CONTROL OF ECCENTRIC BUILDING VIBRATION WITH BASE ISOLATION

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Base isolation is found effective in reducing torsional response of structures with mass eccentricity when subjected to earthquakes. In this study, dynamic characteristics of an eccentric five-storey benchmark model, isolated with laminated rubber bearings (LRB) and lead core rubber bearings (LCRB), were examined using a shaker table and four different ground motions. The earthquake-resistant performance of LRB and LCRB isolators was evaluated. It was observed that both transverse and torsional responses were significantly reduced with the addition of an LRB or LCRB isolated system regardless of ground motion input. However, the LRB was identified to be more effective than LCRB in reducing relative torsional angle, model relative displacements, accelerations and angular accelerations, and therefore, provided a better protection of the superstructure and its contents.

INTRODUCTION

Ground motions produced by severe earthquakes are often quite damaging to structures and their contents. Conventional earthquake-resistant designs often focus on the strengthening of structures to resist such disturbances and avoid structural collapse, whilst little attention is given to the prevention of damage. Using such design approaches, it is almost impossible to construct completely ' earthquake-proof' structures that are both reasonable in cost and aesthetically acceptable.

Seismic isolation of the building structure is an efficient design scheme that can successfully reduce earthquake loading to improve safety and reduce building damage [1]. A seismically isolated structure can have a fundamental frequency considerably lower than the fundamental frequency of the same structure built without isolation and also lower than the usual predominant frequencies of a typical earthquake [2]. This is achieved by mounting the structure on a set of isolators that provide low horizontal stiffness, thereby shifting the fundamental frequency of the structure to a much lower value. As a result, most deformations occur within the isolation level, allowing the superstructure to remain essentially undeformed and able to move like a rigid body. This technique prevents damage to the structural and nonstructural components of the building [1].

However, a real world structure is usually eccentric, meaning its centre of stiffness is offset from its centre of mass. Some structures are inherently eccentric, due to an asymmetric floor plan (usually dictated by the needs of the building occupancy) leading to an asymmetric layout of the structural members, or may be eccentric due to the location of stairwells and lift-shafts, etc. When a transverse mode is coupled to a rotational mode, arising from the eccentricity, the torsional component of seismic responses will be amplified if certain conditions are met.

Up to now, studies of the seismic behaviour of asymmetric structures, especially using shaker table tests, have been very limited. As a result, understanding of the role and effectiveness of rubber bearings in protecting eccentric structures has remained limited. Consequently, experimental studies on the response of eccentric structural systems with base isolators will provide valuable insight to this technique. Well-conducted experimentation will provide data for analysis and design of such structures isolated with rubber bearings. This paper describes a series of shaker table tests designed to evaluate the seismic performance of an eccentric five-storey building model subjected to various simulated earthquake inputs. The effectiveness of two rubber isolation systems against torsional response is investigated in detail to assist further development of new and effective isolation systems for asymmetric structures.

EXPERIMENTAL STUDIES

Five-storey benchmark steel model

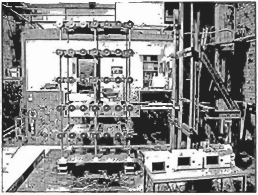

Figure 1. Eccentric five-storey model with isolators

The experimental benchmark building model, having dimensions of 1.5m x 1.0m x 3m, designed by Samali [3], offers the flexibility needed to model and test various building configurations. The eccentric model was created by adding a total of 350 kg mass to one side of a symmetrical concentric steel frame weighing 1200 kg, as shown in Figure 1. The additional 350 kg mass consisted of 140 steel disks equally distributed on the front side of each floor. This produces an eccentricity of 0.125L, where L is the width of the floor. This level of eccentricity is regarded as moderate eccentricity.

CHARACTERISTICS OF RUBBER BEARING ISOLATORS

The laminated rubber bearings (LRB) used in this study consisted of 25 thin rubber sheets with a sheet thickness of 2.2 mm and 25 thin layered steel plates each 1.8 mm thick. The rubber sheets were vulcanized and bonded under pressure and heat so as to alternate with each thin steel plate. The effect achieved by including the inner steel plates is to control the shape factor of each elastomeric rubber layer, so as to prevent lateral bulging, achieving a vertical stiffness approximately 500 times the lateral stiffness of 220 kNm^{-1}. This ensures a large vertical load carrying capacity. Horizontal flexibility is provided through shear deformation of the individual rubber sheets. The overall dimensions of the laminated bearing used for the experiment were 120 x 120 x 100mm. Two thick mounting steel plates (200 x 200 x 20 mm) were bonded to the bottom and top surfaces of each laminated bearings so as to provide for connection fixings to the shaker table and to the superstructure, as shown in Figure 1.

