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TECHNICAL NOTE

Effects of Inherent Structural Characteristics on Seismic Performances of Aseismically Base-Isolated Buildings

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Abstract

Effects of inherent characteristics of both isolation system (IS) and superstructure on seismic performances of aseismically base-isolated buildings subjected to near- and far-field ground motions are investigated through extensive numerical analyses. ISs considered are friction pendulum system (FPS) and high-damping laminated rubber bearing (HRB), as the most practical ISs. Superstructures are 3-, 7-, and 11-story buildings with steel and reinforced concrete moment-resisting and braced frames. Seven isolation strategies are practically designed by the ISs, using three target displacements and two coefficients of friction. Eighty-four structural models are created for the 12 superstructures isolated by the two ISs. 1176 nonlinear time history analyses are carried out on the two-dimensional models of the isolated buildings subjected to seven near-field and seven far-field ground motions. Base shears, story displacements, and story accelerations are studied as the performance criteria. It is shown that the effectiveness of aseismic base isolation depends significantly on inherent mass, stiffness, and damping of the structure. The effect of isolation damping is more than mass and stiffness of the superstructure. The effectiveness of aseismic base isolation with the design strategies controlled by target displacement increases by increase in the inherent mass and stiffness of the superstructure, while facing reduction due to inherent increase in the isolation damping. The effects are similar in near- and far-field ground motions. Seismic performances of FPS are less sensitive to the effects of inherent structural characteristics. With the conditions and parameters set in this study, it is found that FPS performs better than HRB, specifically in near-field excitations.

Keywords Aseismic base isolation · Inherent structural characteristics · Ground motion · Sensitivity · Seismic performances

1 Introduction

Aseismic isolation is a well-accepted effective method for protecting structures against earthquakes. It is generally used in the foundation level and is known as base isolation. This strategy of structural design is based on reducing the demand instead of increasing the capacity. Increasing the capacity can sometimes be uneconomical or impractical and may lead to situations in which the structure itself is undamaged but the contents are damaged or destroyed and the occupants injured. Aseismic base isolation reduces the seismic demand by reducing the fundamental frequency of the structure and also provides an amount of damping. If this technology is used properly, the seismic performance of the structure will be improved (Tavakoli et al. 2014). Base isolation of a structure can result in the reduction of inter-story drifts and floor accelerations, which are considered as the performance measures in most of the design codes such as IBC (2012) and ASCE 41-13 (2013). The first application of aseismic base isolation refers to the ancient Iran (Sepahbodnia 2006; Botis and Harbich 2012; Bek et al. 2013). It continues to get considerable attention, particularly after the recent strong earthquakes such as the Kobe earthquake in 1995. Base isolation technology is used in many countries (Warn and Ryan 2012). To date, different isolation systems (ISs) have been developed (Martelli et al. 2014; Narjabadifam 2015; Falborski and Jankowski 2017). Isolated buildings have performed well in the previous earthquakes (Du and Han 2014). Seismic performances, however, depend on the characteristics of both structures and earthquakes (Kelly

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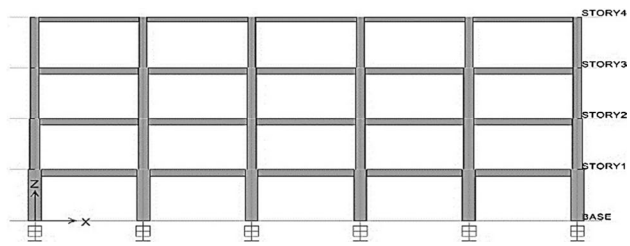

Fig. 1 The building frame studied by Tavakoli et al. (2014)

1999). Several studies have been carried out about the roles of the properties of superstructures and ISs on the performances of base-isolated structures. Jangid (2002) studied these performances through a parametric study and concluded that structural parameters significantly influence the effect of isolation. Jain and Thakkar (2004) investigated the effect of structural stiffness and showed that increasing stiffness in superstructure increases the effectiveness of isolation. Jalali and Narjabadifam (2006) presented a study on the effects of additional mass and damping on the seismic performances of isolated buildings and indicated that the performances can be improved by the modification of dynamic properties of superstructures. In a study by Providakis (2009), the effects of supplemental damping on laminated rubber bearings (LRBs) and friction pendulum systems (FPSs) were investigated and it was shown that additional damping is the main parameter affecting the seismic response of isolated buildings located in near-fault regions. It had already been revealed by Kelly (1999) and Hall (1999) that isolated buildings subjected to near-fault ground motions are struggling with large displacements and the solution for this problem is to use damping to mitigate displacements. Sharbatdar et al. (2011) have also studied the seismic performances of structures isolated with FPS and high-damping laminated rubber bearing (HRB), showing that large displacement and velocity pulses of near-fault motions severely affect the performances of base isolation. The references reviewed above are not the only references related to the subject, and some other remarkable works have also been reported by Fan et al. (1990), Kulkarni and Jangid (2003), Hong and Kim (2004), Matsagar

Table 1 Base shears obtained for the building frame studied by Tavakoli et al. (2014) based on the design and analysis method of this research, compared to those reported in the reference work (Tavakoli et al. 2014)

Earthquake	Station	Base condition	Base shear (kN) Tavakoli et al. (2014)	Base shear (kN) this research
Duzce	Duzce	Fixed-base	1250	1245
		Base-isolated	541	569
	Cekmece	Fixed-base	1248	1239
		Base-isolated	455	448
Imperial Valley	El Centro (array 7)	Fixed-base	1147	1156
		Base-isolated	630	620
Northridge	Anaverde	Fixed-base	1142	1183
		Base-isolated	431	417
	Jensen	Fixed-base	1248	1186
		Base-isolated	728	700

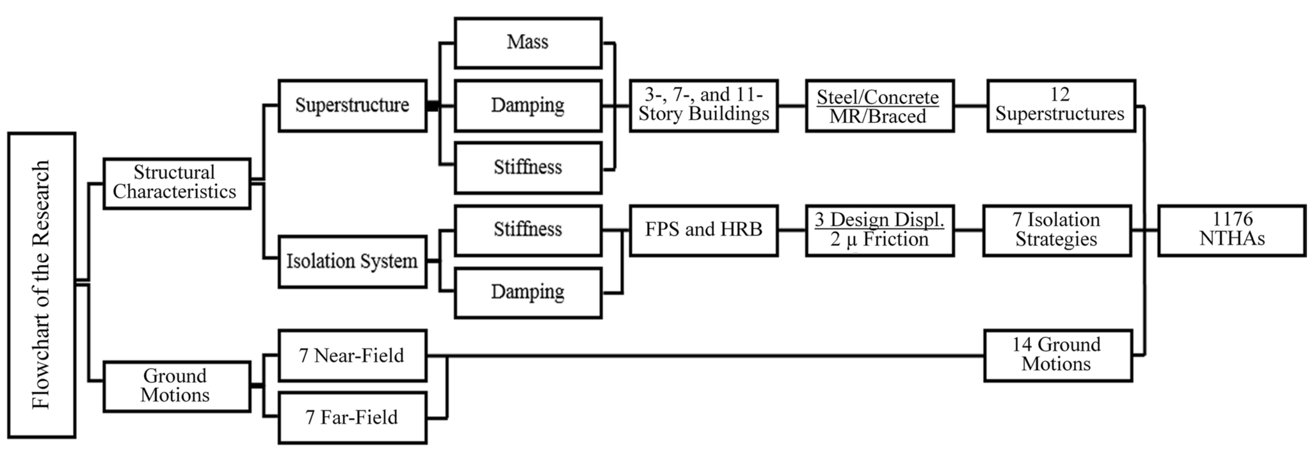

Fig. 2 Flowchart of the research

Table 2 The structural models

Name	Description	Name	Description
3TMS	3-story traditional moment-resisting steel	7TMC	7-story traditional moment-resisting concrete
3FMS	3-story FPS-isolated moment-resisting steel	7FMC	7-story FPS-isolated moment-resisting concrete
3HMS	3-story HRB-isolated moment-resisting steel	7HMC	7-story HRB-isolated moment-resisting concrete
3TBS	3-story traditional braced (X-bracing) steel	7TBC	7-story traditional braced (shear wall) concrete
3FBS	3-story FPS-isolated braced (X-bracing) steel	7FBC	7-story FPS-isolated braced (shear wall) concrete
3HBS	3-story HRB-isolated braced (X-bracing) steel	7HBC	7-story HRB-isolated braced (shear wall) concrete
3TMC	3-story traditional moment-resisting concrete	11TMS	11-story traditional moment-resisting steel
3FMC	3-story FPS-isolated moment-resisting concrete	11FMS	11-story FPS-isolated moment-resisting steel
3HMC	3-story HRB-isolated moment-resisting concrete	11HMS	11-story HRB-isolated moment-resisting steel
3TBC	3-story traditional braced (shear wall) concrete	11TBS	11-story traditional braced (X-bracing) steel
3FBC	3-story FPS-isolated braced (shear wall) concrete	11FBS	11-story FPS-isolated braced (X-bracing) steel
3HBC	3-story HRB-isolated braced (shear wall) concrete	11HBS	11-story HRB-isolated braced (X-bracing) steel
7TMS	7-story traditional moment-resisting steel	11TMC	11-story traditional moment-resisting concrete
7FMS	7-story FPS-isolated moment-resisting steel	11FMC	11-story FPS-isolated moment-resisting concrete
7HMS	7-story HRB-isolated moment-resisting steel	11HMC	11-story HRB-isolated moment-resisting concrete
7TBS	7-story traditional braced (X-bracing) steel	11TBC	11-story traditional braced (shear wall) concrete
7FBS	7-story FPS-isolated braced (X-bracing) steel	11FBC	11-story FPS-isolated braced (shear wall) concrete
7HBS	7-story HRB-isolated braced (X-bracing) steel	11HBC	11-story HRB-isolated braced (shear wall) concrete

and Jangid (2004), Rabiei (2008), Sharma and Jangid (2009), Abrishambaf and Ozay (2010), Ounis and Ounis (2013), Chun and Hur (2015), Tolani and Sharma (2016), Folic and Stanojev (2016), and Bhandari et al. (2017). In practice, however, it is still required to investigate the effects of inherent characteristics of both superstructure and IS to reveal the practical effectiveness of ISs, remaining as an important engineering question. This is intrinsically different than the investigations of the effects of additional mass and damping or stiffening the superstructure. A comprehensive study to investigate the

