Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

EXPERIMENTAL INVESTIGATION OF BASE-ISOLATED SECONDARY SYSTEMS

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ABSTRACT

An experimental study, using shake table, on base-isolated and non-isolated anchored secondary systems is presented herein. Sensitive equipments and lifeline structures such as nuclear power plant vessels, computer equipments, active components of power supply and monitoring units, control boards, communication networks and power transmission facilities are highly susceptible to earthquakes. Such secondary systems are almost invariably housed in large hospitals, airports, emergency structures, laboratories, industries and nuclear power plants. Damages to these secondary systems may result in significant social chaos and costly economic loss. Hence, it is important to protect the secondary systems from damages caused by earthquakes and to ensure their continual functioning after earthquake events. Protection to the secondary systems can be provided effectively through base isolation as an efficient passive control system. It was observed from the experimental results that the base isolation system reduces the acceleration response of the secondary systems, thereby their seismic design forces. Time histories and frequency spectra plots for the secondary systems and their supporting floors showed that the acceleration experienced by the base-isolated secondary system are decreased by about 35% to 40% in comparison with their fixed-base condition. A permanent displacement of the secondary systems mounted on sliding bearings was observed after the earthquake excitation ends. A soft spring, added in this case as a re-centering force device, reduced the permanent displacement; however, with some compromise with effectiveness of base isolation. In case, if the secondary structures are stiff, i.e. in the velocity control zone of response spectra then base isolation is not necessarily effective. The reported experimental results here bring about the fact that design of isolation for SS requires separate treatment.

INTRODUCTION

In most of the nuclear power plants and industrial facilities relatively lighter structures are attached to the walls or housed on certain floors of heavier structures. The lighter structures are conventionally called as secondary systems (SS) when compared to the supporting structures which are called as primary structures (PS). The SS generally include architectural elements, mechanical, electrical, plumbing equipments, any furniture, fixtures, piping systems etc. The classification of SS can be done into several categories; however, for the purpose of analysis SS are commonly divided into systems with single or multiple supports. A singly supported SS is simple equipment housed on the floor of multi-storey PS attached at one point only; however, piping system attached to the generating system in the nuclear power plants is supported or attached to the PS at different floors and referred as multiply-supported SS (Singh 1988, Villaverde 1996). Safety of the SS is vital for proper functioning of power plants, industrial facilities, hospitals and other important structures after the events of earthquakes.

Damages and failures of the SS poses hazards to occupants and reduces the overall performance of many buildings and also results into direct and indirect economic losses, sometimes damage to these SS exceeds the cost of the structural damages Villaverde (1997). Many investigators have reported the performance of the SS during earthquakes. Despite being enclosed among walls, thereby away from experiencing any wind, snow or temperature loads, the SS are subjected to earthquake-borne vibrations. The earthquake induced vibrations are transmitted to the SS through their supporting PS. Hence, the vibratory effect felt by the SS during an earthquake is greatly influenced by the characteristic of the supporting PS. Therefore, it is necessary to understand and comprehend the mutual interaction between the structure in which the SS are housed; and the SS when subjected to earthquake induced vibrations. Chen and Soong (1988) have reported a comprehensive summary of many important aspects, engineering practices and research conducted in the area of seismic behavior of SS which are anchored to the PS prior to 1988.

Seismic performance of the SS can be improved and those also can be safeguarded effectively from the disastrous effects of earthquake vibrations by using the seismic base isolation technology. Seismic isolation of the structures is an aseismic design approach which averts the building from destroying earthquake forces by a mechanism which reduces the transmission of horizontal acceleration into the structure. The base-isolated structures have their fundamental frequency much lower than that of the fixed-base counterpart and frequency content of the earthquake ground motions (Dubey et al. 2008, Rai et al. 2009). This evolved base isolation technology which decouples the entire structure from the earthquake ground motions may also be used to decouple the secondary systems from the vibrating floors to which those are attached. Khechfe et al. (2002) have carried out an experimental study on feasibility of base isolation for seismic protection of the SS. In this study, effectiveness of base isolation for protecting the SS was investigated by conducting shake table tests on a scaled down model. The performance of the fixed-base and base-isolated PS in seismic zones are relatively well understood, the performance of the fixed-base and base-isolated SS is still a largely unsolved problem. In comparison to the structural components and systems, there is little information available giving specific guidance on the seismic design of the SS. Little basic research has been done in this area and most of the seismic regulations and guidelines for the SS are generally empirical in nature. The code information currently available for the most part is based on judgment and intuition rather than on experimental and analytical results (Filiatrault et al. 2001).

From the extensive literature study, it is observed that full-scale testing and model testing of primary-secondary systems in the laboratory, with due interaction effects, have not been studied as extensively as analytical and numerical work. Hence, it is deemed necessary to investigate experimentally the behavior of anchored fixed-base/ non-isolated and base-isolated SS housed in the PS. The current experimental study reports a part of the performance of the non-isolated and base-isolated SS systems housed at different floors of the PS.

