Seismic performance of double skin semi-base-isolated structures

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Abstract. Base isolation technology is a popular and powerful isolation technology. This technique can greatly reduce the seismic response of the structure, so as to reduce the damage to the structure. Base isolation method decouples the superstructure from the base by installing a flexible layer under each column to reduce dynamic response in the earthquake and elongate the time period of structures due to its inherent flexibility. However, the long time period causes large displacement. In addition, base isolation devices are highly vulnerable due to uplift forces produced by lateral force resisting systems (LFRS). In this study, an adjustable structure with a new configuration, namely double skin semi-base-isolated (SBI) structure is presented to solve the above problems. The LFRS is omitted in the proposed SBI structure and the time period and displacement are reduced compared to the conventional base-isolated structure. The force-deformation behavior of an isolator is modeled as bi-linear hysteretic behavior which can be effectively used to model all isolation system in practice. This study investigates the seismic performance of 10-story double skin SBI reinforced concrete (RC) structure under far-fault earthquake ground motion by numerical method. Results demonstrate that the SBI system is significantly adjustable with the use of RC coupling beams between the inner core and outer frames. By increasing or reducing the number of connected floors in the SBI system, dynamic behaviors of the SBI system can be changed. The adjusted structure can be created by adding and removing RC coupling beams at every arbitrary floor level.

1 Introduction

Base isolation is a passive control technique that used to separate the superstructure from the base with a low stiffness layer to transfer the fundamental frequency of structural vibration to a value lower than the frequencies of earthquake ground motions [1-3]. The aim of using base isolation devices is to lengthen the fundamental period of the structure by its inherent flexibility to reduce the transmission of energy from the ground [4, 5]. This flexible layer is utilized to reduce the amount of force induced by the ground motions such as story accelerations, relative story drift, and story shear forces. These forces are diminished drastically, while the isolators would undergo reasonable displacement [6-8]. Base isolation can elongate the time period of structures because of its flexibility. Therefore flexible structures have large lateral displacement. Furthermore, the efficiency of base isolation in tall and flexible structures that inherently had a long time period and large displacements drastically reduced. In the structures with lateral force resisting system (LFRS), in order for the lateral-load resisting system to work, shear walls and bracing systems receiving the lateral force must transfer on the isolators at the base. The lateral forces will induce uplift forces due to overturning and vertical force during the large earthquake. For a structure, isolated on

elastomeric bearings, the effect of uplift cause a large to tensile forces in the rubber bearings [9,10]. The tensile force can cause instability in the isolation system. To overcome this problem, the best method suggested, is to diminish uplift forces on the isolators. This is done by accurately configuring the lateral load-resisting systems. Furthermore, several research projects have been conducted to account for various cases of double skin facade (DSF) buildings in which the lateral loads that have been assigned to and are resisted by the primary building structure, while the exterior skin is employed as a curtain wall. McKay et al. [11] studied the importance of designing facade envelope components against the seismic. Furthermore, Pipitone et al. [12] employed several layouts of DSF with mass dampers to reduce the seismic vibration in structures subjected to the variety of earthquake excitations. Fu and Zhang [13] also proposed an integrated control system to combine double-skin facade and mass dampers in buildings. Their results indicated that mass damper systems can significantly reduce structural motions under earthquake excitation. In [14], the effect of distributed mass dampers in multi-story double-skin facade building under a set of 20 earthquake excitations was investigated. It was concluded that DSF panels can reduce the seismic response up to 35% of the uncontrolled case.

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Therefore, based on the above findings, this study presented an adjustable structure with a new configuration, namely double skin semi-base-isolated (SBI) structure. To study the seismic performance of the double skin SBI structure, six double skin SBI RC structures in 10-story were designed. The finite element analysis of the structures under the action of far-fault earthquake ground motions were carried out based on the OpenSees program.