The configuration and dimensions of lead core rubber bearings (LCRB) (Figure 2) were the same as LRB but a lead plug with a diameter of 30 mm was inserted into a machined hole at the center of each bearing. In addition to the elastomeric characteristics of the LRB type, a further energy dissipation mechanism can be achieved with the LCRB due to the plastic deformation of the lead plug. A lead rubber bearing also provides initial rigidity under lateral service loads, such as during wind loads, due to the high stiffness prior to yielding of the lead plug. In that arrangement, however, the energy dissipation mechanism is activated only after the lead plug has yielded. Lead rubber bearings also provide a greater restoring effect to re-centre the isolators at their original locations after normal service loads.

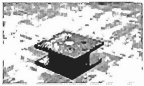

Figure 2. Photo of an individual lead core rubber bearing.

Shaker table testing

Tests were carried out using the unidirectional shaker table facility at University of Technology, Sydney. The plan dimensions of the table are 3m x 3m. The table allows movement in a horizontal direction operated by a hydraulic actuator with a maximum acceleration of 2.5g (bare table), with a maximum stroke and piston velocity of ±100 mm and 550 $mm.s^{-1}$ respectively. As shown in Figure 3, two accelerometer and two LVDT (linear variable displacement transducer) measurement locations were utilized for each survey measurement level. Two accelerometers and two LVDTs were located at each of the rubber bearing level, the 2nd and the 5th floor levels respectively. A further accelerometer and LVDT combination was installed on the shaker table to measure the table response.

A total of 14 channels of data were therefore recorded using two YOKOGAWA Analyzers. The shaker table was driven in the longitudinal direction of the five-storey model. To determine a suitable input excitation to the table, motion records from four earthquakes were used: El Centro (1994), Hachinohe (1968), 50%-intensity Kobe (1995) and Northridge (1994). Measured maximum accelerations on the shaker table were 0.42g, 0.23g, 0.41g and 0.45g representing the above four earthquakes respectively. To maintain dynamic similitude, each record was compressed in time by a factor of 3 to ensure the first mode frequency of the model was consistent with dominant frequency of the earthquake record. That is, the dominant frequencies of the simulated earthquakes were increased by a factor of 3.

The shaker table tests were conducted using both fixed-base and base-isolated structures, with the experimental set-up for the LRB-isolated five-storey benchmark model on the shaker table shown in Figure 1.

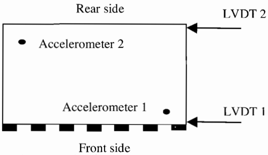

Figure 3. Location of accelerometers and LVDTs in plan.

RESULTS AND DISCUSSION

The effectiveness of the base isolation systems was evaluated by comparing the structural transverse and torsional responses of the two models – isolated and non-isolated – for each load case. This was determined by measuring the variation in maximum relative displacement with floor height in the direction of shaker for each model. For the non-isolated model this was defined as the floor displacement relative to the shaker table, and for the isolated model as displacement relative to the base of column pads.

These results are shown in Figure 4. It can be seen that relative displacement increases with the floor height, as expected. A comparison of maximum relative displacements between front side and rear sides of the models reveals larger values for the front than the rear, attributable to a higher mass distribution on the front side. Time histories of relative displacement at 5th floor level due to El Centro earthquake are shown in Figure 5. Clearly, both LRB and LCRB isolators are effective in reducing the relative movements of the model in both displacement amplitude and time. However, LRB isolator is the superior isolator. The smaller improvement to earthquake

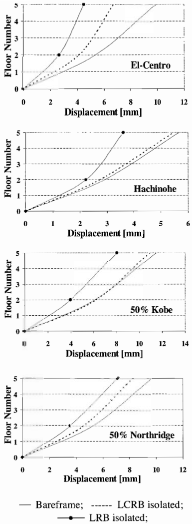

Figure 4. Variation of maximum relative displacement with floor height.

response achieved by the LCRB-isolated model is attributable to its non-linear stiffness characteristic, where high initial stiffness is maintained until the elastic limit of the lead core is reached, however the superior damping effects of the LCRB isolator are visible in the diminished time effects.

