isolators CI was obtained for ten ground motion records scaled to building design acceleration [13, 14] in some high-rise buildings equipped with base isolation and non-traditional tuned mass dampers exposed to various far-field and near-field earthquake records. The largest reduction of the responses of tall buildings accompanied with isolator and tuned mass dampers is a significant result of this study [15]. The performance of a resetting passive stiffness damper (RPSD), for protecting a nonlinear base-isolated building subject to near-field earthquake ground motions was assessed by wallsh et al [16]. It is shown that the RPSD is effective in reducing the peak base drifts while maintaining the building response within the elastic range. Also direct-displacement-based design (DDBD) procedure proposed by some other researchers [17], to make a base-isolated building structure with lead-rubber bearing (LRBs). This method satisfies the performance objectives prescribed by displacement thresholds.

In this study, the seismic performance of frames with PYSDRB was compared with the seismic performance of frames with LRB. Then, by selecting 3, 8, and 12 story frames and designing the appropriate LRB according to AISCE [18], the dimensions of the bearing including the number and thickness of the steel and rubber plates were obtained. Dimensions of the shear plates that have been replaced by lead core were obtained by the distance between the bottom and top of the bearing's thick plates. PYSDRB design differed from the usual design of the LRB due to the bearing displacement limitation. Therefore, the author proposed a new method to get started. Then, the cyclic behavior of the bearing for each frame was presented. In the following, 7 earthquake records were selected and scaled. In the end, the base shear, story drift of frames with LRB and frames with PYSDRB were compared.

2. Frame specifications

The 3, 8, and 12 story moment resisting steel frames (SMRFs) with residential assumption were selected for analysis and design (Fig 1). Each width frame is selected 20 m with 4 spans of 5 m and the story height is selected 3.2 m. The frames are assumed to be of Intermediate Moment Resisting Frame (IMRF). The beam load width of the frame is assumed to be 5 m. Gravity and seismic loading are selected based on the ASCE7-10 [19] and [20]. The dead load of the stories is 600 kg/m^2 and the live load is considered 200 kg/m^2 . The steel used in the frames is St37. The yield stress, modulus of elasticity, and Poisson's ratio of the steel material are considered equal to 240 MPa, 200 GPa, and 0.3, respectively.

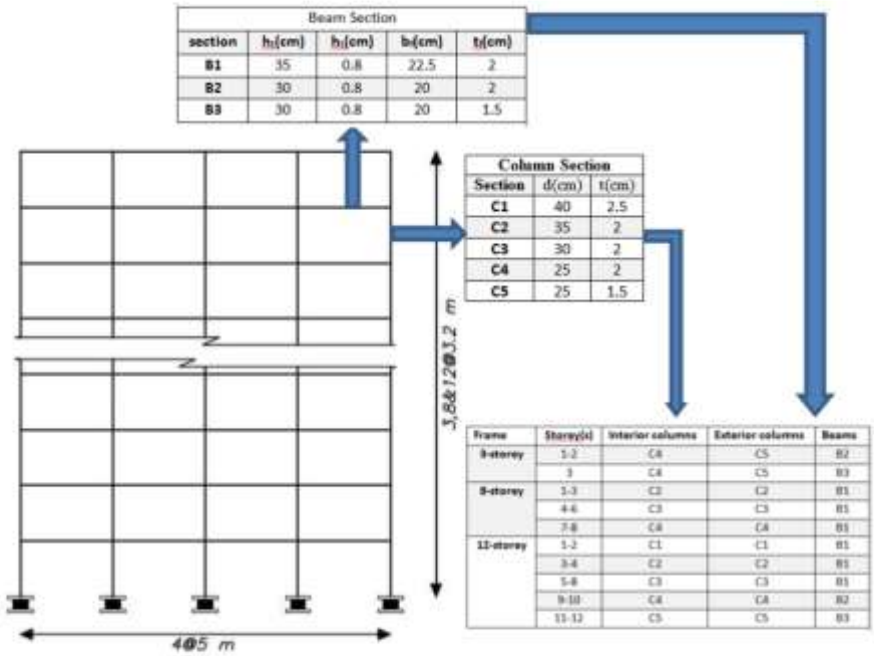


Fig.1 Configuration of SMRFs in this study

The LRB specifications of the 3, 8, and 12 story frames calculated by the AISCE7 are shown in Table (1).

Table1 Final specifications for LRB separator system

Number of Story	Bearing diameter (m)	Lead core diameter (m)	Height of rubber part (m)	Design displacement (m)
3	0.50	0.077	23× 0.012	0.279
8	0.67	0.104	16 ×0.018	0.275
12	0.80	0.124	14 ×0.020	0.276

3. Design process

Due to the bearing height obtained from the LRB design, the square dimensions of the shear plates are determined by the distances of the top and bottom thick plates. The shear plate dimensions of 3, 8, and 12-story frames with the shear plates are 34.2, 41.9, and 41.9 cm, respectively. Because of the PYSDRB displacement constraints, the nonlinear behavior of the superstructure with PYSDRB was greater than that of the LRB, so the design process of the LRB could not be generalized to the PYSDRB.

The proposed design method comprises 1 to 12 story frames. The 34.2 square shear plates were provided for 3 to 6-story frames and the 41.9 square shear plates were provided for 7 to 12-story frames. The shear plate thickness and shear plate holes were determined by the design process.

3-1 The effective stiffness-target displacement curve

The effective stiffness- target displacement diagrams were obtained by varying the shear plate perforation of the 3 and 4 mm thick plates. Fig.2a and Fig2b are related to the 3 to 6-story frame and the 7 to 12-story frame respectively. The effective stiffness achieved from the force-displacement curve was calculated from the following relation.

$$K_{H_{eff}}(\gamma) = \frac{F_{\max} - F_{\min}}{\Delta_{\max} - \Delta_{\min}} \tag{1}$$

In the first step, the effective bearing stiffness was calculated by selecting the target displacement. Target displacement was selected so that the shear plate failure did not occur in the target displacement. This is possible by controlling the plate fracture strain in the Abaqus software.