2 Double skin semi-base-isolated (SBI) structure

Double skin SBI structure is consisted of two parts: an inner core and outer skin. Inner core includes gravity columns with base isolated, while outer skin has frames with the fixed base including lateral force resisting system (LFRS). Base isolation requires a gap between the inner core and its surroundings to afford enough distance for the displacement of isolators. This gap should be appropriately preserved and must remain free through the entire life of the structure [15, 16]. RC coupling beams were utilized in the seismic gap distance between the inner core and outer skin to connect the story floor level to outer frames. In this system to overcome the instability of the isolation devices, LFRS such as shear walls and bracings were completely transferred from inner core to the outer skin with fixed-base. The isolation system consists of layers of thin steel shim and rubber, to provide vertical stiffness and horizontal flexibility. For dissipating the seismic energy and reducing the bearing displacement, a lead-core has been inserted into the holes in the elastomeric bearing [7, 17]. The mechanical properties of the isolators were set to comply with the recommendation of the UBC building code subjected to critical reaction force in inner core columns. Three parameters were used to simulate the nonlinear force-deformation behavior of the isolators through the bilinear hysteresis loop as shown in Fig. 1 (b), namely (i) pre-yield stiffness (K_1), (ii) post-yield stiffness (K_2), and characteristic strength (Q). Cross section configuration and bi-linear hysteretic model of lead rubber bearing (LRB) device are shown in Fig. 1.

Fig. 1. Lead rubber bearing (LRB).

2 Finite element modeling

In order to evaluate the seismic performance of double skin SBI structure, a 10-story double skin reinforced concrete was presented in this paper. The typical floor plan of the structural is depicted in Fig.2.

The prototype structure is assumed to be as a residential structure with usual live and dead loads. The design of building satisfies UBC-97 [18] and ACI 318-11 [19] requirements. The prototype building is assumed to be located in seismic zone 3 on the stiff soil (S_D) based on UBC-97 classification. All stories have typical heights equal to 3.0 meters. The compressive strength of concrete is assumed to be 25 MPa and the tensile strength of rebar is 400 MPa. Concrete slabs are at story levels with 150 mm thickness. All elements in superstructure were created using the frame element such as beam and column sections. Moment resisting connections are used at the intersection of beams and columns. RC coupling beams were designed with pinned connections to connect the inner core to the outer skin. Four RC shear walls are located in the outer frames in both longitudinal and transverse directions to withstand

lateral earthquake forces were designed according to ACI 318-11 code. Summary of cross-sectional

dimensions of structural elements are tabulated in Table 1.

Table 1. Cross-sectional dimensions of structural elements.

	Outer elements			Inner elements	
Story	Column (mm)	Beam (mm)	Shear wall (mm)	Column (mm)	Beam (mm)
1-7	700*700	600*400	Thickness=350	500*500	600*400
8-10	500*500	600*400	Thickness=250	400*400	600*400

For the purpose of this study, Three-dimensional (3D) numerical model of 10-story double skin SBI RC structure prototype building that has been modeled in OpenSees software, as illustrated in Fig. 3.

Fig. 3. 3D OpenSees model for 10-story structure

Nonlinear dynamic analysis was selected to estimate the response of the structure subjected to earthquake motion. For dynamic analysis, the mass of the structure was lumped at the beam-column joint at each floor level. Rigid constraints were imposed to define rigid diaphragms in every floor level nodes, to have equal lateral displacements in the structures.

Concrete01 was used for simulating uniaxial Kent-Scott-Park concrete material behavior. The steel were modeled using the uniaxial *Steel02*. In RC elements, Mander's model [20] was employed to define the properties of the concrete core (confined concrete). Superstructure elements were model using linear behavior of the beam-column element. The RC shear walls were simulated using the multi-layered shell element *ShellMITC4*. In this study, the section of solid shear walls was modeled with eight-layer shell elements, including the multi-dimensional concrete, reinforcement

material, with corresponding thicknesses. The analytical model of the LRB with bilinear force-deformation behavior was generated using the elastomeric bearing element with two nodes. Therefore, LRB isolator is able to withstand the weight of the superstructure, to provide horizontal flexibility with restoring force [17].