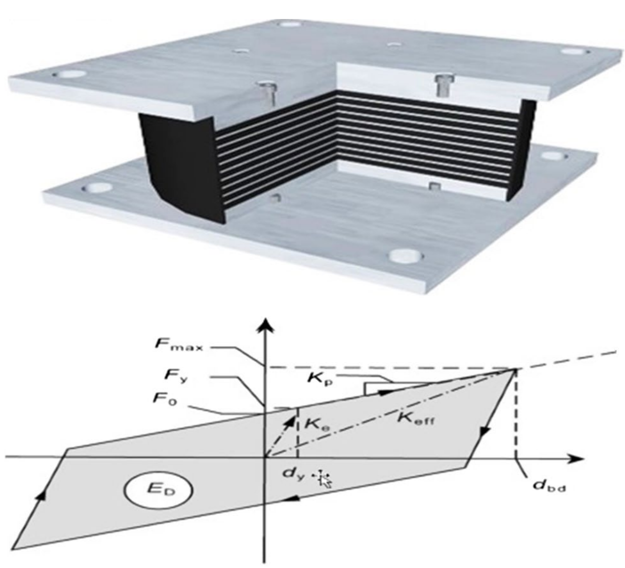

Fig. 3 The HRB isolator and its mechanical behavior (AGOM 2017)

effects of inherent structural characteristics on seismic performances of ISs, in this regard, has been carried out within a postgraduate research program to find the answer to the above-discussed question. Next sections report on the methodology and outcomes of this research.

2 The Methodology of Research

For the investigation of effects of inherent structural characteristics on seismic performances of ISs, a detailed parametric study is required. Numerical analyses for such a study must be nonlinear, due to the nonlinearities of isolators, and the structures must be properly designed. Both the design and the analysis procedures must be verified before to be sure about the accuracy of results. The reference work for the purpose of verification is the work reported by Tavakoli et al. (2014). They have studied the responses of the base-fixed and isolated building frames and reported the base shears of a base-fixed and isolated 4-story reinforced concrete building frame, as shown in Fig. 1. The same has been carried out in this research, and the results have been compared with the results reported by Tavakoli et al. (2014). Base shears are compared in Table 1.

As can be seen, the base shears obtained are close to those reported by Tavakoli et al. (2014). So, the design and the analysis procedures used in this research are verified.

Flowchart of the research conducted as the basis for this paper is represented in Fig. 2, with the details given for the structural characteristics varying inherently in the

Table 3 The mechanical properties of HRBs in this research

Structure	D_d (m)	K_{eff} (kN/m)	K_{e} (kN/m)	F_y (kN)
3HMS	0.2	537.2149	2238.395	22.3
	0.3	239.159	996.4996	14.9
	0.4	134.8407	561.8361	11.2
3HBS	0.2	547.15	2279.792	22.7
	0.3	243.575	1014.898	15.2
	0.4	137.3244	572.1852	11.4
3HMC	0.2	646.501	2693.757	26.9
	0.3	379.835	1582.648	23.7
	0.4	656.323	2734.681	54.6
3HBC	0.2	626.631	2610.964	26.1
	0.3	467.012	1945.887	29.1
	0.4	636.1509	2650.629	53.0
7HMS	0.2	1242.612	5177.549	51.7
	0.3	552.669	2302.79	34.5
	0.4	202.399	843.3324	16.8
7HBS	0.2	1292.287	5384.531	53.8
	0.3	574.747	2394.782	35.9
	0.4	323.608	1348.37	26.9
7HMC	0.2	1789.046	7454.357	74.5
	0.3	1037.72	4323.832	64.8
	0.4	1032.541	4302.255	86.0
7HBC	0.2	1530.731	6378.048	63.7
	0.3	1139.089	4746.203	71.1
	0.4	1133.404	4722.516	94.4
11HMS	0.2	1967.879	8199.495	81.9
	0.3	492.506	2052.111	41.0
	0.4	875.010	3645.877	54.6
11HBS	0.2	2087.10	8696.253	86.9
	0.3	927.998	3866.659	57.9
	0.4	522.312	2176.301	43.5
11HMC	0.2	2683.211	11,180.04	111.8
	0.3	2737.676	11,406.98	171.1
	0.4	2724.009	11,350.04	227.0
11HBC	0.2	2236.128	9317.201	93.1
	0.3	1917.602	7990.008	119.8
	0.4	2270.126	9458.86	189.1

practical ranges. This research investigates the effects of inherent structural characteristics through 1176 nonlinear time history analyses (NTHAs) on 84 structural models (as described in Tables 3 and 4) subjected to 14 near- and far-field ground motions. The superstructures are 3-, 7-, and 11-story steel and reinforced concrete moment-resisting (MR) and braced frame buildings (12 cases) with different inherent structural characteristics in terms of mass, stiffness, and damping, while the superstructure damping will not be studied due to its negligible effect discussed already in the literature (e.g., Jangid 2002; Jalali and Narjabadifam 2006). Seven isolation strategies are designed based on three design displacements (D_d) and two coefficients of friction (μ, representing the lubricated and nonlubricated sliding surfaces in practice) using HRB and FPS.

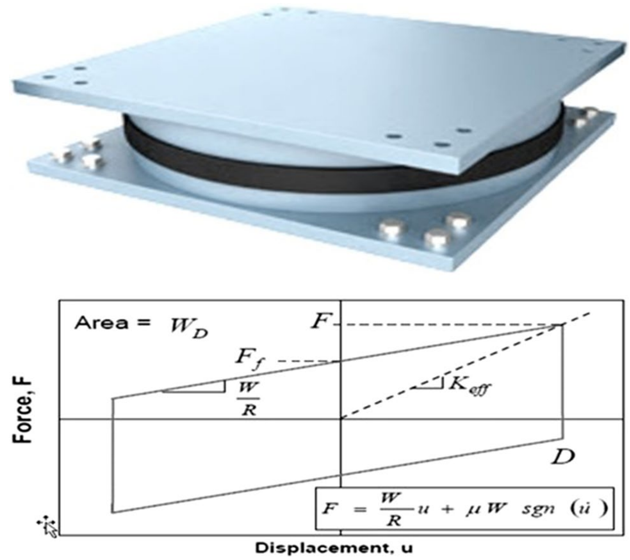

Fig. 4 The FPS isolator and its mechanical behavior (OILES 2017)

3 Superstructures

The superstructures are two-dimensional models of typical 3-, 7-, and 11-story buildings on soil type III in a region with very high level of relative seismic hazard of Standard No. 2800 (2015), designed according to ACI 318-11 (2011) and AISC 341-10 (2010) using ETABS (2016).

The seismic performances of these superstructures are studied for three earthquake-resistant structural systems resulting in 36 structural models described in Table 2.

4 Isolation Systems

The isolators considered for this research are HRB and FPS, as the most practical ISs. The mechanical behavior of HRB is shown in Fig. 3. These isolators provide damping around 20% according to AGOM (2017), FIP (2017), Maurer (2017), DIS (2017), and OILES (2017). The Isolator1 nonlinear link element (rubber isolator) of ETABS is used to model the HRBs with the design details given in Table 3. Figure 4 shows the force–displacement behavior for FPS isolator. Frictional parameters (rate parameter, coefficient of friction at slow and fast velocities) are calculated based on Dolce et al. (2005). FPSs are modeled by Isolator2 nonlinear