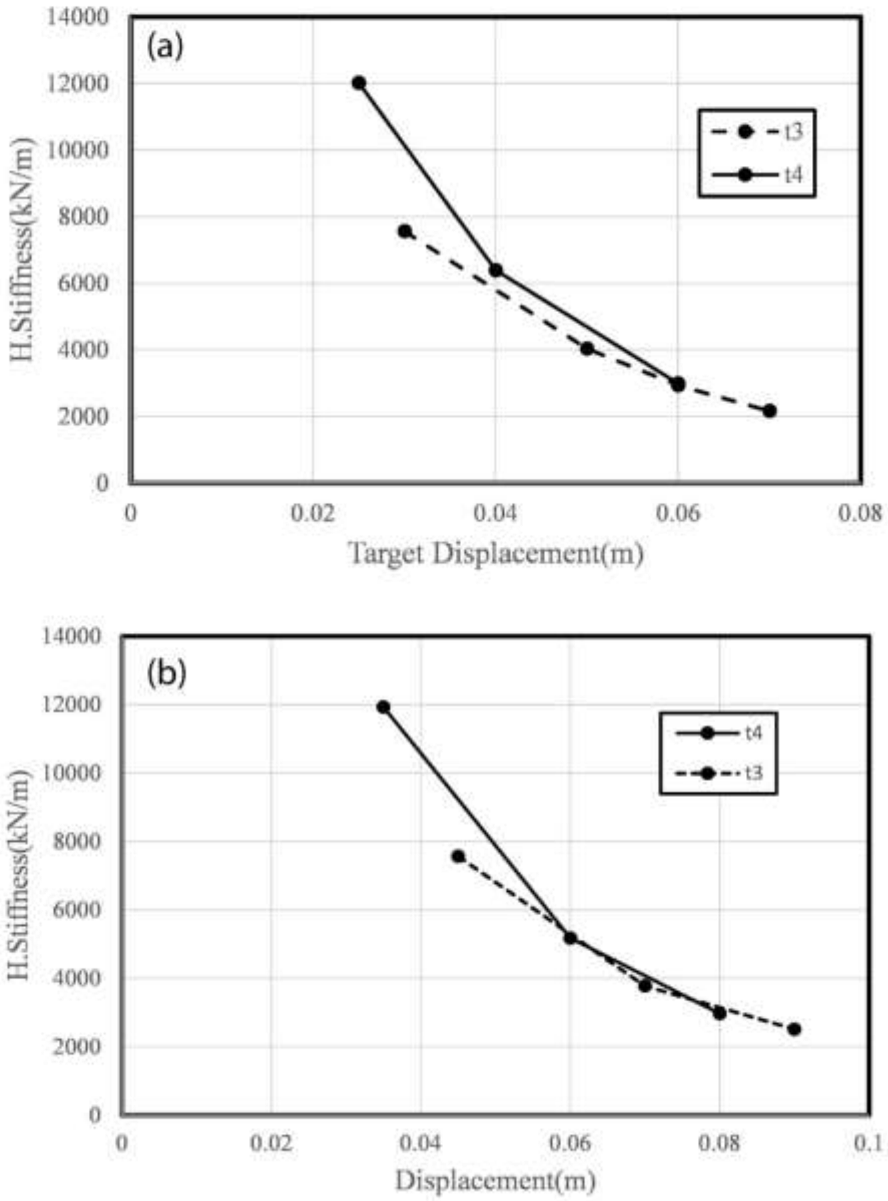


Fig.2 effective stiffness-target displacement curve of 3 and 4 mm thick plate. (a) 3 to 6 story frames. (b) 7 to 12 story frames

3-2 The viscous damping-target displacement curve

The viscous damping - target displacement curves of the different frame bearings were obtained from the previous effective stiffness step, according to the relation (2) (Fig.3).

$$\beta = \frac{EDC}{4\pi U_r}$$

(2

where EDC is the dissipated energy per cycle equal to the area inside the lateral force-deflection hysteresis curve in each cycle. U_r is the restored (elastic) energy in the rubber bearing

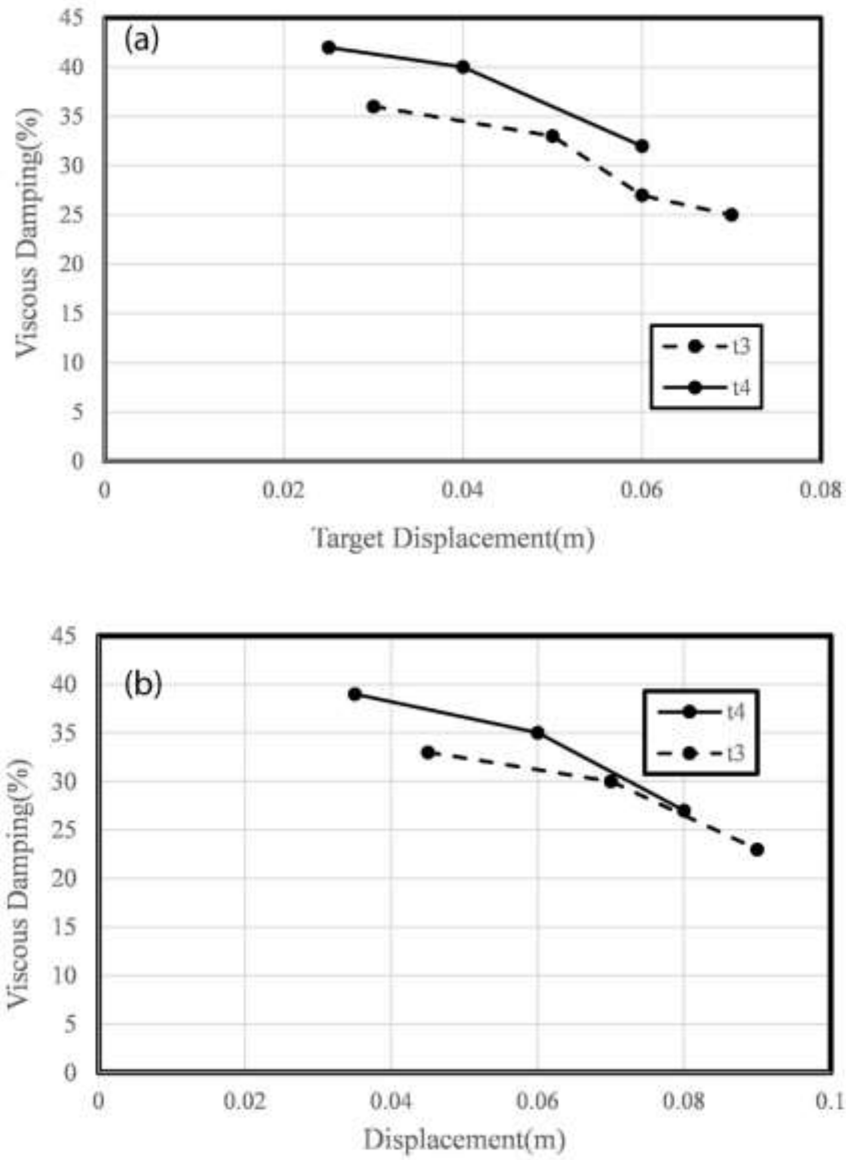


Fig.3 viscous damping-target displacement curve of 3 and 4 mm thick plate. (a) 3 to 6 story frames. (b) 7 to 12 story frames