DESCRIPTION OF EXPERIMENT

Primary Structure (PS) and Secondary System (SS)

In order to conduct the shake table experimental study on seismic performance of fixed-base and base-isolated secondary systems housed in fixed-base primary structure, mild-steel models of the PS and SS were fabricated. The PS model, as shown in Figure 1(a), consisted of a single bay five storied steel frame of 3042 mm height and plan dimension 860 mm × 860 mm, behaving like a five degree of freedom (DOF) system when subjected to lateral loads. Floor-to-floor height of each storey of the PS was 600 mm. Columns and floor beams of the frame were fabricated using an ISA 65 mm × 65 mm × 6 mm angle sections. Floor beams of the frame were connected with the mild-steel plate having plan dimension of 830 mm × 830 mm and 6 mm thickness in cross-section. Every floor plate of the PS had an arrangement of holes for attachment of the SS at respective floor while testing. The fabricated PS is shown in Figure 1(b). All the connections of the PS frame were made with high strength bolts to avoid failure of the connections during testing.

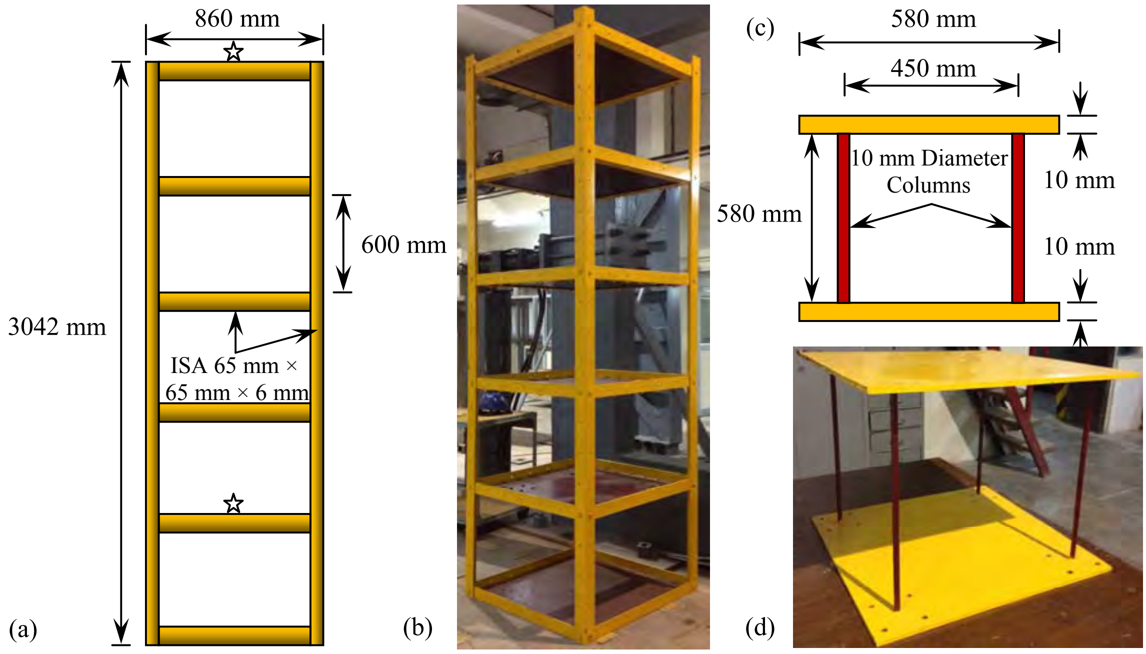

Figure 1. PS and SS: (a) geometry of five storied primary structure, (b) fabricated primary structure, (c) geometry of single storied secondary system, and (d) fabricated secondary system.

A single bay single storied SS as shown in Figure 1(c) was fabricated using two mild-steel plates having plan dimensions 580 mm × 580 mm and 10 mm thickness in cross-section, welded at top and bottom of the mild-steel circular columns of 10 mm diameter and 450 mm height. Floor-to-floor distance of the SS was 450 mm and centre-to-centre distance between the columns was also 450 mm. Top and bottom plates of the SS were drilled with the holes to facilitate the attachments of the SS with the PS, and attachment of additional mass for conducting the parametric studies by attaching the additional mass on the SS floors for changing its dynamic properties. Such SS behaves like a single-DOF system when subjected to lateral loads. The SS fabricated here represents dynamically some of the building equipments mounted on different floors of the building. The fabricated SS is shown in Figure 1(d). Dynamic properties of the PS and SS used in experimental work are described in Table 1.

Table 1: The dynamic characteristics of the fabricated PS and SS models.

Sr. No.	Model	Mass (kg)	Floor Stiffness (kN/m)	Damping (%)	No. of Floors
1	Primary Structure	382.62	12933.33	2	5
2	Secondary System	54.23	51.71	2	1

Elastomeric Isolation System

The most commonly used elastomeric isolation system is represented by the laminated rubber bearings (LRB). The LRB consist of steel and rubber plates bonded together in alternate layers to form a unit through vulcanization in a single operation under heat and pressure in the mould (Matsagar and Jangid 2011). The LRB shown in Figure 2(a) also consist of thick steel plates bonded to the top and bottom surfaces of the bearing to facilitate its connection to the foundation below and the superstructure above. The natural or synthetic rubbers used for manufacturing of these bearings have inherent damping, usually ranging from about 2% to 10% of critical viscous damping. The horizontal steel shims prevent the rubber layer from bulging and so that the unit can support the high vertical loads with small vertical deflections (1 mm to 3 mm under full gravity load). The internal shims do not restrict any horizontal deformations of the rubber layers in shear; thereby, the bearing exhibits much more flexibility under lateral loads than vertical loads. The load carrying capacity of the bearing in unreformed state is the function of plan dimension and layer thickness (Naiem and Kelly 1999).