Considering Figure 4 further, it is apparent that the high initial stiffness of the LCRB isolator appears to have provided little control of relative displacement for the lower intensity load case of Hachinohe, but also for 50% Kobe where loads were comparable with El-Centro. This may indicate a difference in the frequency content of Hachinohe, however in all cases the improved damping characteristics of the LCRB isolator would be evident in more rapid decay of oscillation in the building structure.

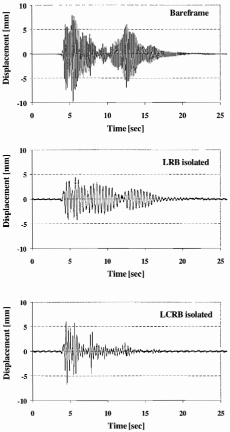

Figure 5. Time histories of relative displacement on level 5 under El Centro earthquake.

Torsional angle was used to characterize the torsional behaviour of the model. This is simply defined as the rotational angle of movement of the rigid floor diaphragm of the model.

Relative torsional angle is defined as the difference in torsional angle between the fifth floor and the base (isolation level), which characterizes the torsional deformation within the building model. Variation of maximum relative torsional angle with floor height for each case is presented in Figure 6. It is clear that a significant reduction in model torsional angle can be obtained when either LCRB or LRB isolators are installed. The isolated models behave more like a rigid body than does the bareframe. In the isolated case, rubber bearings absorb most of the total torsional component, resulting in only a small torsional component of energy being transmitted into the building. Moreover, the effectiveness of LCRB is almost as good as that of LRB. The capacity of isolators to reduce torsional damage is achieved by ensuring the fundamental horizontal frequency of the isolator is far lower than the dominant frequencies generated by earthquakes.

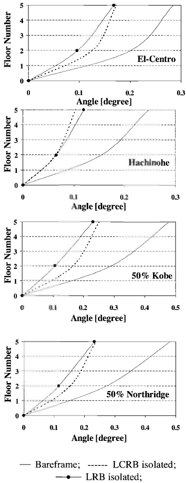

Figure 6. variation of relative torsional angle with floor height.

Time histories of the model torsional angle for the fifth floor under 50% intensity Kobe earthquake are depicted in Figure 7. Maximum torsional angle for the bareframe reaches a maximum of 0.48 degrees compared with 0.23 and 0.25 degrees for LRB and LCRB isolated models respectively. In addition, decay of the torsional angle vibration effects is considerably faster for the isolated models than it is in the bareframe.

Time histories of model acceleration at the back of fifth floor subjected to 50% intensity Northridge earthquake are plotted in Figure 8, and the full test data are presented in Table 1.

Maximum angular accelerations of base floor (rubber bearing), second and fifth floors of bareframe, LRB and LCRB isolated models under the four earthquakes are summarized in Table 2. Angular accelerations of both LRB and LCRB isolated models show considerably lower outcomes for all earthquakes and floor levels, compared with that of bareframe. For instance, maximum angular acceleration on fifth floor of bareframe under Hachinohe earthquake amounts to 16.7 rad.s^{-2}, while those of LRB and LCRB isolated models are only 3.56 and 5.36 rad. s^{-2} respectively. It is also clear that LRB is more effective in reducing angular acceleration than LCRB.

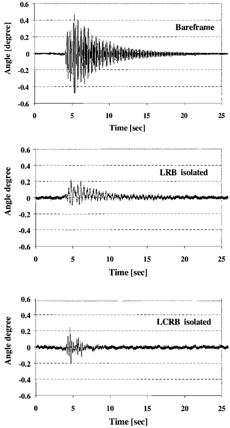

Figure 7. Time histories of model torsional angle under Kobe earthquake.

In considering the LRB and LCRB characteristics it must be emphasised that LCRB is stiffer at low deflections and therefore more stable than LRB under normal working loads such as wind. This is an outcome of the presence of a rigid lead core. For situations where stability of the structure is of concern, such as with increased height, the use of LCRB over LRB may be preferred.