3-3 bearing characteristic strength

At this step, the dissipated energy in each cycle was achieved by the following equation, including the effective stiffness and the viscous damping calculated from the previous steps.

$$W_D = 2\pi K_{eff} D_D^2 \beta_{eff}$$

(3)

The bearing characteristic strength is obtained by using the following equation.

$$Q_D = \frac{W_D}{4(D_D - D_y)}$$

(4)

It is possible to design the bearing shear plate with the specific thickness and plate perforation if the value of Q (bearing characteristic resistance) is determined.

3-4 determine the shear plate perforation by the bearing characteristic strength

The relationship between the characteristic strength and the percentage of shear plate holes were calculated from the following equation, by PYSDRB numerical studies.

$$Q_{FEM} = 0.6 Q_y (1 - \alpha \frac{A_h}{A_g})$$

(5)

Since two shear plates were used in each bearing direction, half of the PYSDRB characteristic strength was considered. Q_y is the yield strength of the shear plate obtained from the following equation.

$$Q_y = \frac{f_y}{\sqrt{3}} dt$$

(6) where d is the steel shear plate width and t is the thickness of the diaphragm plate and f_y is its tensile yield stress. A_h and A_g represent the amount of cross-sectional of plate holes and the shear plate area, respectively. To obtain the α coefficient, it is necessary to calculate the Q_{FEM} shear plate with different perforations. Fig.4a shows the relationship between

the bearing characteristic strength and the displacement for different shear plate's perforation. Fig.4b shows the linear relationship between the percentage of the shear plate holes and the normalized bearing characteristic strength. The α coefficient was calculated to be 1.90 from the linear relation of (Fig.4b). Therefore, the plate holes percentage was determined by the characteristic strength achieved from the relation (5).

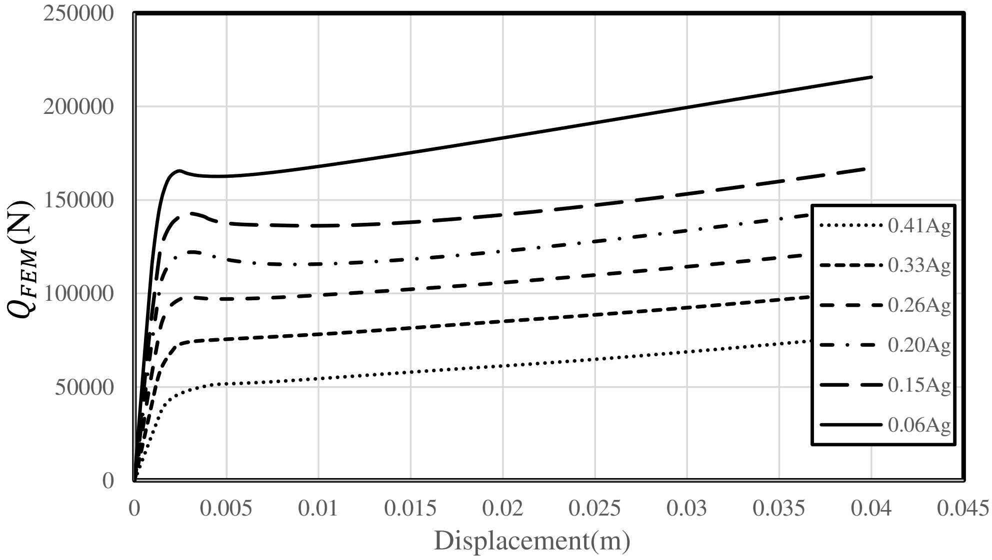


Fig.4 bearing characteristic resistance in the percentage of shear plate perforation

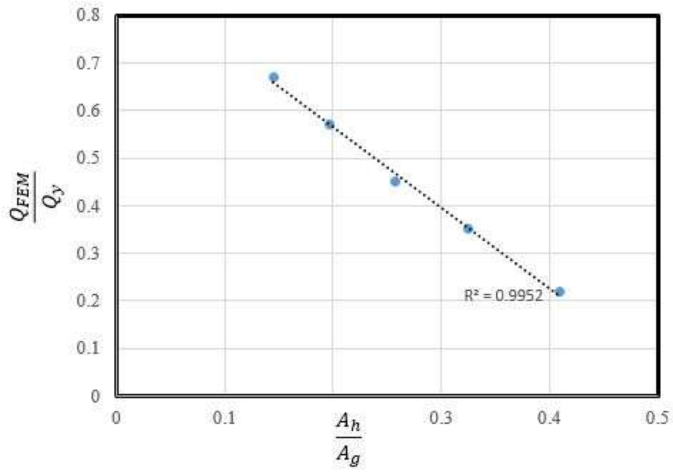


Fig.5 normalized bearing characteristic resistance- the percentage of plate holes curve.

4. Introducing the PYSDRBs

Following the design process mentioned above, the 3-story frame bearing was designed to accommodate a 50 mm target displacement. Fig.6 shows half of the three-story frame bearing modeled on the Abaqus software. The shear plates of 3 mm thickness with hole cross-section of 20% of cross-sectional of plate surface area were selected for 3-story frame bearing. The shear plates of 4 mm thickness with hole cross-section of 15% of cross-sectional plate surface area were selected for 8 and 12 story frame bearings. The cyclic behavior of the 3, 8, and 12-story frame bearings were shown in the 50 mm target displacement (Fig.7).