Table 4 The mechanical properties of FPSs in this research

Structure	D_d (m)	$\mu_{Nominal}$	K_{eff} (kN/m)	K_e (kN/m)	μ_{Fast}	Rate parameter	Radius (m)
3FMS	0.1	0.02	660	5500	0.024	0.008	1
	0.2	0.02	605	5500	0.024	0.008	1
	0.2	0.05	495	13,500	0.093	0.016	1.5
	0.3	0.02	311	5500	0.024	0.008	2
3FBS	0.1	0.02	648	5400	0.024	0.008	1
	0.2	0.02	594	5400	0.024	0.008	1
	0.2	0.05	504	13,750	0.093	0.016	1.5
	0.3	0.02	396	5400	0.024	0.008	1.5
3FMC	0.1	0.02	780	6500	0.024	0.008	1
	0.2	0.02	715	6500	0.024	0.008	1
	0.2	0.05	595	16,250	0.092	0.016	1.5
	0.3	0.02	368	6500	0.024	0.008	2
3FBC	0.1	0.02	756	6300	0.024	0.008	1
	0.2	0.02	693	6300	0.024	0.008	1
	0.2	0.05	577	15,750	0.092	0.016	1.5
	0.3	0.02	357	6300	0.024	0.008	2
7FMS	0.1	0.02	1500	12,500	0.024	0.009	1
	0.2	0.02	1375	12,500	0.024	0.009	1
	0.2	0.05	1191	32,500	0.090	0.016	1.5
	0.3	0.02	708	12,500	0.024	0.009	2
7FBS	0.1	0.02	1848	15,400	0.024	0.009	1
	0.2	0.02	1430	13,000	0.024	0.009	1
	0.2	0.05	1155	38,500	0.090	0.016	2
	0.3	0.02	736	13,000	0.024	0.009	2
7FMC	0.1	0.02	1560	18,000	0.024	0.009	1.5
	0.2	0.02	1380	18,000	0.024	0.009	1.5
	0.2	0.05	1650	45,000	0.088	0.016	1.5
	0.3	0.02	1020	18,000	0.024	0.009	2
7FBC	0.1	0.02	821	15,400	0.024	0.009	3
	0.2	0.02	667	15,400	0.024	0.009	3
	0.2	0.05	898	38,500	0.089	0.016	3
	0.3	0.02	616	15,400	0.024	0.009	3
11FMS	0.1	0.02	1716	19,800	0.024	0.009	1.5
	0.2	0.02	1518	19,800	0.024	0.009	1.5
	0.2	0.05	1815	49,500	0.089	0.016	1.5
	0.3	0.02	1122	19,800	0.024	0.009	2
11FBS	0.1	0.02	2520	21,000	0.024	0.009	1
	0.2	0.02	2310	21,000	0.024	0.009	1
	0.2	0.05	1925	52,500	0.088	0.016	1.5
	0.3	0.02	1190	21,000	0.024	0.009	2
11FMC	0.1	0.02	1890	27,000	0.023	0.009	2
	0.2	0.02	2070	27,000	0.023	0.009	2
	0.2	0.05	898	38,500	0.086	0.016	3
	0.3	0.02	1530	27,000	0.023	0.009	2
11FBC	0.1	0.02	1200	22,500	0.024	0.009	3
	0.2	0.02	975	22,500	0.024	0.009	3
	0.2	0.05	1312	56,250	0.088	0.016	3
	0.3	0.02	900	22,500	0.024	0.009	3

Table 5 Near-field ground motions used in the NTHAs

Event name, year	Record station	Magnitude (M_W)	R_{Rup} (km)	PGA (g)
Bam, 2003	Bam	6.6	1.7	0.629
Tabas, 1978	Tabas	7.3	2	0.86
Imperial Valley, 1979	El Centro	6.5	10.3	0.212
Northridge, 1994	Jensen	6.7	5.4	0.617
Manjil, 1990	Abbar	7.3	12.5	0.498
Duzce, 1999	Duzce	7.1	6.6	0.52
Kocaeli, 1999	Gebze	7.5	10.9	0.143

Table 6 Far-field ground motions used in the NTHAs

Event name, year	Record station	Magnitude (M_W)	R_{Rup} (km)	PGA (g)
Bam, 2003	Baft	6.6	169.5	0.014
Tabas, 1978	Tabas	7.3	120.8	0.066
Imperial Valley, 1979	Plaster City	6.5	31.7	0.057
Northridge, 1994	Anaverde	6.7	38.4	0.06
Manjil, 1990	Tonekabon	7.3	93.6	0.137
Duzce, 1999	Arcelik	7.1	131.4	0.008
Kocaeli, 1999	Erikli	7.5	142.3	0.101

link element (friction isolator) of ETABS with the design details given in Table 4.

5 Ground Motions

The structures are subjected to seven near-field and seven far-field ground motion records. The records are selected and downloaded from the ground motion database of PEER (2017). The events are the same for both the near- and far-field records. The stations are selected as the nearest stations to the origin in the cases of near-field records, and the largest distances are selected for the far-field records.

Table 5 shows the details for the near-field ground motion records, regarding the names of the stations that the ground motions have been recorded, magnitude of the main event, closest distance to the rupture, and the peak ground acceleration in the record. Far-field ground motion records are similarly shown in Table 6 for their technical details, the same as those given above for the near-field records.

All the ground motions are scaled to the design spectrum of the structures, using SeismoMatch (2016). The design spectrum is obtained based on the specific requirements of the Iranian guideline for design and practice of base ISs in buildings (2010) known as guideline No. 523 of office of deputy for strategic supervision of the bureau of technical execution system of the vice presidency for strategic planning and supervision and the Iranian guidelines for design of seismic base-isolated buildings (2016) considered in addition to the Iranian code of practice for seismic-resistant design of buildings (2015) known as the yellow book or Standard No 2800. The matching algorithm is the default well-known wavelets algorithm of the SeismoMatch, proposed by Hancock et al. (2006). Matching is carried out for the period range 0.05–2.05 s based on the period range of the structural models varied between 0.1 and 2 s, as reported in Tables 7 and 8.

Figure 5 shows the near-field spectra obtained from SeismoMatch for the near-field ground motion records of Table 5 scaled to match the design spectrum within the period range of the structural models.

Figure 6, similarly, shows the scaled far-field spectra obtained from SeismoMatch for the far-field ground motion records of Table 6.

All the 14 scaled ground motion records are used in both nonlinear (for the base-isolated building frames) and linear (for the fixed-base building frames) time history analyses carried out by ETABS, when the results are presented and discussed in the next section.

6 Results and Discussion

Seismic performances of the aseismically base-isolated building frames are studied in terms of base shears, story accelerations, and story displacements obtained from 1176 NTHAs on the structural models introduced in Tables 2, 3, and 4 subjected to the ground motion records of Tables 5 and 6 scaled to the design spectrum as shown in Figs. 5 and 6. These performance criteria are also studied through 168 additional linear time history analyses for the traditional fixed-base buildings (see the descriptions for 3TMS, 3TBS, 3TMC, 3TBC, 7TMS, 7TBS, 7TMC, 7TBC, 11TMS, 11TBS, 11TMC, and 11TBC in Table 2) subjected to the same records in order to provide the opportunity of comparing the seismic performances of the base-isolated buildings to those of the traditional fixed-base buildings.

Table 7 summarizes the base shears obtained from the analyses carried out on the isolated and the fixed-base buildings subjected to the near-field records. The base shears are reported on average over the all isolation strategies (three cases for HRB and four cases for FPS) designed with the details given in Tables 3 and 4, respectively, for isolation with HRB and FPS. The same are reported in Table 8 for the buildings subjected to the far-field records. The data provided in Tables 7 and 8 are used to generate the diagrams of Figs. 7 and 8 in order to reflect the

Table 7 Base shears in near-field ground motion records

Structure			Tabas	Northridge	Manjil	Kocaeli	Imperial Valley	Duzce	Bam	Average
Name	ζ (%)	T (s)								
3TMS	5	0.7	237	385	414	390	468	412	304	397
3FMS	10	1.4	67	187	186	167	146	180	178	173
3HMS	16	1.4	77	146	170	162	151	156	218	168
3TBS	5	0.2	954	555	623	388	378	476	957	573
3FBS	9	1.2	48	117	124	63	52	117	126	104
3HBS	16	1.2	57	149	178	172	155	159	208	169
3TMC	5	0.6	286	434	461	491	536	447	485	482
3FMC	10	1.4	61	149	152	120	92	155	236	154
3HMC	16	1.4	130	211	265	252	259	242	334	258
3TBC	5	0.1	479	215	891	329	188	331	713	433
3FBC	10	1.1	68	56	89	111	36	214	59	130
3HBC	16	1.1	117	213	276	260	278	260	272	260
7TMS	5	1.3	310	575	513	602	570	509	685	577
7FMS	10	1.8	171	379	429	287	225	390	365	345
7HMS	16	1.8	176	355	364	335	299	372	364	357
7TBS	5	0.4	789	982	1134	976	570	1184	913	969
7FBS	11	1.3	78	168	202	116	80	208	191	182
7HBS	16	1.3	120	343	385	366	318	302	455	360
7TMC	5	0.9	401	985	960	908	987	925	885	953
7FMC	11	1.5	138	262	291	163	131	270	275	257
7HMC	16	1.6	280	434	585	548	581	599	795	597
7TBC	5	0.2	2223	1571	1674	1492	700	1345	2380	1676
7FBC	18	1.6	267	280	428	405	212	858	284	374
7HBC	16	1.2	208	485	634	620	619	578	645	591
11TMS	5	1.5	458	969	1181	1110	1160	1036	1287	1124
11FMS	11	2	213	468	499	217	209	419	421	394
11HMS	16	2	265	593	570	503	435	530	571	537
11TBS	5	0.5	3203	1147	1973	1104	1539	1834	2877	1768
11FBS	10	1.3	110	144	237	187	96	309	206	240
11HBS	16	1.4	188	493	601	535	457	497	674	540
11TMC	5	1.4	362	693	940	832	936	891	1024	891
11FMC	12	1.9	252	485	613	259	228	474	456	455
11HMC	16	1.9	432	899	999	932	977	1039	915	978
11TBC	5	0.2	924	1613	1597	1518	1172	1408	1422	1429
11FBC	18	1.7	406	486	705	533	349	926	563	733
11HBC	16	1.3	327	705	946	911	898	834	978	868

sensitivities of the ISs to the inherent structural characteristics, regarding base shear as the main performance criteria indicating the energy input during ground motion.