To study the seismic performance of the structure subjected to earthquake ground motions, six RC buildings based on the 10-story double SBI RC structures were designed. All prototype buildings with identical configuration are described as following. The double skin structures in consideration can be split into two parts, namely; inner core and outer frames. Among these, the outer frames were considered to be fixed with RC shear walls in both longitudinal and transverse directions that are hatched in the plan view. Each model is given a name, starting with the letters "IFBC" or "IIC" to represent inner fixed-base core and inner isolated core, (respectively), followed by numbers or with the word "All" to denote the floor number in inner core that is connected as a pinned connection to the outer frames with coupling beams.

Based on the above statements, six prototype models are defined as (IIC-10th), (IFBC-10th), (IIC-All), (IFBC-All), (IIC), and IFBC. Configurations of all the models are explained as the following. Model IIC-10th and model IFBC-10th stands for a double skin structure with the inner isolated core and inner fixed-base core in which the inner core has been connected to the outer frames at the tenth-floor level, respectively, as illustrated in Fig. 4 and Fig. 5. Model IIC-All and model IFBC-All stands for a double skin structure with the inner isolated core and inner fixed-base core in which the inner core has been connected to the outer frames at all floor levels, respectively, as illustrated in Fig. 6 and Fig. 7. Model IIC and model IFBC stands for a structure with an inner isolated core and inner fixed-base core only, respectively, which has no outer frames, as illustrated in Fig. 8 and Fig. 9. The detail-1 and detail-2 of the models were illustrated in Fig. 10.

Fig. 4. Model IIC-10th.

Fig. 5. Model IFBC-10th.

Fig. 6. Model IIC-All.

Fig. 7. Model IFBC-All.

Fig. 8. Model IIC.

Fig. 9. Model IFBC.

Fig. 10. Detail-1 and detail-2 of the models

3 Ground motion input

This paper selected 22 component pairs of horizontal bi-directional far-fault earthquake ground motions records from the next generation attenuation (NGA) project database developed by pacific earthquake engineering research (PEER), as shown in Table 2. The records had a moment magnitude between 6.5 and 7.51, and the closest distance to fault rupture ranged from 10.97 to 25.47 km [21]. The 22 component pairs of horizontal ground motions including the directional component (ϕ), which shows the direction of seismic input in E and N directions, where the letters E and N indicate the global direction of structures in X and Y direction, respectively, moment magnitude (M), closest distance to fault rupture (R), and peak ground acceleration (PGA) values.

The selected ground motions in this study were scaled using the first-mode vibration period with 5% critical damping. The design response spectrum site location on the soil condition S_D consists shear wave velocity 180 to 360 m/s on effective of zone 3 with seismic coefficient $C_v=0.54$ and $C_a=0.36$. Based on the first mode time period of each building the design spectral acceleration was estimated and tabulated in Table 3. A value of 5% Rayleigh damping, mass, and stiffness proportional damping, was used in the dynamic analysis [22]. The effective seismic weight for each floor was converted to lumped masses at the beam-column joint in the story levels for dynamic analysis.

Table 2. Properties of twenty-two ground motion records used.