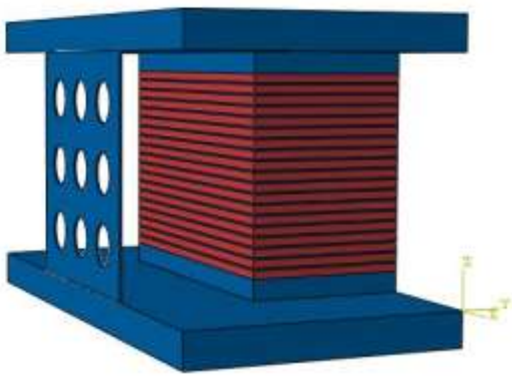


Fig.6 Half of the 3-story bearing

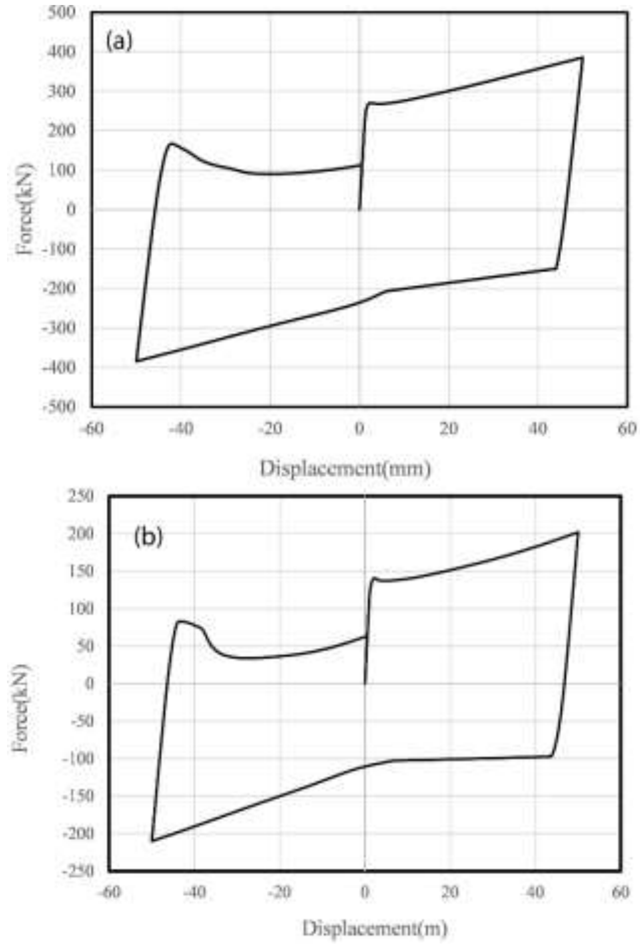
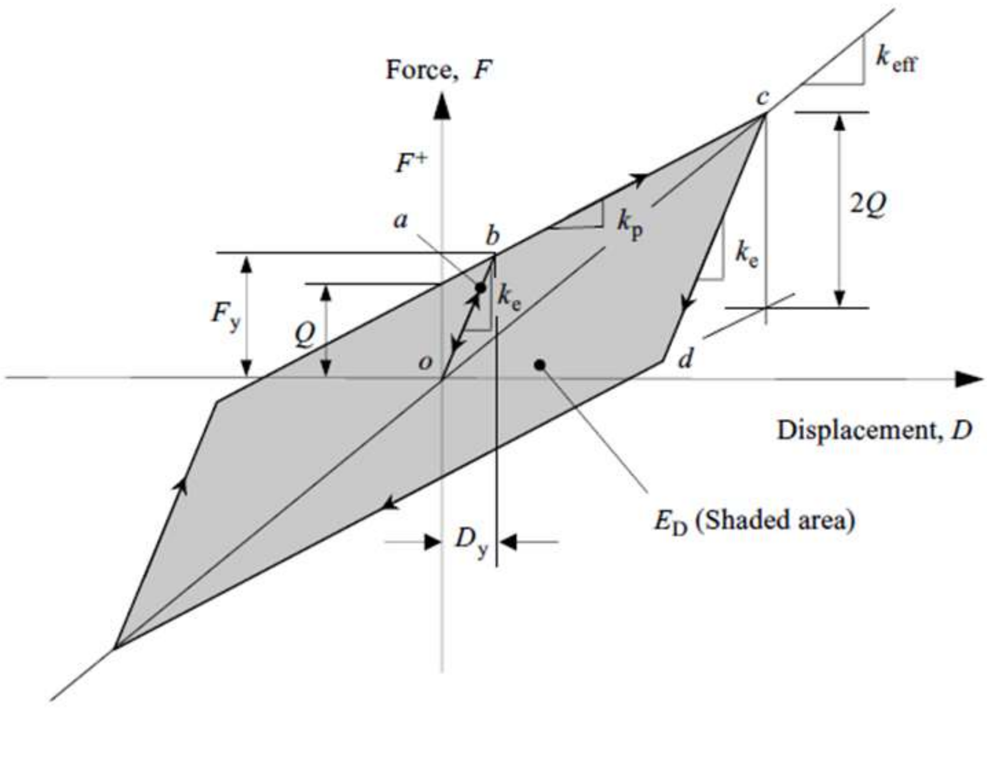


Fig.7 Lateral force-deflection curve of PYSDRB, a 3story, b 8, and 12 story

The bilinear is the most widely model used for displaying rubber-bearing behavior. Three basic parameters are elastic stiffness (k_e), the post-yield stiffness (k_p), and characteristic strength



Q shown in (Fig. 8).

Fig.8 bilinear model' parameters [21]

In the 3 and 8-story frames, two types of LRB with two different target displacements were used. The period times of LRB-1 and LRB-2 were assumed 2 and 1.4 seconds respectively in the 3-story frame. The period time of the fix base frame was 0.7 seconds. The period times of the 8-story frame of the LRB-1 and LRB-2 were assumed 2.5 s and 1.8 s. The period time of the fix base 8 story frame was 1.4. Since the period time of the fixed base, the 12-story frame was about 2 seconds, for the LRB design, unlike the 3 and 8-story frames, only one 2.5-second period time was considered. The period time of fewer than 2.5 seconds was ignored for designing of the LRB, because of the proximity of the period time of 12-story frame with the bearing to the fixed base 12-story frame period time. The bearing properties of the different frames were shown in Table (2).