Detailed effects of the inherent structural characteristics on base shears are represented by the trend lines logarithmically fitted on the analytical data in Figs. 9, 10, and 11. As it was already mentioned in Sect. 2, superstructure mass and stiffness and isolation damping are considered as the variables. The isolation stiffness is not discussed because it is basically controlled through the design for the target displacement. The effect of the superstructure damping is also neglected compared to the effect of the damping in IS.

As far as the discussion regarding other performance criteria (story acceleration and story displacement) is considered, for the purpose of brevity the sensitivity diagrams and the trend-line curves reflecting the effects of pre-defined inherent structural characteristics on the seismic performance are presented without reporting the numerical data given in tables. Figures 12 and 13 reflect the sensitivities of the ISs (in terms of reducing the story accelerations) to the inherent structural characteristics. Figure 12 presents the sensitivities of the ISs in near-field ground motions, and

Table 8 Base shears in far-field ground motion records

Structure			Tabas	Northridge	Manjil	Kocaeli	Imperial Valley	Duzce	Bam	Average
Name	ζ (%)	*T* (s)								
3TMS	5	0.7	237	334	502	538	405	168	317	357
3FMS	10	1.4	67	170	242	136	178	85	120	143
3HMS	16	1.4	77	157	190	147	134	79	128	130
3TBS	5	0.2	954	399	400	477	631	99	329	470
3FBS	9	1.2	48	83	314	77	92	28	64	101
3HBS	16	1.2	56	159	190	154	140	71	126	128
3TMC	5	0.6	286	423	542	579	570	260	485	449
3FMC	10	1.4	61	125	276	111	135	59	95	123
3HMC	16	1.4	130	265	258	255	212	98	226	206
3TBC	5	0.1	479	705	289	346	394	100	221	362
3FBC	10	1.1	68	52	373	128	129	53	44	121
3HBC	16	1.1	117	295	287	280	235	136	198	221
7TMS	5	1.3	310	645	671	601	555	234	382	485
7FMS	10	1.8	171	291	750	276	339	141	238	315
7HMS	16	1.8	176	302	600	307	332	229	327	325
7TBS	5	0.4	789	915	1105	766	1067	932	1065	948
7FBS	11	1.3	78	126	631	140	143	40	88	178
7HBS	16	1.3	120	322	476	319	305	156	270	281
7TMC	5	0.9	401	892	1049	1084	1022	215	899	795
7FMC	11	1.5	138	204	749	199	214	77	161	249
7HMC	16	1.6	280	556	633	564	487	274	486	469
7TBC	5	0.2	2223	1295	1123	1155	1369	299	1129	1228
7FBC	18	1.6	267	335	138	449	478	135	202	286
7HBC	16	1.2	208	683	621	638	503	238	427	474
11TMS	5	1.5	458	1066	1180	1175	1138	545	1002	938
11FMS	11	2	213	363	1263	221	243	106	251	380
11HMS	16	2	265	492	581	423	515	349	427	436
11TBS	5	0.5	3203	1858	1861	1925	1543	593	1334	1760
11FBS	10	1.3	110	178	1195	198	187	52	101	289
11HBS	16	1.4	188	464	781	465	447	235	404	426
11TMC	5	1.4	362	910	967	808	962	536	655	743
11FMC	12	1.9	252	377	330	332	355	124	272	292
11HMC	16	1.9	432	913	927	882	993	721	621	784
11TBC	5	0.2	924	1659	1588	1112	1588	674	1237	1255
11FBC	18	1.7	406	540	1499	631	570	203	341	599
11HBC	16	1.3	327	944	891	925	737	376	632	690

Fig. 13 reflects the situation in far-field ground motions. Detailed effects of the inherent structural characteristics on story accelerations are also represented in Figs. 14, 15, and 16. Similarly, Figs. 17 and 18 reflect the sensitivities of the ISs (in terms of reducing the story displacements) to the inherent structural characteristics. Detailed effects of the inherent structural characteristics on story accelerations are also represented in Figs. 19, 20, and 21.

Comparing the dashed lines passing separately over the average responses of FPS and HRB in Figs. 7 and 8, it is clear that FPS is less sensitive to the inherent structural characteristics, in terms of reducing the base shear. It can also be obviously concluded from the average response curves on the histograms of Figs. 7 and 8 that FPS is almost always more effective than HRB, when the base shear is considered, in both the near- and far-field ground motions. The average 65% reduction of base shear in the lighter structures compared to 85% reduction of base shear in the heavier structures in Fig. 9 indicates that aseismic base isolation is more effective in heavier structures. As shown in Fig. 10, base isolation further reduces the base shear if the superstructure is stiffer. A minimum amount of damping is useful for the reduction of base shear through aseismic base isolation, as it is shown in Fig. 11 for FPS. The higher sensitivity

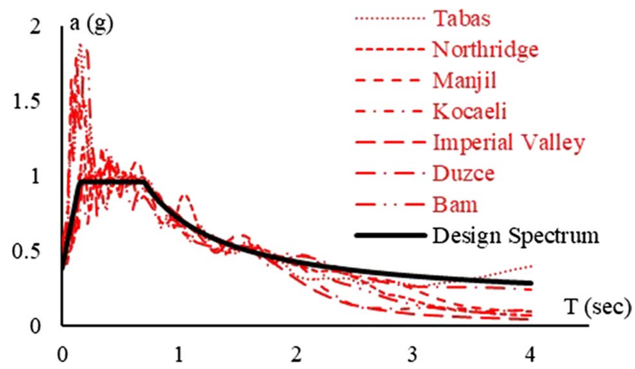

Fig. 5 Near-field spectra scaled to design spectrum

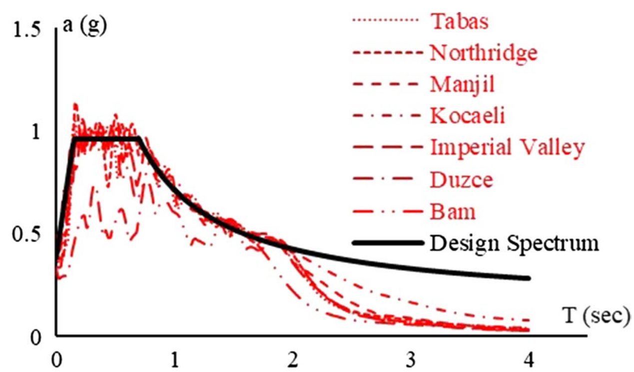

Fig. 6 Far-field spectra scaled to the design spectrum

of HRB to the inherent structural characteristics is more evident based on the higher zigzaggedness of the dashed line passing over its average responses compared to those of FPS in Figs. 12 and 13. It is again clear that FPS better controls the story accelerations compared to HRB, in both the near- and far-field ground motions. Story accelerations in the structure mounted on FPS are almost 20% less than those controlled by HRB. Based on the data presented in Fig. 14, the effectiveness of HRB in reducing the story acceleration reduces obviously by the inherent increase in the superstructure mass, while the effect is lighter for the effectiveness of FPS in controlling the story acceleration. The effect of the stiffness in terms of controlling the story accelerations is like its effect on base shear. Damping is always useful for the reduction of story accelerations.

Both FPS and HRB are almost similarly sensitive to the inherent structural characteristics, in terms of controlling the story displacements (see Figs. 17 and 18). The sensitivities are less than those in terms of the base shears and story accelerations. HRB is, however, more effective than FPS in terms of reducing the story displacements, always, in both the near- and far-field ground motions. All the effects of the inherent structural mass, stiffness, and damping on the

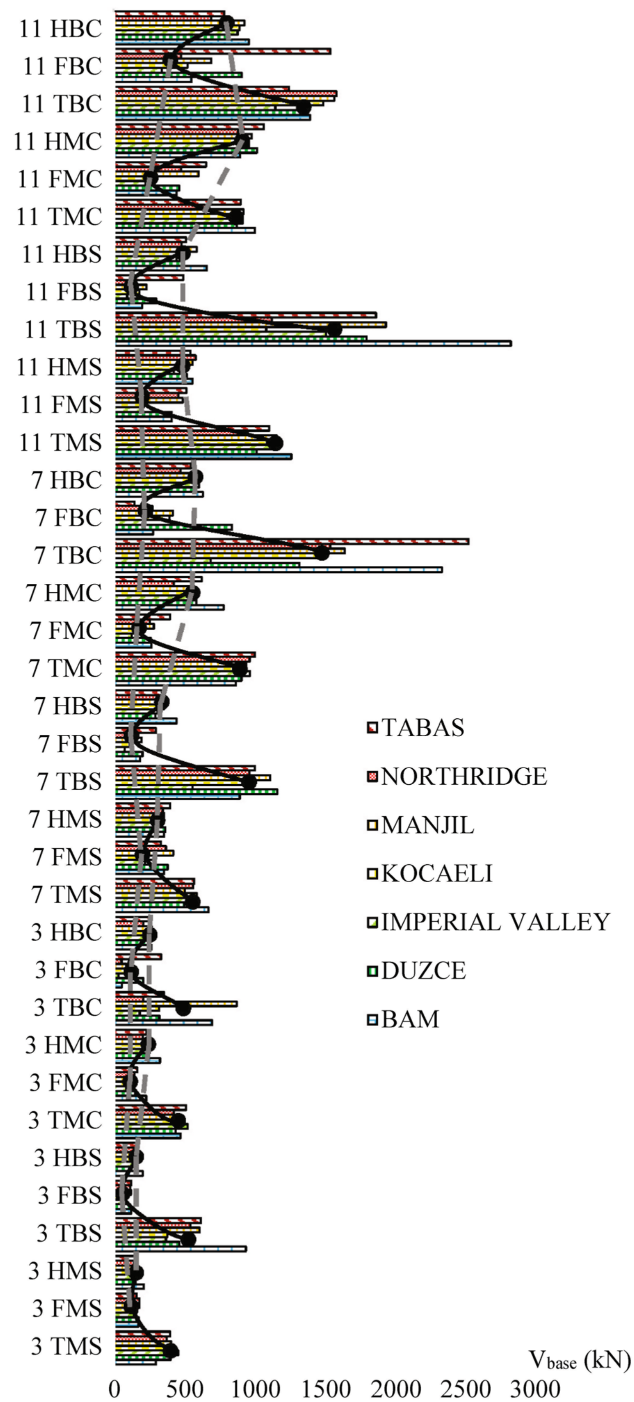

Fig. 7 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the base shear, in the near-field ground motions

control of story displacements via base isolation are less important compared to the effects of those on the control of story accelerations and base shears (compare Figs. 19, 20, 21 to Figs. 14, 15, 16 and Figs. 9, 10, 11, 12, 13, 14, 15, 16). It is, however, remarkable that inherent increase