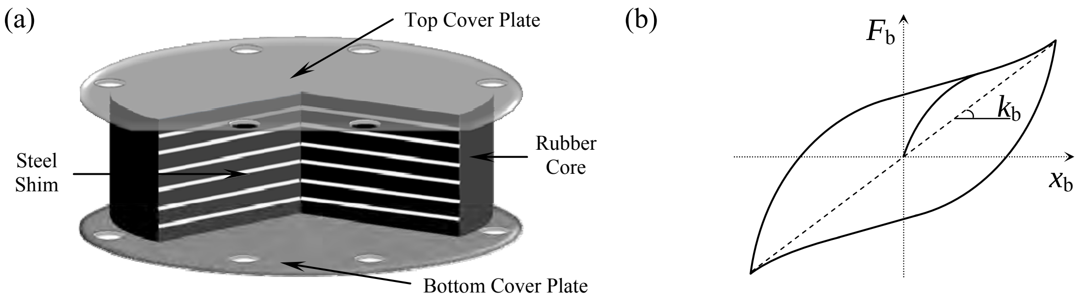

Figure 2. LRB: (a) elastomeric base isolatator (b) hysterisis loop of the elastomeric base isolator.

The LRB can easily withstand large lateral deformations and requires minimum maintenance. Generally, the LRB is characterized by high damping capacity, large horizontal flexibility due to low shear modulus of elastomer and high vertical stiffness (Villaverde 2009). The ideal force-deformation behavior of the LRB is generally represented by non-linear characteristics, as shown in Figure 2(b).

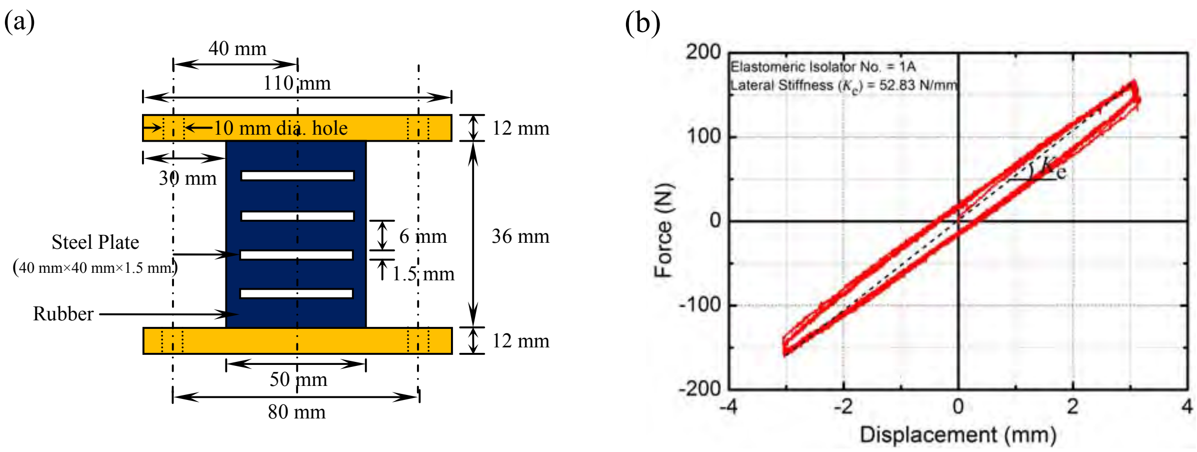

Figure 3. (a) Elastomeric bearing cross-section (b) experimental force-deformation curve of the isolator.

Herein the present study, four numbers of elastomeric base isolators were designed and fabricated based on the existing knowledge for manufacturing of the bridge bearings in India. These bearings are currently manufactured and used in India; and, in this context, the present study will be useful for the development of indigenous isolation systems and their implementations for safeguarding the SS. The fabricated isolators were square in plan and cross-sectional model of these isolators is shown in Figure 3(a). Experimentally obtained force-deformation behavior of these isolators along horizontal direction is plotted in Figure 3(b) by conducting several characterization tests, which are not reported here. The experiments were carried out by placing different static vertical loads ranging from 0-60 kg over the top cover plate of the bearings and applying horizontal loads on the top cover plate in cyclic manner (slow cyclic tests). The damping was evaluated by calculating area enclosed in the force-deformation loops. The dynamic characteristics of the four elastomeric isolation systems, used in the present investigation, are shown in Table 2.

Table 2: The dynamic characteristics of elastomeric base isolators.