Table2 Specifications of the LRB and PYSD-NRB for 3, 8, and 12 story frames

Frame Type	Bearing Type	$K_{eff}\ (\frac{kN}{m})$	$K_1(\frac{kN}{m})$	$F_y\,(kN)$	$\frac{K_2}{K_1}$
3 story frame	PYSD-NRB	4040	81000	137	0.017
	LRB-1	410	2474	30	0.16
	LRB-2	834	4997	45	0.16
8 story frame	PYSD-NRB	8350	137500	275	0.011
	LRB-1	656	4380	61	0.1
	LRB-2	1265	17658	113	0.1
12 story frame	PYSD-NRB	8350	1375500	275	0.011
	LRB	1000	5160	129	0.1

4. Earthquake Record Selection

Seven earthquake records with maximum acceleration and magnitude of the earthquake and different frequency content have been used to analyze the nonlinear time history of the frame equipped with the bearing (Table 3). To obtain acceptable responses from the behavior of the frames equipped with bearings, earthquake records must be scaled appropriately [22]. The response spectrum should not be less than the design spectrum for fix base frames in the range of $0.2T$ to $1.5T$. Whereas the response spectrum should not be less than the design spectrum of ASCE **7**-98 [22]for structures with bearing within the range of $0.5T$ to $1.25T$.

5. **Comparison of PYSD-NRB and LRB behavior for 3, 8, and 12 story Frames**

The base shear of the 3, 8, and 12-story frame with bearing is shown in Tables (4-6), respectively. The Δ results show the base shear reduction of the frame with the bearing relative to the frame without the bearing. Fig (9) shows the time history response of the frames equipped with bearing under the Mendocino earthquake record.

Table 4. the base shear of 3 story frame for non-isolated frame, frame with LRB-1, frame with LRB-2, and frame with PYSDRB

Earthquake	Non-isolated structure	PYSDRB		LRB-1		LRB-2	
	F_{max} (kN)	F_{max} (kN)	Δ^*	F_{max} (kN)	Δ^*	F_{max} (kN)	Δ^*
Northridge	2113	1178	44%	839	60%	1794	15%
Duzce	1791	884	51%	550	69%	593	67%
Loma Prieta	1693	862	49%	492	71%	893	47%
Erzincan	1517	1031	32%	1349	11%	1532	0%
Imperial valley	812	700	14%	479	41%	529	34%
Mendocino	1446	905	37%	504	65%	760	47%
Tabas	2039	1110	46%	918	55%	1161	43%
Average	1630	953	39%	733	53%	1037	36%

$^*\Delta$ Differences between bare frame base shear and the base shear of the frame with bearing in percent.

Table 5. the base shear of 8 story frame for non-isolated frame, frame with LRB-1, frame with LRB-2, and frame with PYSDRB

Earthquake	Non-isolated structure	PYSD1-NRB		LRB-1		LRB-2	
	F_{max} (kN)	F_{max} (kN)	Δ^*	F_{max} (kN)	Δ^*	F_{max} (kN)	Δ^*
Northridge	2856	1687	41%	740	74%	1931	32%
Duzce	2269	1558	31%	1039	54%	1638	28%
Loma Prieta	2760	1669	40%	542	80%	1378	50%
Erzincan	3053	1975	35%	1743	43%	2936	4%
Imperial valley	2341	1551	34%	755	67%	1348	42%
Mendocino	2519	1542	39%	598	76%	1374	45%
Tabas	3166	1901	40%	2193	30%	2673	15%
Average	2709	1698	37%	1087	61%	1897	31%

$^*\Delta$ Differences between bare frame base shear and the base shear of the frame with bearing in percent.

Table 6. the base shear of 12 story frame for non-isolated frame, frame with LRB-1, frame with LRB-2, and frame with PYSDRB

Earthquake	Non-isolated structure	PYSD-NRB		LRB	
	(kN) F_{max}	(kN) F_{max}	Δ^*	(kN) F_{max}	Δ^*
Northridge	2520	1505	40%	904	64%
Duzce	2745	1721	37%	1401	49%
Loma Prieta	1987	1411	29%	736	62%
Erzincan	3387	1916	43%	2006	40%
Imperial valley	2606	1537	41%	989	62%
Mendocino	1481	1311	11%	779	47%
Tabas	3730	2136	43%	3278	12%
average	2637	1648	35%	1442	48%

$^*\Delta$ Differences between bare frame base shear and the base shear of the frame with bearing in percent.