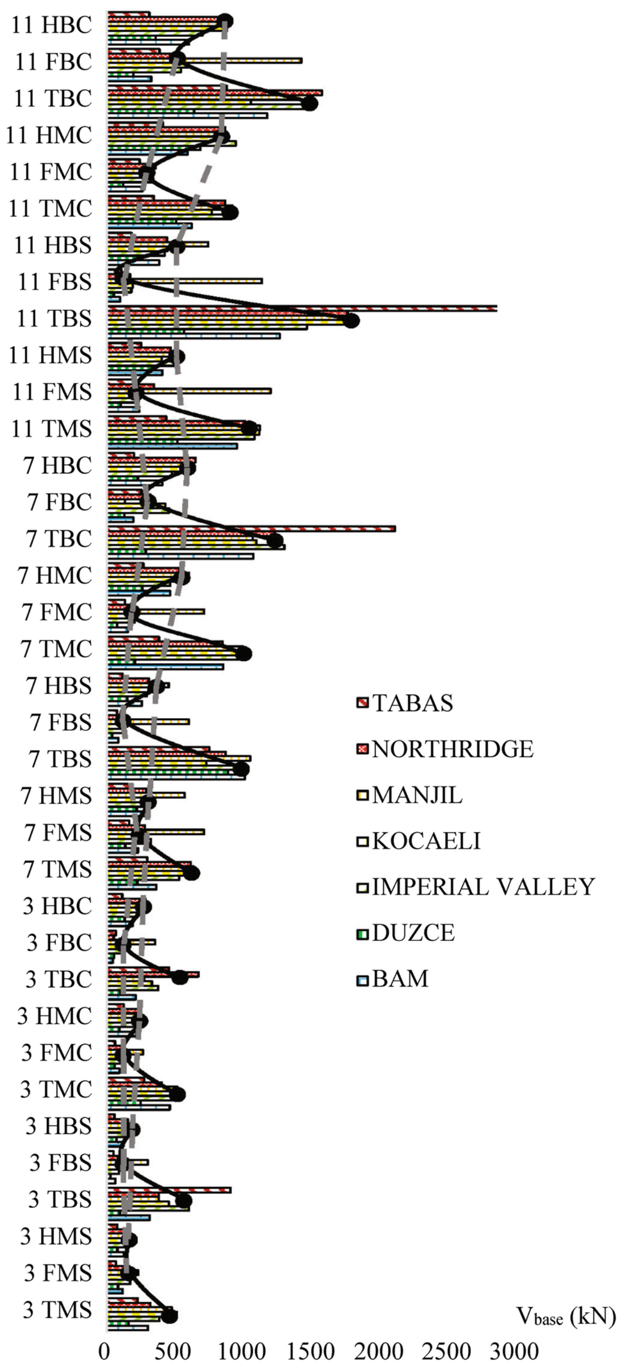

Fig. 8 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the base shear, in the far-field ground motions

in the isolation damping will increase the story displacements, as it can be concluded from Fig. 21. It is expectable because the damping generally adds an amount of stiffness to the IS. Superstructure stiffness increases the effectiveness of isolation in terms of reducing the story displacements a little. As far as the effects of the inherent structural mass are considered, Fig. 19 shows that the effectiveness of base isolation in terms of controlling the story displacements reduces for the heavier structures.

7 Conclusions

The outcomes of an extensive parametric study investigating the effects of the inherent structural characteristics on the performances of aseismic isolation were reported. It was discussed that this study is different than the investigations of the effects of additional mass and damping or stiffening the superstructure, which are aimed at evaluation of the performance enhancement. The purpose of this study is to understand the effects of the inherent structural characteristics to reveal the practical effectiveness of ISs (isolation systems), which is also different than the study of the aging effects that result in some deteriorations through the increases in post-yield stiffnesses and characteristic strengths (McVitty and Constantinou 2015).

Mass, stiffness, and damping (the fundamental dynamic characteristics) were varied through the variation of the materials, the structural systems of the superstructures, heights of the superstructures, types of the ISs, and the design parameters of the ISs to practically capture the effects of the inherent structural characteristics. The materials used in the superstructures were steel and concrete, as in the everyday practice of construction, leading to the consideration of the two common types of buildings (steel-framed and reinforced concrete buildings). Structural systems considered were braced frames (X-bracing for steel-framed and shear walls for reinforced concrete buildings) and moment-resisting frames, as the two practical systems. The heights were varied based on the numbers of the stories of the buildings designed with 3, 7, and 11 stories. All the buildings were designed according to the provisions of the Iranian code of practice for seismic-resistant design of buildings known as the yellow book or Standard No 2800 (2015) for soil type III in a region with very high relative risk of seismic hazard. The ISs were chosen to be HRB (high-damping laminated rubber bearing) or FPS (friction pendulum system), as the most famous currently used practical ISs. Damping and coefficient of friction, varied in the practical ranges, were, respectively, selected as the main design parameters of ISs. The seismic performance criteria were base shear (as the criterion for the energy input) and story acceleration and displacement (as the serviceability criteria). The methodology was described, and the results were discussed including the sensitivities of the ISs to the inherent structural characteristics together with the effectiveness of the ISs in terms of reducing the performance criteria. The conclusions are summarized as follows:

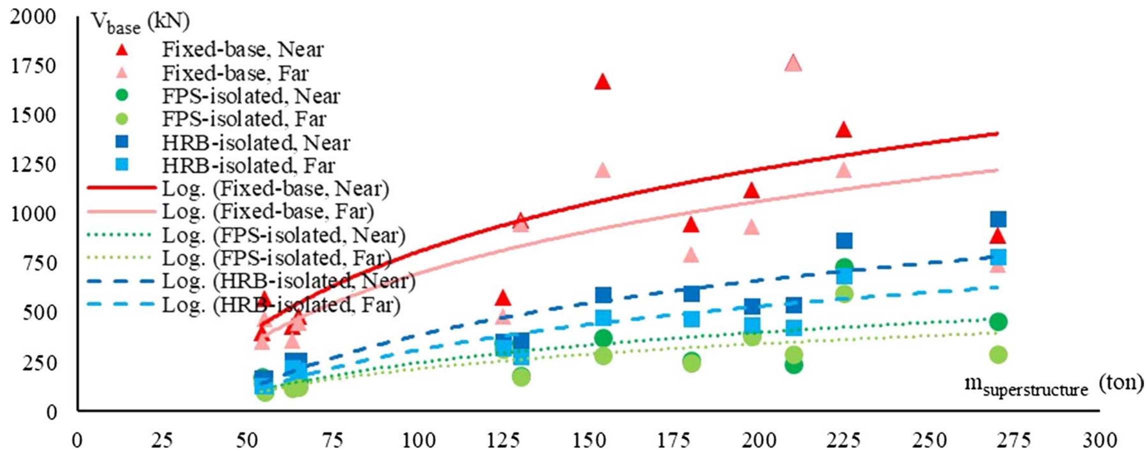

Fig. 9 The effects of the inherent superstructure mass on the reduction of base shear through aseismic isolation

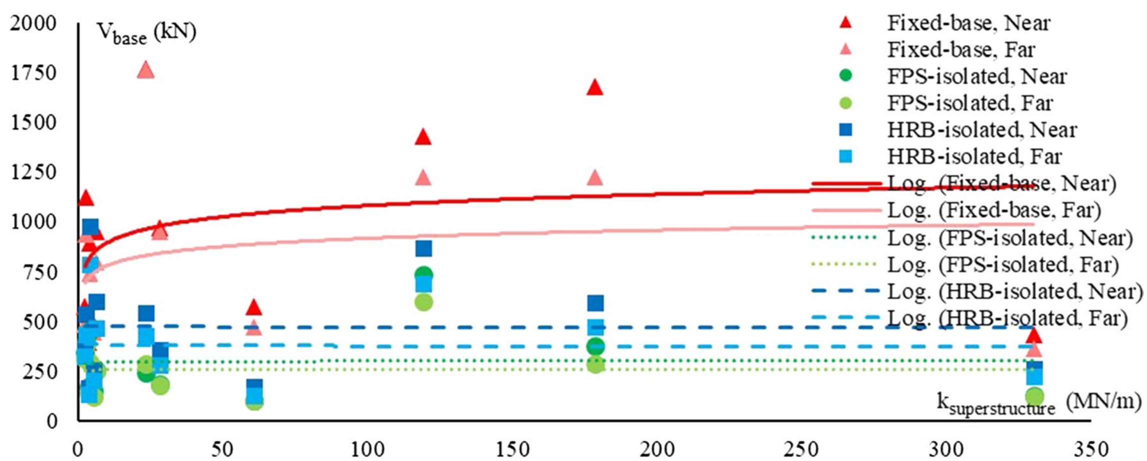

Fig. 10 The effects of the inherent superstructure stiffness on the reduction of base shear through aseismic isolation