Sr. No.	Isolator No.	Mass (m), kg	Stiffness (K_e), N/mm	Damping (ξ), Percent
1	1A	2.44	52.83	4.88
2	2A	2.48	57.67	5.10
3	3A	2.44	50.77	4.92
4	4A	2.35	60.58	4.97

Earthquake Samples

To record experimentally the seismic response of the PS and SS under the near-fault and far-fault earthquake ground excitations simulated using shake table, three different earthquake time histories were considered in the present study as described in Table 3. Here, g is gravitational acceleration; PGA denotes peak ground acceleration and PGD denotes peak ground displacement (original and scaled down).

Table 3: Details of earthquake time histories.

Sr. No.	Earthquake	Recording Station	Component	PGA (g)	PGD (mm)
1	Imperial Valley, 1940	El-Centro, Array #9	180	0.313	133.2 (61)
2	Loma Prieta, 1989	LGPC	000	0.563	411.8 (67)
3	Northridge, 1994	Sylmar	090	0.604	160.5 (67)

SHAKE TABLE EXPERIMENTAL STUDY

In this section, shake table tests of the non-isolated and isolated SS mounted on different floors of the PS are discussed. The shake table facility available at Heavy Structures Laboratory of Department of Civil Engineering, Indian Institute of Technology (IIT) Delhi is capable to simulate the uni-directional earthquake excitation. The platform size of the shake table is 0.914 m × 0.914 m in plan with provision for connection to the test models. Control parameter of the servo-hydraulic actuator attached to the shake table is displacement. Hydraulic actuator also has a payload capacity of 907.18 kg and force capacity of 36 kN. The actuator can produce a double amplitude displacement of 150 mm ($\pm$ 75 mm). In this study, during the experimental works, because of the limited displacement capacity of the shake table, displacement excitations were scaled down using the moving average filtering method; for which, PGDs are shown in Table 3, in parenthesis.

The fabricated PS was connected securely to the shake table top in fixed-base condition by means of high strength bolts. Shake table tests were carried out by housing the fabricated SS on first and fifth (top) floor of the fixed-base PS, shown by stars in Figure 1(a). First set of the tests was carried out for non-isolated and isolated SS housed on first floor, whereas the second set of the tests was carried out when non-isolated and isolated SS were housed on fifth floor of the PS. Experiments were carried out by importing the scaled down displacement time histories of all the earthquakes as a control signal for the shake table. During the tests dynamic properties of the SS were varied by changing its floor mass, by securely attaching steel plates, in both the non-isolated and isolated cases. Figure 4 shows the experimental setup for the shake table tests on the primary-base-isolated-secondary system.

The response quantities of interest are the top floor absolute acceleration of the SS and relative bearing displacement (relative to the floor to which it is attached). These response quantities are important because the absolute acceleration is directly proportional to the force exerted in the SS due to corresponding floor accelerations generated from earthquake ground motion. On the other hand, relative bearing displacement is crucial from the design point of view of the isolation system. For measurement of the acceleration response quantity of interest two accelerometers and displacement transducers were attached to the top and bottom floors of the SS. Amongst the other six accelerometers one accelerometer recorded the data at shake table top and other five accelerometers recorded acceleration responses from first to fifth floor of the PS. From the recorded acceleration data, base displacements at required locations were obtained analytically and compared with that recorded using the displacement transducers.

Performance of non-isolated and seismically isolated secondary systems, housed in a non-isolated primary structure, was experimentally evaluated. Seismic isolation of secondary systems was carried out by using both the steel reinforced elastomeric bearings and sliding (Polytetraflouroethelene - PTFE) systems; however results of sliding system are not reported here. It was observed initially from the experimental results that the base isolation system reduces the acceleration response of the secondary systems, thereby their seismic design forces. Time histories and frequency spectra plots for the secondary systems and their supporting floors showed that the acceleration experienced by the base-isolated secondary system are decreased by about 35% to 40% in comparison with their fixed-base condition. A permanent displacement of the secondary systems mounted on sliding bearings was observed after the earthquake excitation ends. A soft spring, added in this case as a re-centering force device, reduced the permanent displacement; however, with some compromise with effectiveness of base isolation. However, it was conceived that, if the SS are stiff, i.e. in the velocity control zone of response spectra then base isolation may not necessarily effective. Hence, further studies were conducted and the results of experiments presented herein pertain mainly to the base isolation of the stiff SS in relatively stiffer PS.