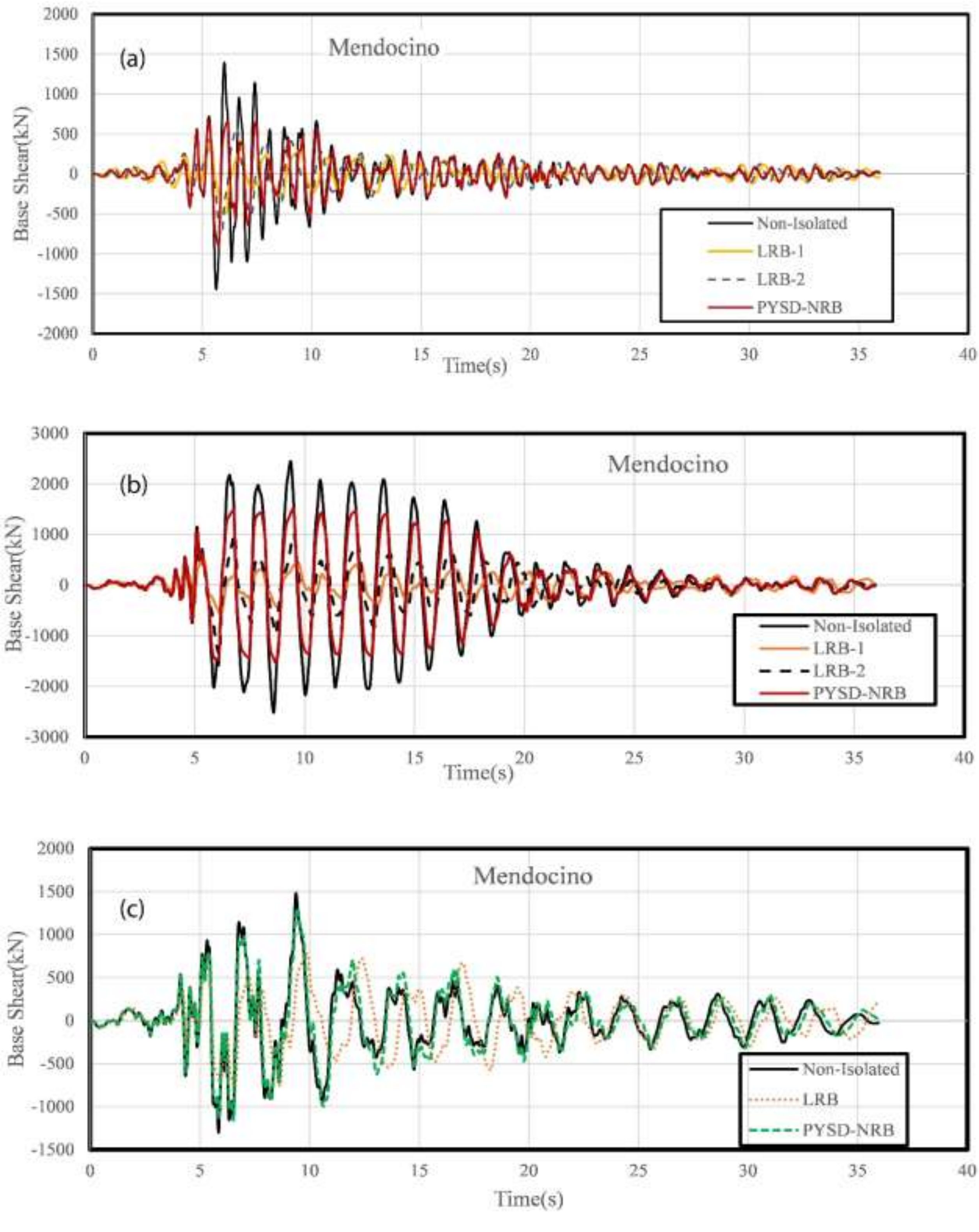


Fig 9. Time history response of frame base shear under Mendocino earthquake a) 3 story, b) 8 story and c) 12 story

5.1 base shear of the 3 story frame with PYSDRB

The maximum base shear reduction for the 3-story frame with the PYSDRB was related to the Duzce earthquake and the lowest base shear was related to the Imperial Valley earthquake. The base shear rate of PYSDRB was higher than that of LRB-2 and lower than that of LRB-1. However, the base shear reduction of LRB-2 under the Duzce and Mendocino earthquakes was higher than that of the PYSDRB. By averaging the response of 7 earthquake records, the base shear reduction rate for the frame with the PYSDRB was about 40%, for the frame with the LRB-1 was about 53% and for the frame with the LRB-2 was about 36%. Comparing the results achieved from the bearing displacement, it can be seen that the base shear reduction rate of the PYSDRB compared to the LRB occurred at a much less displacement (Table 7). For example, the PYSDRB displacement under the Duzce earthquake record was about 21 mm, which resulted in about 51% base shear reduction. The displacement of the LRB-1 under the Duzce earthquake record was about 200 mm, which resulted in about 69% base shear reduction. Although the base shear reduction of LRB-1 was more pronounced, a 50% reduction in base shear at 21 mm displacement was significant. By averaging the responses of the seven earthquake records, the maximum displacement of the PYSRB, LRB-1, and LRB-2 were about 32 mm, 30 mm, and 210 mm respectively. It can be concluded that the PYSDRB performs better than the LRB for frames with less target displacement.

Table 7 Displacement of the 3-story frame bearings under 7 earthquake records

Earthquake	PYSD-NRB	LRB-1	LRB-2
	$d_{\max}(mm)$	$d_{\max}(mm)$	$d_{\max}(mm)$
Northridge	58	345	378
Duzce	24	200	98
Loma perieta	21	171	172
Erzincan	43	703	364
Imperial valley	2.7	165	82
Mendocino	27	178	139
Tabas	50	385	237
Average	32.25	306	210

5.2 base shear of the 8 story frame with PYSDRB

The maximum base shear reduction of the frame with the PYSDR was related to the Northridge, Loma Prieta, and Tabas earthquakes, and the lowest base shear was related to the Duzce earthquake. The base shear reduction rate of the 8-story frame with the LRB-1 was better than the other two bearings for each of the 7 earthquake records. The base shear reduction of the LRB-2 and PYSDRB were the same approximately. However, the base shear reduction rate of PYSDRB for some records, such as the Erzincan earthquake record, was significantly higher than for the LRB-2. By averaging the response of 7 earthquake records, the base shear reduction of the frame with the PYSDRB, LRB-1, and LRB-2 was about 37%, 60%, and 31% respectively. The results of the bearing displacement show that the base shear reduction of the 8-story frame with the PYSDRB occurred much less in the displacement, compared to the bearing displacement of the frame with LRB (Table 8). For example, the PYSDRB displacement under the Northridge earthquake record was about 44 mm, which resulted in about 41% base shear reduction. However, the LRB-1 displacement under the Northridge earthquake record was about 212 mm, which resulted in about 74% base shear reduction. Although the base shear reduction of LRB-1 was better, the 41% reduction in base shear at 21 mm displacement was significant. Also, the base shear reduction of the frame with PYSDRB at 44 mm displacement under the Northridge earthquake record, shows a 22% increase compared to LRB-2 at 158 mm displacement. To be exact, the performance of the PYSDRB assuming low target displacement was better than that of the LRB. On the other hand, there is less bearing displacement and more frame base shear reduction. By averaging the responses of the seven earthquake records, the maximum displacement of the PYSDRB, LRB-1, and LRB-2 was about 41 mm, 369 mm, and 153 mm respectively. It can be concluded that the PYSDRB performs better than the LRB for frames with less target displacement.

Table 8 Displacement of the 8-story frame bearings under 7 earthquake records

Earthquake	PYSD-NRB	LRB-2	LRB-1
	$d_{\max}(mm)$	$d_{\max}(mm)$	$d_{\max}(mm)$
Northridge	44	158	212
Duzce	24	126	348
Loma perieta	38	97	122
Erzincan	73	267	668
Imperial valley	23	93.5	219
Mendocino	21	96.5	147
Tabas	67	239	873
Average	41	153	369

5.3 base shear of the 12 story frame with PYSDRB

The maximum base shear reduction of 12 story frame with LRB compared to the non-isolated frame was 64% related to the Northridge earthquake record and the minimum base shear reduction was 12% related to the Tabas earthquake record. The maximum base shear reduction of 12 story frame with PYSDRB was 43% following the Tabas earthquake record and the minimum base shear reduction was 11% accordance with the Mendocino earthquake record.