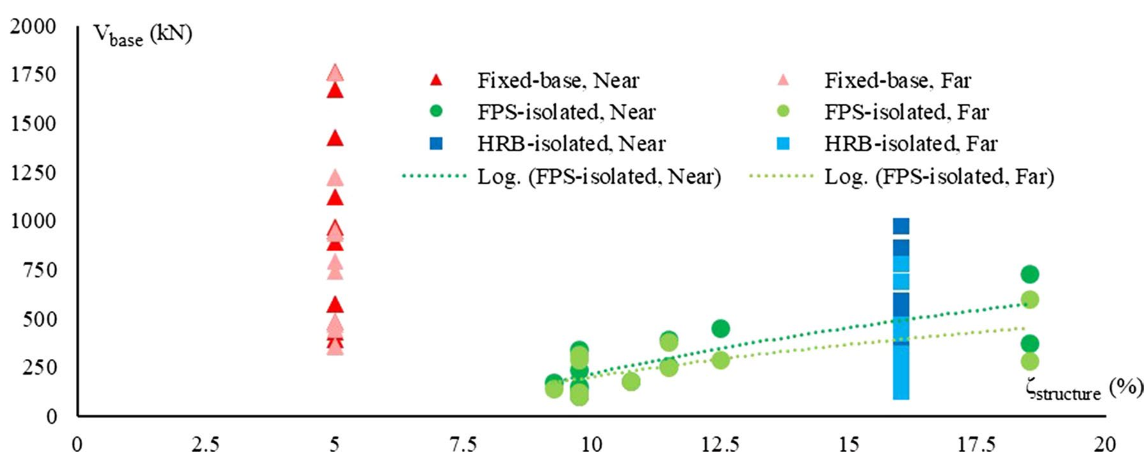

Fig. 11 The effects of the inherent structural damping on the reduction of base shear through aseismic isolation

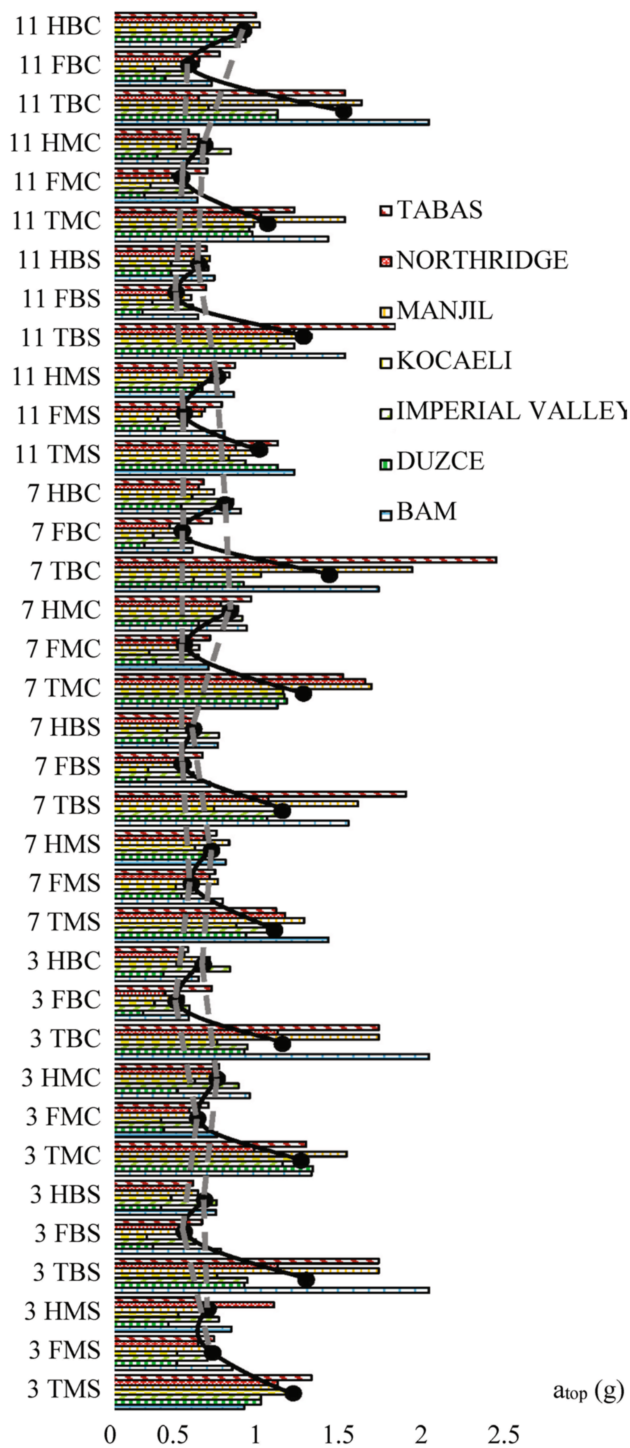

Fig. 12 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the story acceleration, in the near-field ground motions

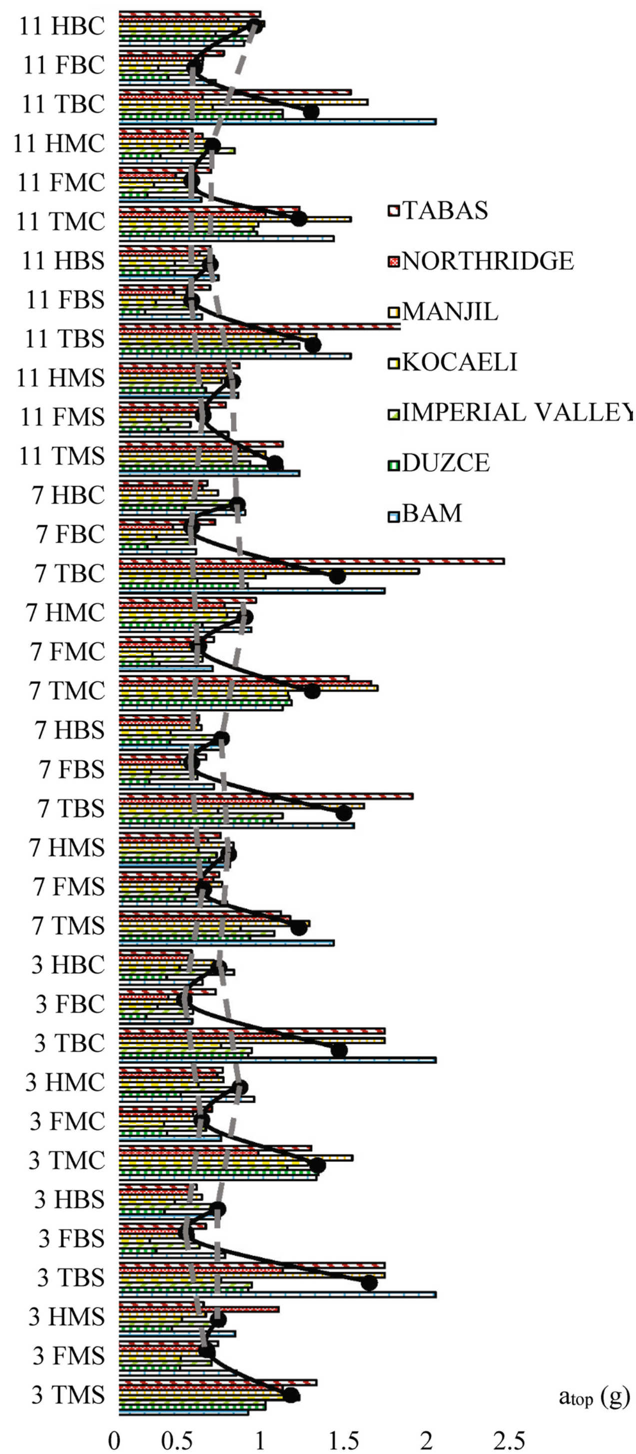

Fig. 13 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the story acceleration, in the far-field ground motions

- The inherent structural mass has a positive effect on the reduction of energy input through aseismic base isolation. This means that aseismic base isolation is more effective for the structures with larger mass. The story accelerations and story displacements, however, will poorly be controlled in the heavier superstructures.