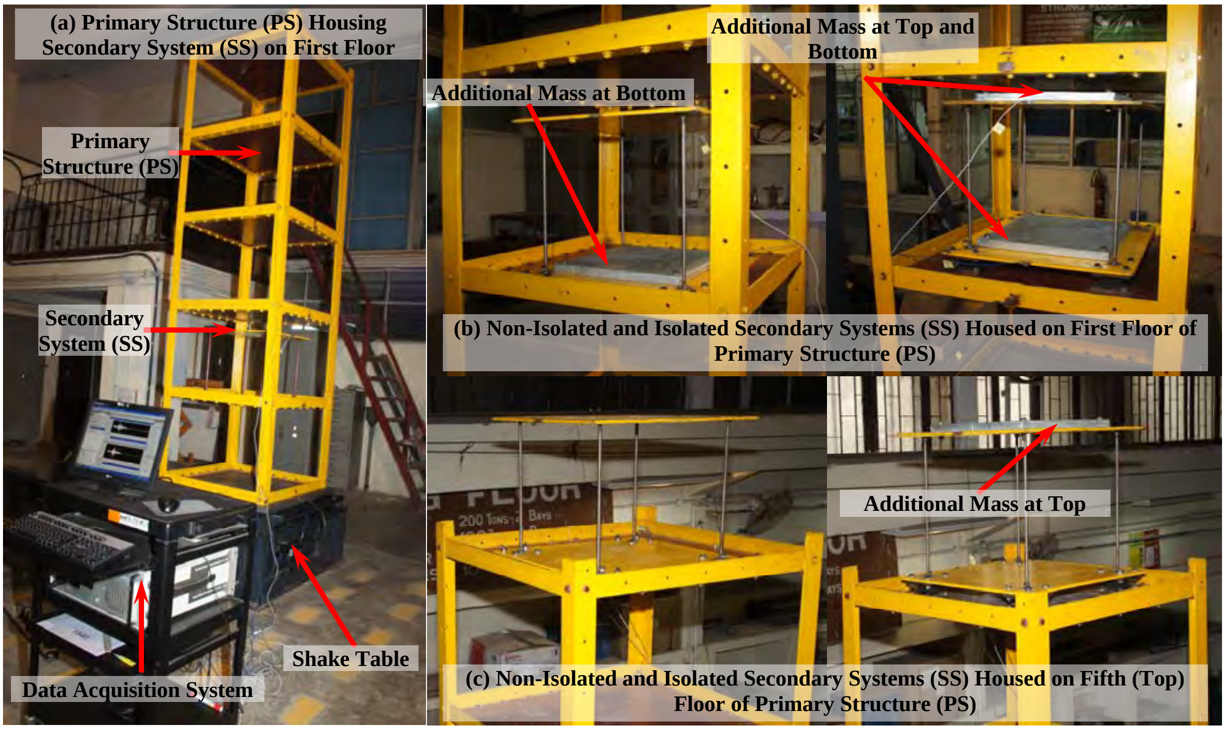

Figure 4. Experimental setup for shake table test on primary-base-isolated-secondary system.

EXPERIMENTAL RESULTS

Performance of the non-isolated and seismically isolated secondary systems (SS), housed in a fixed-base primary structure (PS) was experimentally evaluated and is reported in the present study. Seismic isolation of the SS was carried out by using steel reinforced elastomeric bearings. Tests were carried out by housing fixed-base and base-isolated SS on first and fifth (top) floors of the PS; floor acceleration and displacement spectra for these two floors obtained by recording the floor responses experimentally under the three different earthquakes are shown in Figure 5. Note that, the results in Figure 5 pertain to the case when the SS was installed but without any additional masses on it.

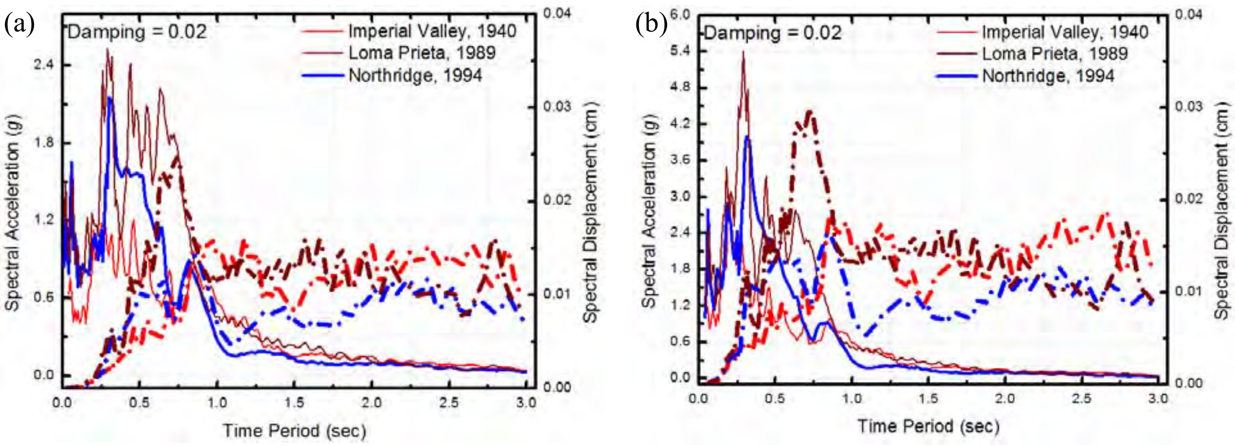

Figure 5. Acceleration and displacement response spectra: (a) first floor of PS and (b) fifth floor of PS.

Seismic responses of both the top and bottom floors of the SS were recorded by varying top floor (m_t) and base floor mass (m_b) for the set of mass parameters (Table 4). The time periods (T) of the SS tested are shown in Table 4.

Table 4: Details of the SS without and with top mass and base mass.