No.	Event	Year	Station	M	R(km)	ϕ	PGA(g)
1	Cape Mendocino	1992	Fortuna Fire	7.01	20.41	E	0.283
						N	0.333
2	Cape Mendocino	1992	Centerville Beach	7.01	18.31	E	0.318
						N	0.477
3	Duzce, Turkey	1999	Lamont	7.14	11.46	E	0.131
						N	0.101
4	Friuli Italy-01	1976	Tolmezzo	6.5	15.82	E	0.357
						N	0.315
5	Imperial Valley-06	1979	Calipatria Fire	6.53	24.60	E	0.128
						N	0.078
6	Imperial Valley-06	1979	Superstition Mtn	6.53	24.61	E	0.111
						N	0.202
7	Irpinia Italy-01	1980	Calitri	6.9	17.64	E	0.126
						N	0.136
8	Irpinia Italy-01	1980	Brienza	6.9	22.56	E	0.219
						N	0.183
9	Kobe Japan	1995	Kakogawa	6.9	22.5	E	0.24
						N	0.324
10	Kocaeli Turkey	1999	Duzce	7.51	15.37	E	0.312
						N	0.364
11	Landers	1992	Coolwater	7.28	19.74	E	0.284
						N	0.417
12	Loma Prieta	1989	Gilroy-Historic Bldg	6.93	10.97	E	0.242
						N	0.285
13	Loma Prieta	1989	Sunnyvale - Colton Ave	6.93	24.23	E	0.2072
						N	0.2073
14	Northridge-01	1994	Beverly Hills	6.69	18.36	E	0.621
						N	0.45
15	Northridge-01	1994	Canyon Country	6.69	12.44	E	0.404
						N	0.472
16	Chuetsu-oki	2007	Kubikiku Hyakken	6.8	22.18	N	0.253
						E	0.214
17	Chuetsu-oki	2007	Shiura Nagaoka	6.8	20.17	N	0.22
						E	0.23

18	San Fernando	1971	Lake Hughes #9	6.61	22.57	E	0.170
						N	0.143
19	San Fernando	1971	Pasadena-CIT Athenaeum	6.61	25.47	E	0.097
						N	0.110
20	Spitak Armenia	1988	Gukasian	6.77	23.99	E	0.200
						N	0.174
21	Superstition Hills-02	1987	Plaster City	6.54	22.5	E	0.136
						N	0.200
22	Superstition Hills-02	1987	Poe Road	6.54	11.6	E	0.475
						N	0.286

Table 3. Spectral acceleration based on the time period.

Structures	Time period	S_a (Design spectrum)
IFBC-10th	0.51	0.90
IIC-10th	0.569	0.90
IFBC-All	0.3947	0.90
IIC-All	0.40	0.90
IIC	0.87	0.61
IFBC	0.717	0.76

4 Result and analysis

The results from the Incremental dynamic analysis (IDA) in the limit-state capacities (yielding and collapse) can be summarized into 16%, 50%, and 84% fractile values of IM (S_a) and DM (θ_{max}) capacity for each limit state [23-27], as shown in Table 4. The S_a was spectral acceleration. The θ_{max} was the maximum inter-story drift ratio.

Table 4. Summary of 16%, 50%, and 84% fractile values in terms of DM and IM.

Structures	Limit state	16%		50%		84%	
		$S_a(T_1, 5\%)(g)$	θ_{max}	$S_a(T_1, 5\%)(g)$	θ_{max}	$S_a(T_1, 5\%)(g)$	θ_{max}
IFBC-10th	Yielding	0.2366	0.00304	0.382	0.00398	0.698	0.00668
	Collapse	1.415	0.0206	1.73	0.0265	2.44	0.0316
IIC-10th	Yielding	0.076	0.00096	0.099	0.00137	0.134	0.00159
	Collapse	1.166	0.0096	1.601	0.0149	2.293	0.0238
IFBC-All	Yielding	0.1112	0.00046	0.2543	0.0010	0.4128	0.0016
	Collapse	1.8855	0.00891	2.7884	0.01275	3.7451	0.0183
IIC-All	Yielding	0.12856	0.00047	0.2645	0.0011	0.53448	0.00193
	Collapse	1.565	0.00863	2.684	0.01155	3.4257	0.01595
IIC	Yielding	0.0559	0.00149	0.0723	0.00178	0.087	0.00211
	Collapse	3.065	0.15204	5.206	0.20	7.403	0.2760
IFBC	Yielding	0.0884	0.00177	0.1037	0.00216	0.151	0.0034
	Collapse	1.673	0.207	3.336	0.2277	5.296	0.2521