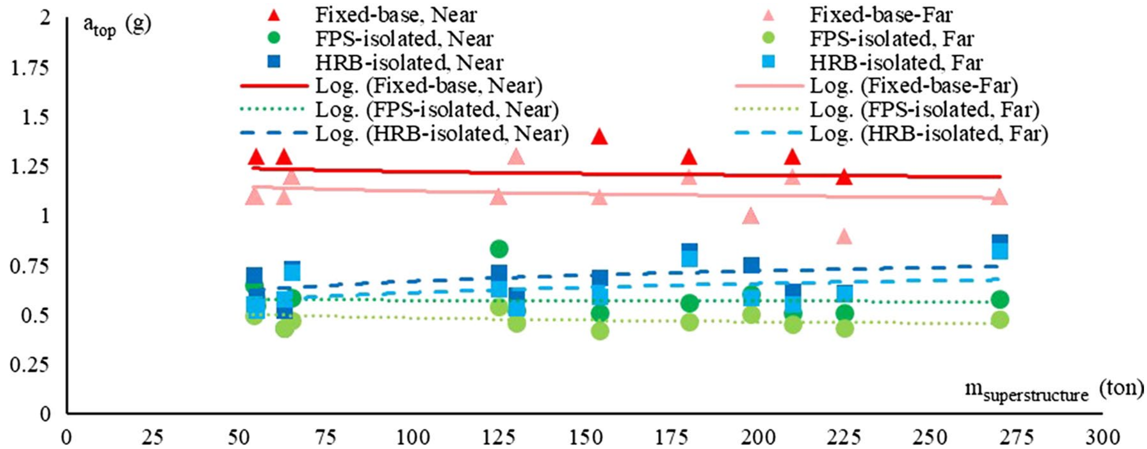

Fig. 14 The effects of the inherent superstructure mass on the story acceleration control through aseismic isolation

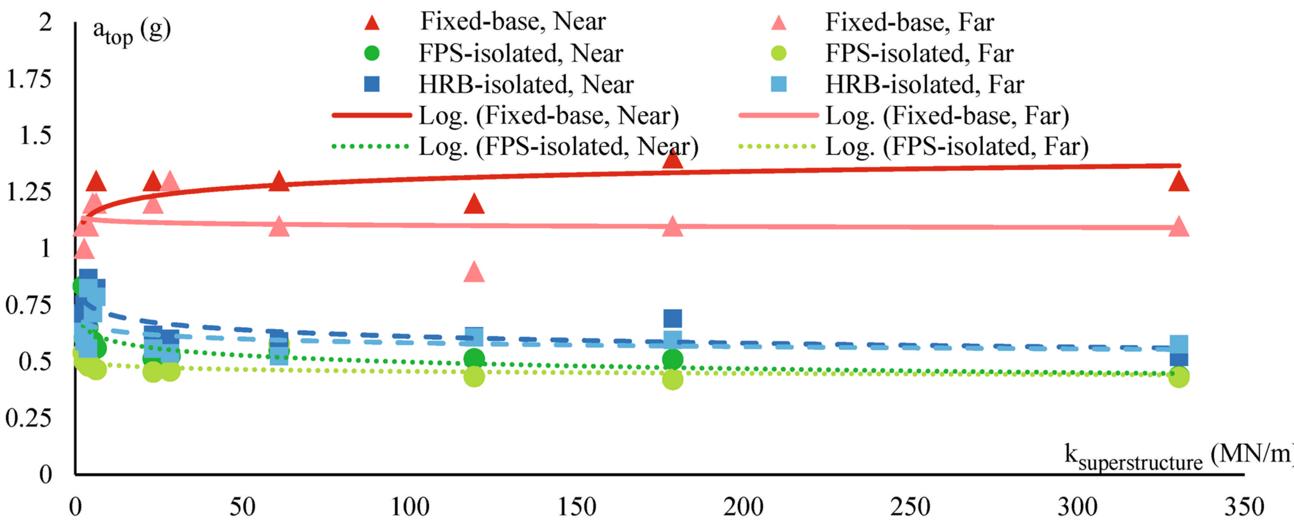

Fig. 15 The effects of the inherent superstructure stiffness on the story acceleration control through aseismic isolation

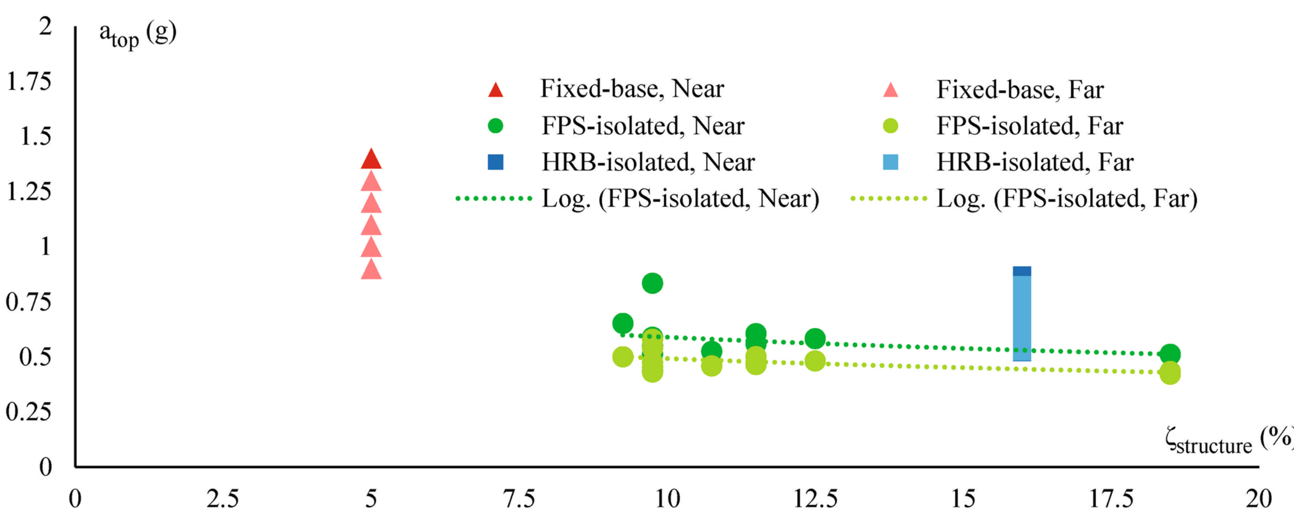

Fig. 16 The effects of the inherent structural damping on the story acceleration control through aseismic isolation

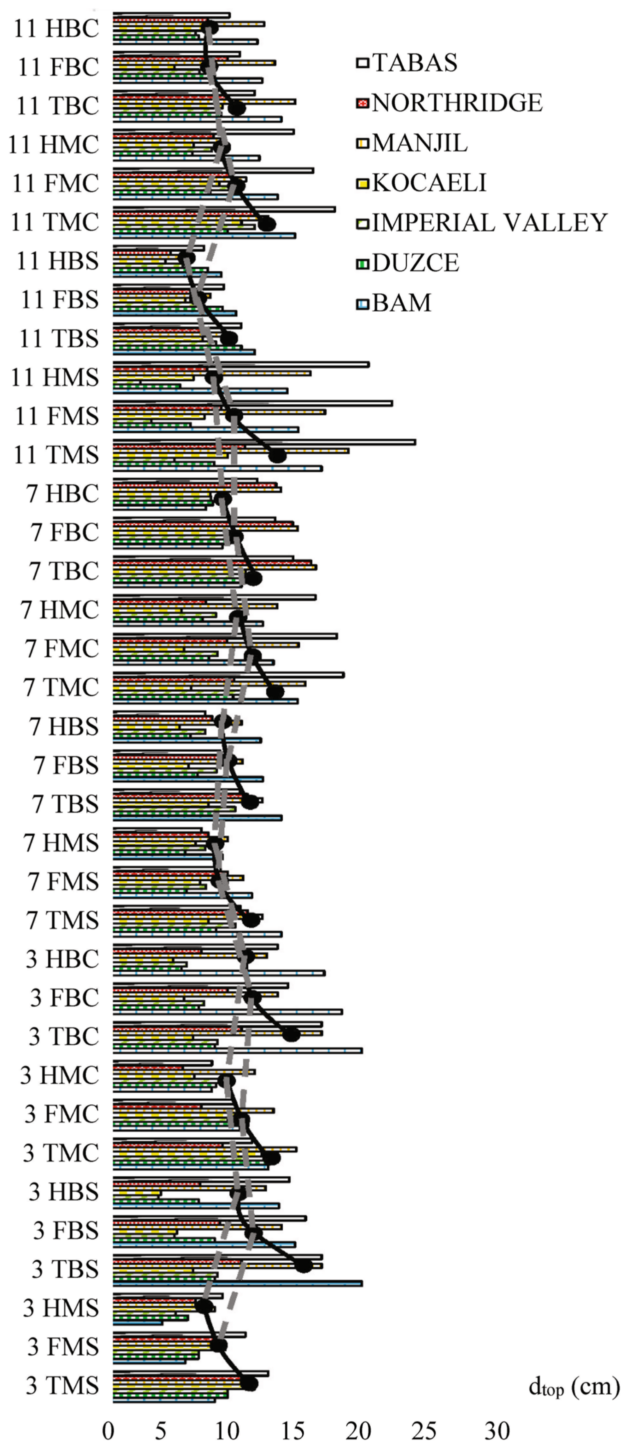

Fig. 17 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the story displacement, in the near-field ground motions