On average, LRB and PYSDRB reduced the base shear by 48% and 35%, respectively. The maximum displacement of the two bearings under 7 earthquake records was shown in Table 9. The maximum displacement of the 12-story frame PYSDRB was 34 mm, which was less than 50 mm of primary target displacement. In contrast, the average maximum displacement of the LRB is 334 mm, which means the maximum displacement of the PYSDRB was $\frac{1}{10}$ compared to the LRB, while the base shear reduction was not more than 27%.

Table 9 Displacement of the 12-story frame bearings under 7 earthquake records

Earthquake	PYSD-NRB	LRB
	$d_{\max}(mm)$	$d_{\max}(mm)$
Northridge	15	124
Duzce	43	317
Loma Prieta	4.0	61
Erzincan	65	551
Imperial valley	19	158
Mendocino	2.0	83
Tabas Average	91 34	1042 334
Average	34	334

6. Story drift

6.1 Story drift of 3 story frame

Fig. 10 shows the story drift of the frame with LRB-1, LRB-2, PYSDRB, and non-isolated frame under the 7 earthquake records, respectively. Bold lines indicate the mean story drift. The story drift of the frames with the bearing compared to the fix-base frames shows a decrease in most earthquake records. It is observed that the maximum story drift of the frame with the LRB-1 shows a 57% decrease compared to the non-isolated frame. The maximum story drift of the frame equipped with the LRB-2 and the PYSDRB showed a decrease of about 34% and 38%, respectively compared to the maximum displacement of the non-isolated frame. According to AISC360-10 [20], the story drift of the frame with bearing should be less than 2% story height. The mean maximum story drift for the 3-story frame equipped with the LRB-1 was about 0.87%, which was less than 2% story height. This value for LRB-2 was about 1.36% which is less than 2% story height. The mean maximum story of the 3-story frame equipped with PYSDRB was 1.18%, which was less than 2%. This represents a 13% decrease compared to LRB-2. It is found that, like the base shear, the story drift of the 3-story frame with PYSDRB performs better than the 3-story frame with LRB-2. The story drift performance of the 3-story frame equipped with LRB-1 was better than PYSDRB. It is possible to replace the PYSDRB with the LRB to the low target displacement.

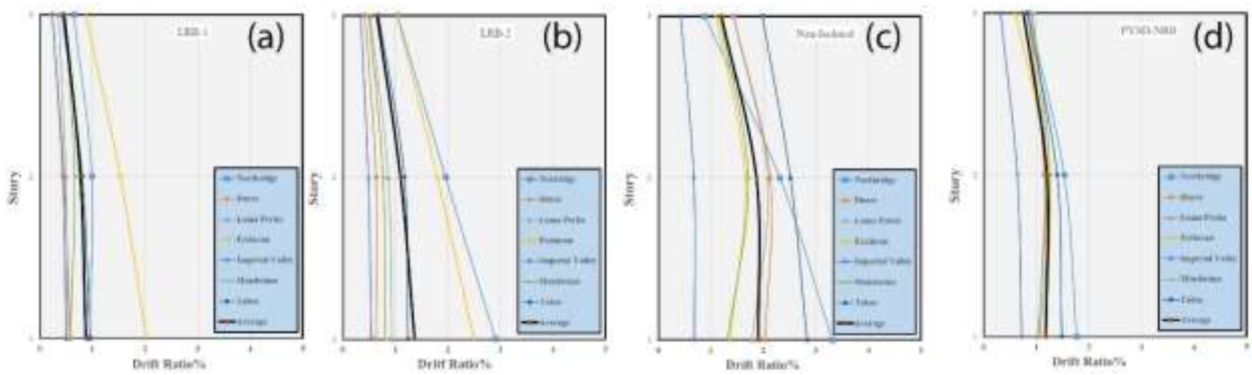


Fig 10. Story drift of 3 stories. a) LRB-1, b) LRB-2, c) PYSDRB, d) Non-Isolated

6.2 relative displacement of 8 story frame

Fig. 11 shows the story drift of the 8-story frame with LRB-1, LRB-2, PYSD-NRB, and non-isolated frame under 7 earthquake records, respectively. Bold lines indicate the mean story drift. Story drift of frames with bearing Indicates a decrease in most earthquake records compared to frames without bearing. The story drift average of an 8-story frame equipped with LRB-1 compared to the story drift average of an 8-story frame without bearing, shows approximately 75% reduction. This represents a 46% and 23% decrease for LRB-2 and PYSDRB, respectively. By comparing the maximum story drift of the frame equipped with PYSDRB and both of LRBs, the story drift of PYSDRB shows a 68% and a 31% increase respectively compared to LRB-1 and LRB-2. The maximum mean story drift of the frame with the LRB-1 and LRB-2 were 0.71 and 1.53%, respectively, which is less than 2% (permitted story drift). The maximum mean story drift of the frame with the PYSDRB was about 2.23%, which is a 12% increase over the permitted story drift. Of course, this difference can be offset by the redesign of the frame with bearing. It is observed that for the 8-story frame equipped with the PYSDRB, although the base shear was as acceptable as the 3-story frame, the story drift did not work well compared to the LRB.