Absolute deformation and torsional angle of rubber bearings are presented in Table 3. In comparing LRB and LCRB, a larger absolute rubber deformation and torsional angle of the model isolated by LRB are seen which is related to smaller torsional stiffness of the LRB. The results also show that LCRB is more stable than LRB due to the presence of a rigid lead core. Therefore, when stability of the structure is of concern the use of LCRB over LRB is recommended.

Table 1. Maximum accelerations [g].

El Centro earthquake				
		Bare	LRB	LCRB
Base	Front		0.46	0.77
	Back		0.52	0.61
2nd	Front	1.21	0.53	0.82
	Back	0.77	0.49	0.65
5th	Front	2.07	0.60	1.35
	Back	1.15	0.54	0.83
Hachinohe earthquake				
		Bare	LRB	LCRB
Base	Front		0.31	0.71
	Back		0.30	0.50
2nd	Front	0.63	0.34	0.60
	Back	0.61	0.33	0.39
5th	Front	1.04	0.40	1.04
	Back	1.08	0.40	0.76
50% Kobe earthquake				
		Bare	LRB	LCRB
Base	Front		0.64	1.30
	Back		0.60	1.13
2nd	Front	1.38	0.68	1.40
	Back	1.42	0.66	1.01
5th	Front	2.26	0.91	2.21
	Back	2.43	0.82	1.72
50% Northridge earthquake				
		Bare	LRB	LCRB
Base	Front		0.70	0.88
	Back		0.51	0.65
2nd	Front	1.24	0.70	1.15
	Back	1.00	0.54	0.78
5th	Front	1.87	0.79	1.77
	Back	1.99	0.66	1.00

Table 3. Absolute deformation (mm) and torsional angle (degree) of rubber bearings

Earthquake	Base isolator	Absolute deformation of rubber bearing (mm)		Absolute torsional angle of rubber bearing (degree)
		Front side	Rear side	
El Centro	LRB	17.54	18.16	0.374
	LCRB	13.33	12.89	0.109
Hachinohe	LRB	18.06	16.62	0.254
	LCRB	14.02	13.77	0.078
50% Kobe	LRB	26.26	23.27	0.468
	LCRB	17.16	16.15	0.118
50% Northridge	LRB	35.26	34.38	0.402
	LCRB	23.60	22.71	0.085

Table 2. Maximum angular accelerations [rad.s^{-2}].

El Centro earthquake			
	Bare	LRB	LCRB
Base		5.60	5.32
2nd	11.3	5.46	9.24
5th	17.2	5.88	13.7
Hachinohe earthquake			
	Bare	LRB	LCRB
Base		2.66	4.51
2nd	8.71	2.94	4.72
5th	16.7	3.56	5.36
50% Kobe earthquake			
	Bare	LRB	LCRB
Base		5.04	8.26
2nd	17.7	5.6	12.18
5th	30.2	6.72	16.80
50% Northridge earthquake			
	Bare	LRB	LCRB
Base		4.76	13.16
2nd	17.3	4.06	13.30
5th	28.2	5.32	24.36

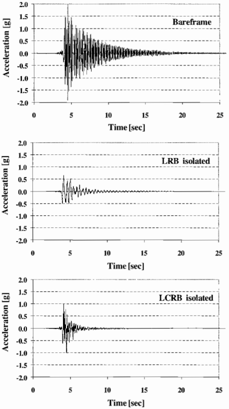

Figure 8. Time histories of acceleration at the rear of fifth floor under Northridge earthquake.

CONCLUSIONS

In this study, a series of shaker table tests were conducted on non-isolated model, LRB-isolated and LCRB-isolated eccentric models. The objective of the tests was to evaluate the benefit to building structures of the incorporation of LRB and LCRB isolators to mitigate against torsional damage under strong ground motions. Both LRB and LCRB have been shown to reduce torsional deformation, relative displacement, acceleration and angular acceleration within the model structures. Important differences between the two isolator types were identified. The LRB was found to be similar to LCRB in protecting torsional deformation of the model but was more effective than LCRB in reducing model relative displacement. LCRB rendered a smaller torsional angle and absolute deformation of the base isolation system, a more stable structural system. Therefore, base isolation can greatly reduce torsional as well as translational response of building structures.

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