According to Table 4, it can be found that the structures of IFBC-All and IIC-All for all the 16%, 50%, and 84% fractile IDA curves have approximately similar performance. It means that, using coupling beams at all floor levels in double skin SBI structure with inner isolated core are slightly idle. Model IIC has low yielding capacity, it means that elastic range in conventional isolated structures is short and maximum yielding capacity is reached early. Models IIC and IFBC experience large displacement during earthquake ground motions, while they are encased into a stiff outer skin, displacement drastically reduced. This mainly expresses one of the significant advantages of double skin SBI structure. The structural capacities of all prototype buildings at the collapse damage level were estimated through IDA on the median (50%) percentile, which defines the capacity of structures as the last IDA point in the non-converging run. The median collapse and yielding capacities for models IFBC-All and IIC-All are 2.788, 2.684 and 0.254, 0.264 with corresponding maximum inter-story drift ratio of 0.01275, 0.0115 and 0.001, 0.00115, respectively, with a minor difference of 0.104 in term of S_a , which means that the SBI with inner isolated core, as connected to the outer frames at all floor levels, has somewhat similar performance compared to that of IFBC-All. In addition, double skin SBI structure with coupling beams at the only topmost floor (model IIC-10th) exhibits a higher probability of collapse, and model IIC-All represent that isolation devices in double skin SBI system since all floors are connected to the outer skin have somewhat trivial efficiency. Therefore, a model configuration of SBI structure between models IIC-10th and IIC-All with for example two connected floor levels can be appropriate for civil structures. Using the base isolation system in the structures with long time period cannot be significantly effective. Whereas, as illustrated in Table 4 results from the analysis of the isolated structure (e.g. IIC) embedded into the outer stiff frames with fixed-bases while connected to the outer frames only at the topmost floor (e.g. IIC-10th) show that time period and inter-story drift ratio decrease from 0.87s to 0.569s and 0.20 to 0.0149 respectively, even in comparison to the IFBC-10th structure. Comparing the elastic behavior of the SBI structure, the IIC-10th and IIC have similar elastic behavior with a short elastic region and both reach yielding capacity quite early. It is evident that in terms of collapse capacity, the IFBC model when compared to those with embedded outer stiff frames (e.g. IFBC-All), displayed a marked reduction of 16.42% and 94.40% in spectral acceleration and inter-story drift ratio, respectively.

5 Conclusions

For the reason of some problems in the conventional isolated structure such as long time period, large displacement and eliminate entire lateral force resisting system that cause instability in isolation devices, this study introduced a double skin SBI structure. The double skin SBI structure consisted of two parts: an inner core and outer skin. Inner core includes gravity columns with

base isolated, while outer skin has frames with the fixed base including lateral force resisting system. To investigate the seismic behavior of the double skin SBI structure, numerical analysis has been presented for estimating the seismic behavior of 10-story SBI structures subjected to 22 component pairs of far-fault bi-directional scaled ground motion, using incremental dynamic analysis based on the OpenSees program. The main achievements of this paper are drawn as following.

Based on the obtained results, this study recommends an appropriate double skin SBI structure to the civil structures domain with a suitable range of connected floor levels. The SBI system can be adjusted with the use of RC coupling beams in the seismic gap distance between the inner core and outer skin. In double skin SBI system connecting the entire story levels in inner core to the outer skin is somewhat idle. This implies that the benefits of base isolation in the SBI system are reduced if the inner isolated core is connected to the outer frames at all floor levels. The double skin SBI system is effective in reducing the time period and displacement in conventional isolated structure with a long time period and large displacement.

The obtained numerical results in the SBI system highlight the drastic reduction of considered time-period, lateral displacement, and inter-story drift ratio as the more floors are given coupling beams. With increasing or reducing the number of connected floors in the SBI system, dynamic behaviors of the SBI system can be changed. Therefore, an adjustable structure can be created by adding and removing RC coupling beams at every arbitrary floor level.

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