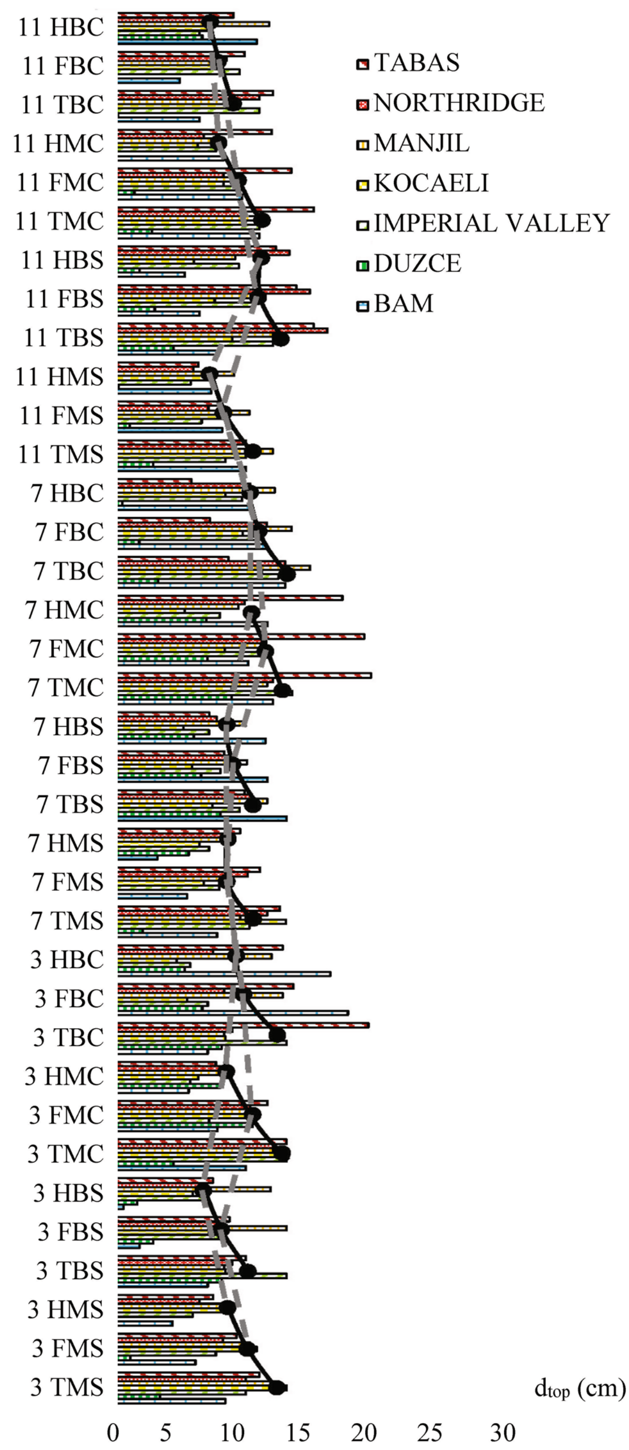

Fig. 18 The sensitivities of the ISs to the inherent structural characteristics, in terms of reducing the story displacement, in the far-field ground motions

Based on the results, it can also be concluded that additional mass will help the aseismic base isolation in energy input reduction. This is in accordance with the results reported already by Jalali and Narjabadifam (2006) through the investigation of the effects of additional mass, stiffness, and damping on the performances of buildings base-isolated using lead-plug laminated rubber bearings.

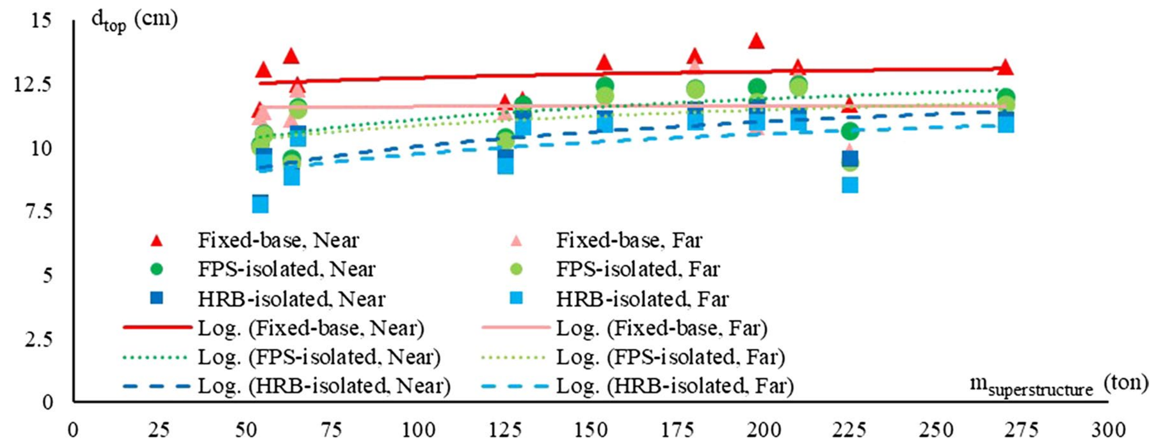

Fig. 19 The effects of the inherent superstructure mass on the story displacement control through aseismic isolation

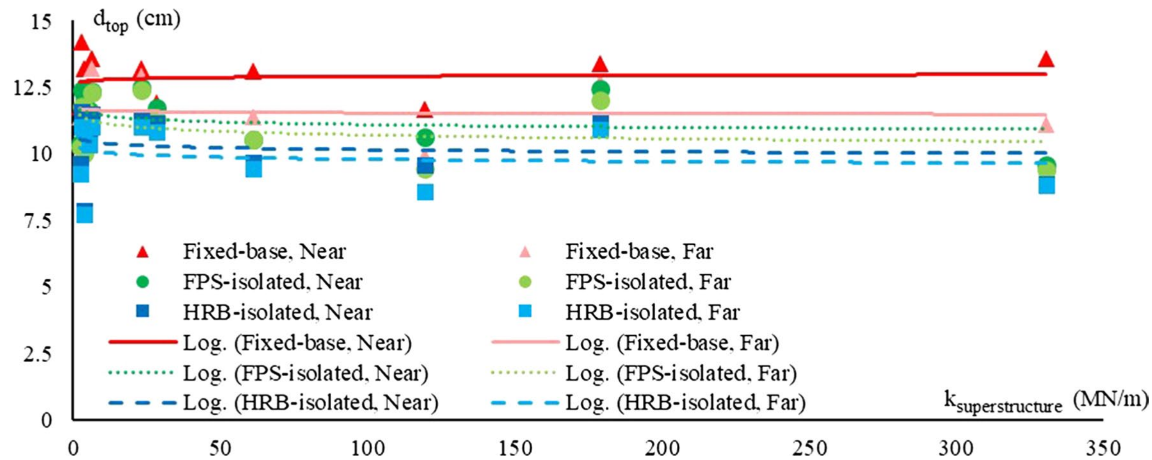

Fig. 20 The effects of the inherent superstructure stiffness on the story displacement control through aseismic isolation

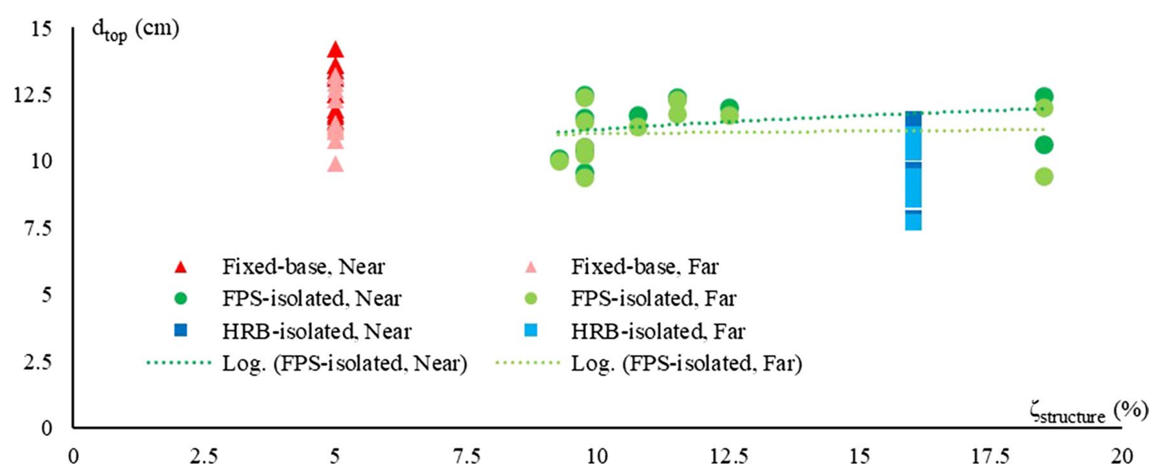

Fig. 21 The effects of the inherent structural damping on the story displacement control through aseismic isolation

- The inherent stiffness of superstructure is useful for the improvement of the performances of aseismic base isolation, regarding all the performance criteria including the energy input and the mitigation of the responses. In the other words, aseismic base isolation performs better with the stiffer superstructures.

The stiffening of the superstructure will also useful in aseismic base isolation, as it was already indicated by Jain and Thakkar (2004) investigating the effects of stiffening on the performances of aseismic base isolation.

- The damping provided inherently by the IS further reduces the story accelerations, while it has a reverse effect on the energy input and story displacements. Damping is, however, required for the mitigation of the large isolation displacements in near-field ground motions.

It should be added that better performances are expected by the modern damping mechanisms like the hysteretic damping provided by austenitic shape memory alloys, as it has been demonstrated by Cardone et al. (2011), regarding also the outcomes of the research by Kelly (1999) and its discussion by Hall (1999).

- The seismic performances of base isolation by FPS are less sensitive to the inherent structural characteristics, when compared to HRB.
- The effectiveness of FPS in reducing the energy input is more than HRB in both near- and far-field ground motions. FPS is also able to better control the story accelerations. Story displacements are, at the same time, better controlled by HRB. It should, however, be noted that while the design displacements of FPS and HRB are taken to be the same in this study, the levels of energy dissipation capabilities should be compared with more details, which was not the scope of this paper, but suggested for further investigations.

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