Sr. No.	Test Parameter Set No.	Fixed-Base SS			Base-Isolated SS		
		Top Mass (m_t), kg	Base Mass (m_b), kg	Time Period (T), sec	Top Mass (m_t), kg	Base Mass (m_b), kg	Time Period (T), sec
1	$M1$	27.00	27.63	0.1436	27.00	32.54	0.1635
2	$M2$	27.00	61.51	0.1436	27.00	66.92	0.1697
3	$M3$	59.23	61.51	0.2126	59.23	66.92	0.2418
4	$M4$	59.23	27.63	0.2126	59.23	32.54	0.2386

The time history plots of the top floor acceleration and displacement responses of the SS are shown in Figures 6 and 7. The corresponding peak top floor acceleration and displacements of the SS for various mass parameters were also recorded and are shown in Figures 8 and 9. Assessment of the time period of the SS is carried out with the floor response spectra of the PS for first and fifth floor (Figure 5). From the assessment, it is observed that the SS considered herein for discussion have their time periods ranging in high frequency zone of the spectra, i.e. the velocity sensitive region. In this region, the spectral acceleration increases with increase in time period. Hence, the top floor accelerations of the SS are seen to be increasing with increased time periods of the SS. Even if there is marginal increase in the time period of the SS upon base isolation, it in fact took the base-isolated SS on increased spectral acceleration ordinate. Thereby, the top floor accelerations in the base-isolated SS are more than their fixed-base counterparts. The peak values of the response for various mass parameters are plotted in Figure 8, which also reveals the similar trend. Hence, it is concluded that the design of isolation systems should be based on the floor response spectra. It may be noted that the current study do not include the plots of experimental response of the SS in the end (displacement sensitive) zone of the response spectra. Thus, the reported experimental results here bring about the fact that design of isolation for SS requires separate treatment, especially for those pertaining to the velocity sensitive zone in the floor response spectrum.

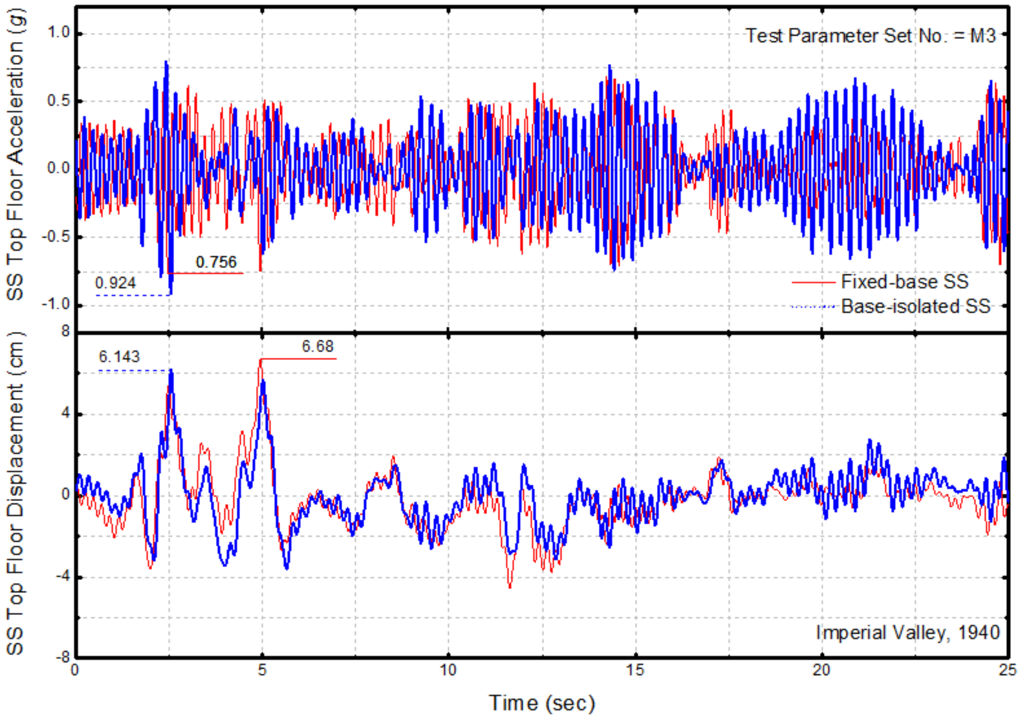

Figure 6. Top floor acceleration and displacement response of the SS housed on first floor of PS.