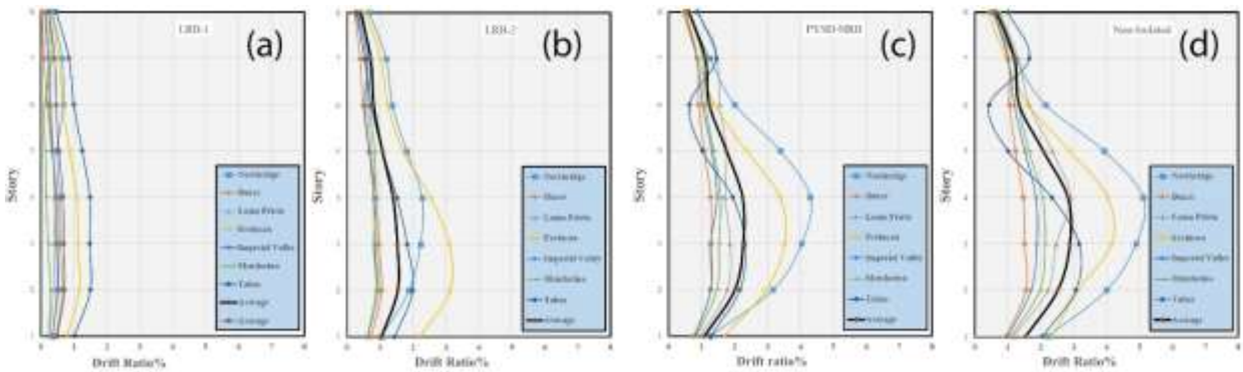


Fig 11. Story drift of 8 stories. a) LRB-1, b) LRB-2, c) PYSDRB, d) Non-Isolated

6.3 relative displacement of 12 story frame

Fig. 12 shows the story drift of the 12-story frame with LRB, PYSD-NRB, and non-isolated frame under 7 earthquake records, respectively. The LRB reduces the story drift significantly. The most significant story drift reduction compared to the 12-story non-isolated frame, which was 47% and 58%, respectively. The PYSDRB has little effect on the story drift of the 12-story frame. Of course, there was a 38% reduction in story drift for the Tabas earthquake record. The maximum mean story drift of the frames equipped with the LRB was about 1.54%, which was less than 2%. The maximum story drift of the frames equipped with the PYSDRB was about 2.26%. This represents a 13% difference compared to the permitted story drift. Given that this amount of difference was related to the story drift of floors 8 and 12, the difference can be offset by the redesign of the frame with bearing. Although the PYSDRB shows acceptable performance in reducing the base shear of the 12-story frame than that of the LRB, the story drift reduction of LRB was better than that of PYSDRB.

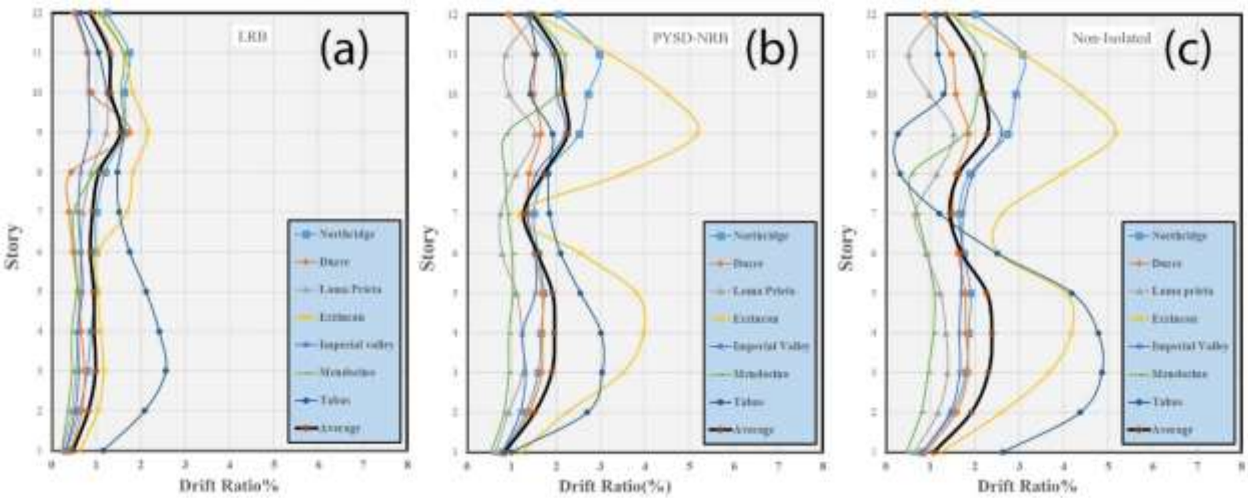


Fig 12. Story drift of 12stories. a) LRB, b) PYSDRB, c) Non-Isolated

7. Conclusion

Since the PYSDRB displacement was much less than that of the LRB, the design pattern presented for the LRB was not suitable for the PYSDRB design. The suitable LRBs were designed for 3, 8, and 12-story frames. The lead core of the bearing was removed and shear plates were instead proportional with bearing dimensions. Due to the distance between the top and bottom of the bearing thick plates, shear plate dimensions were obtained. A suitable design pattern has been calculated by considering the shear plates of 3 and 4 mm thickness and the different plate holes for varying target displacement. The following were considered as the outcome of this study:

1- By averaging the response of 7 earthquake records, the base shear rates of the 3-story frame with PYSDRB, LRB-1 and LRB-2 were about 40%, 53%, and 36% respectively. The maximum displacements of the PYSDRB, LRB-1 and LRB-2 are about 32 mm, 306 mm, and 210 mm respectively. The maximum story drift of the 3-story frame with LRB-1 compared to the non-isolated frame showed a 57% decrease. The maximum story drift of the 3-story frame with LRB-2 and the PYSDRB compared to the non-isolated frame showed a 34% and 38% reduction, respectively. The performance of the PYSDRB of 3 story frame is acceptable compared to the LRB-2.

2- The base shear reduction rate of the 8-story frame with the PYSRB, LRB-1, and LRB-2 was about 37%, 60%, and 31% respectively. The maximum displacements of the PYSDRB, LRB-1 and LRB-2 are about 41 mm, 369 mm, and 153 mm respectively for 8 story frame. The maximum story drift of the 8-story frame with LRB-1 compared to the non-isolated frame showed a 75% decrease. The maximum story drift of the 3-story frame with LRB-2 and the PYSDRB compared to the non-isolated frame showed a 46% and 22% reduction, respectively. However, in terms of story drift, the PYSDRB of the 8-story frame has poorer performance than the LRB. The base shear performance of the PYSDRB is acceptable compared to the LRB-2 for the 8-story frame.

3- In the 12-story frame, the LRB and PYSD-NRB reduced the base shear by 48% and 35%, respectively. The maximum displacements of the PYSDRB and LRB are about 34 mm, 334 mm respectively for 12 story frame. The PYSDRB has little effect on the story drift of the 12-story frame.

4- It can be concluded that the PYSDRB is more acceptable for lower-height frames. In some cases, the new bearing performs better than the LRB

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