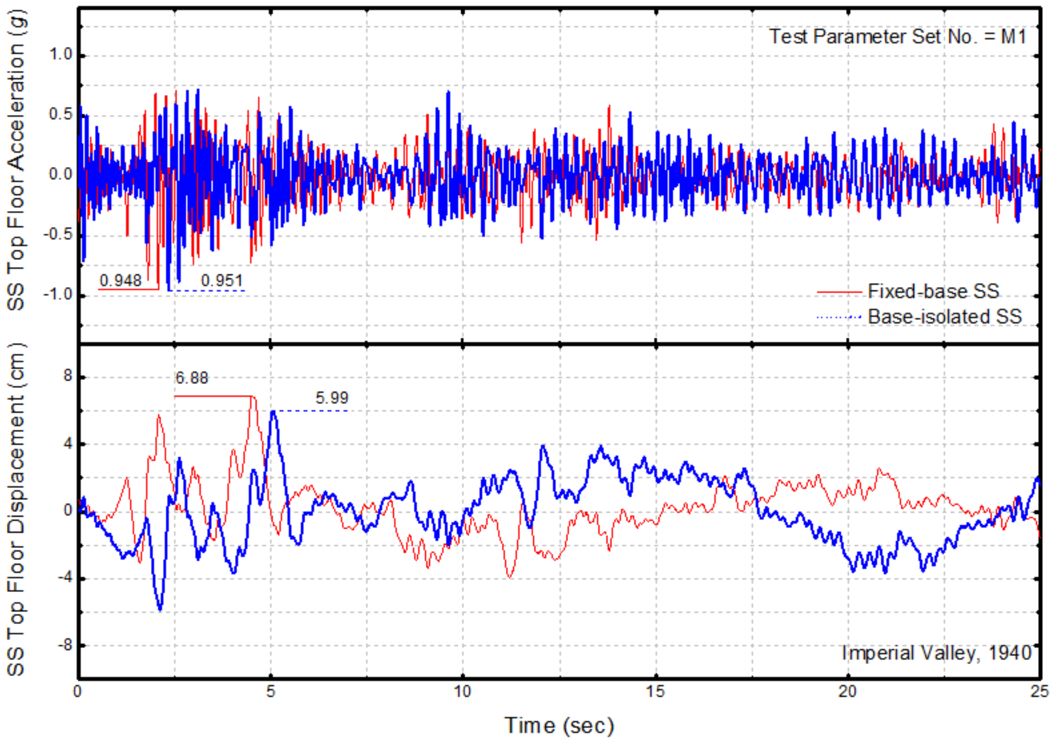

Figure 7. Top floor acceleration and displacement response of the SS housed on fifth (top) floor of PS.

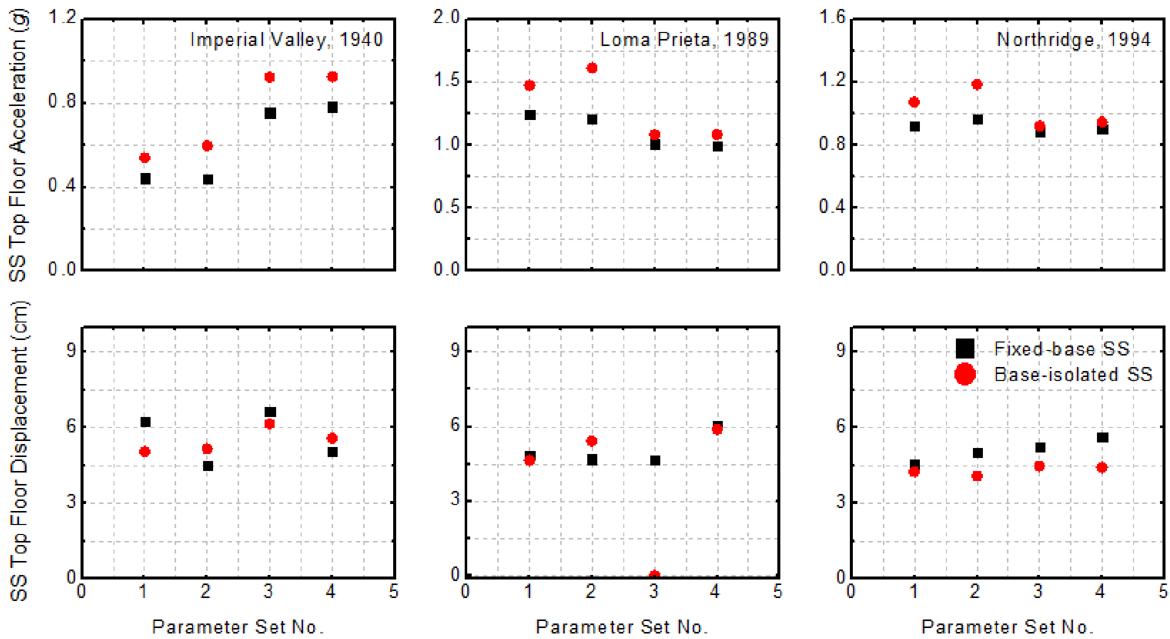

Figure 8. Peak top floor acceleration and displacement response of the SS housed on first floor of PS.

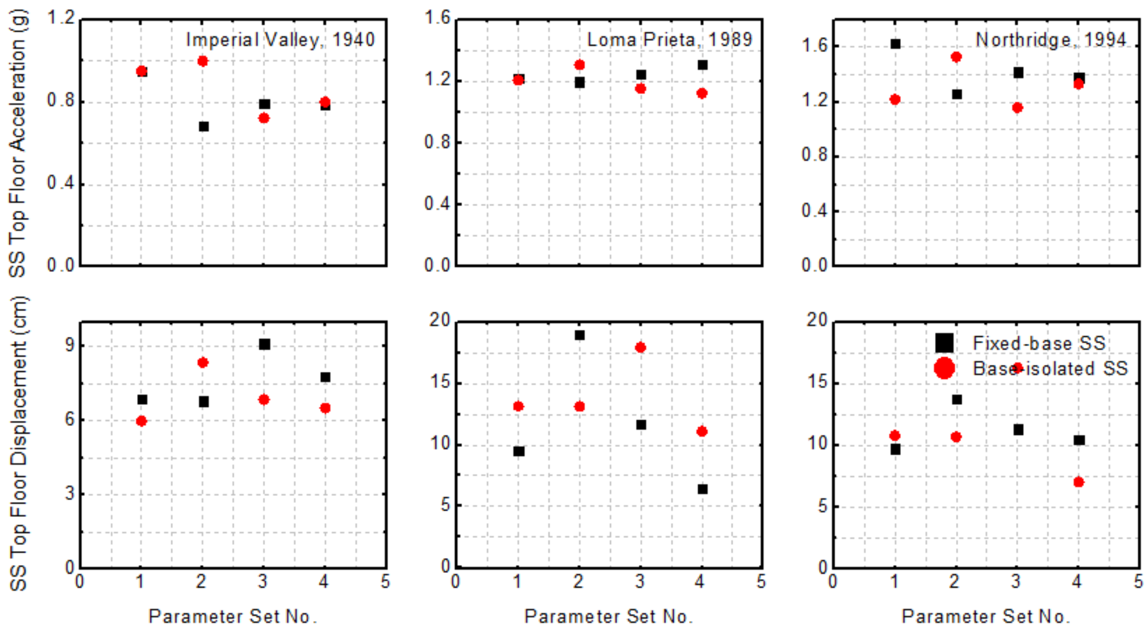

Figure 9. Peak top floor acceleration and displacement response of the SS housed on fifth (top) floor of PS.

For the fixed-base SS contained in the acceleration sensitive zone of the floor acceleration response spectrum, the flexibility introduced due to base isolation system shifts it to the displacement sensitive zone of the floor acceleration response spectrum, thereby reducing largely the spectral acceleration ordinates. For such base-isolated SS, the seismic response reduction was observed to be around 35% to 40% in comparison with their fixed-base condition. However, it happened with compromise in increased base displacements of the base-isolated SS. The base displacement in the SS mounted on sliding isolation systems with a restoring spring was comparatively lower than in case when the elastomeric bearings were used. Also, the restoring spring used helped greatly in re-centering; however, the added stiffness lead to increase in acceleration to some extent.

CONCLUSIONS

This study is mainly focused on investigation of behavior of the fixed-base and base-isolated secondary systems (SS) housed on different floors of the primary structure (PS), accounting for the interaction between the PS and SS. The results are presented here for series of experiments conducted on shake table to investigate the seismic response of the SS which are contained in the velocity sensitive zone of the floor acceleration response spectrum. It is concluded that the design of isolation systems should be based on the floor response spectra. Increase in acceleration response of the SS is observed upon isolated due to increases spectral acceleration ordinate corresponding to the marginally increased isolation time period. Base isolation of the SS which are contained in the acceleration sensitive zone of the floor acceleration response spectrum, however, help reduce the seismic forces induced in it.

ACKNOWLEDGEMENT

The financial aid provided by the Bhabha Atomic Research Centre (BARC), Mumbai for completing the reported study is gratefully acknowledged.

REFERENCES

Chen, Y. and Soong, T. T. (1988). “Seismic Response of Secondary Systems,” *Engineering Structures*, 10(4), 218-228.

Dubey, P. N., Reddy, G. R., Vaze, K. K., Ghosh, A. K., Kushwaha, H. S. and Deb S. K. (2008). “Performance of Base-Isolated RCC Framed Building under Actual Earthquake,” *Journal of Structural Engineering*, 35(3), 195-201.

Filiatrault, A., Christopoulos, C. and Stearns C. (2001). “Guidelines, Specifications, and Seismic Performance Characterization of Nonstructural Building Components and Equipment,” Pacific Earthquake Engineering Research Center (PEER), Report No. PEER 2002/05.

Khechfe, H., Noori, M., Hou, Z., Kelly, J. M. and Ahmadi, G. (2002). “An Experimental Study on the Seismic Response of Base-Isolated Secondary Systems,” *Journal of Pressure Vessel Technology*, ASME, 124(1), 81-88.

Matsagar, V. A. and Jangid, R. S. (2011). “Earthquake Base-Isolated Buildings,” LAP Lambert Academic Publishing, Germany.

Naeim, F. and Kelly, J. M. (1999). “Design of Seismic Isolated Structures: From Theory to Practice,” John Wiley and Sons Inc., New York, USA.

Rai, N. K., Reddy, G. R., Ramanujam, S., Venkatraj, V. and Agrawal, P. (2009). “Seismic Response Control Systems for Structures,” *Defence Science Journal*, 59(3), 239-251.

Singh, M. P. (1988). “Seismic Design of Secondary Systems,” *Probabilistic Engineering Mechanics*, 3(3), 151-158.

Villaverde, R. (1996). “Earthquake Resistant Design of Secondary Structures: a Report on the State of the Art,” *Eleventh World Conference on Earthquake Engineering*, Mexico.

Villaverde, R. (1997). “Seismic Design of Secondary Structures: State of the Art,” *Journal of Structural Engineering*, ASCE, 123(8), 1011-1019.

Villaverde, R. (2009). “Fundamental Concepts of Earthquake Engineering,” CRC Press, New York, USA.