

EXPERIMENTAL STUDY OF BASE-ISOLATED STRUCTURES

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ABSTRACT

An experimental shake table study for the response of structures supported on base isolation systems under harmonic excitation is carried out. Two base isolation systems, namely the laminated rubber bearings with steel plates and sliding bearing, are designed and fabricated. These bearings are tested for their dynamic properties which are used for the design of the isolated structural models of single and two-storey steel frame structures. Experimental shake table studies of these isolated structural models subjected to harmonic base excitation are carried out. The response of the isolated structural system is compared with the corresponding response of non-isolated system in order to investigate the effectiveness of the isolation system. The experimental results are compared with the analytical results to verify the mathematical force-deformation behaviour of the isolation system. There was a good agreement between the experimental and analytical response of the structural models. In addition, the response of isolated system is found to be less in comparison to the corresponding response without isolation system, implying that the isolation is quite effective in reducing the acceleration response of the systems. The presence of restoring force device along with the sliding system reduces the base displacement without significant increase in superstructure acceleration. In addition, the response of the structural models has also been investigated for a real earthquake ground motion and it has been found that the isolation devices are effective in reducing the seismic response of structures.

KEYWORDS: Base Isolation, Laminated Rubber Bearings, Sliding System, Shake Table, Harmonic Motion

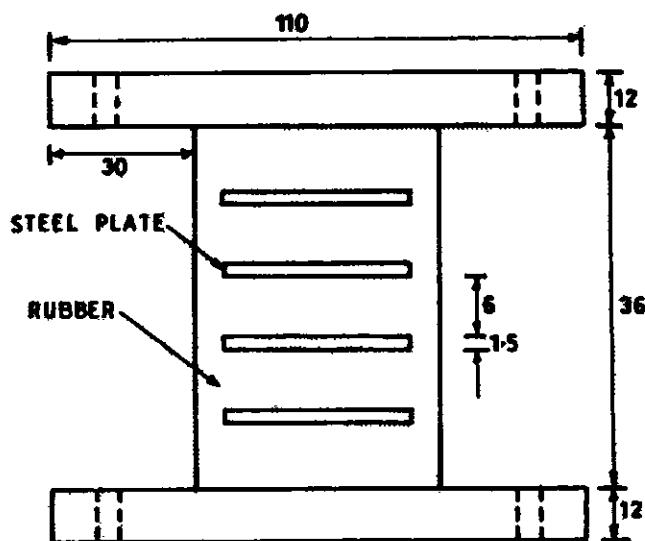
INTRODUCTION

Base isolation is thought of as an aseismic design approach in which the building is protected from the hazards of earthquake forces by a mechanism which reduces the transmission of horizontal acceleration into the structure. The main concept in base isolation is to reduce the fundamental frequency of structural vibration to a value lower than the predominant energy-containing frequencies of earthquake ground motions. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby reducing the transmitted acceleration into the superstructure. Accordingly, by using base isolation device in the foundation, the structure is essentially uncoupled from the ground motion during earthquakes (Kelly, 1986; Buckle and Mayes, 1990; Jangid and Datta, 1995a).

A variety of isolation devices including elastomeric bearings (with and without lead core), frictional/sliding bearings and roller bearings have been developed and used practically for aseismic design of buildings. These isolation systems have been practically used during last 20 years in many new buildings in USA, Japan, New Zealand (Naeim and Kelly, 1999). In addition, these bearings are also used for retrofitting of the existing structures. In India, there have been several analytical studies to understand the behaviour of base-isolated structures. Qamaruddin et al. (1986a, 1986b) have shown that the sliding surface at the base of brick and masonry building is quite effective in reducing the earthquake response. Jangid and Datta (1994, 1995b) and Jangid and Kelly (2000) investigated the influence of torsional coupling on the response of base-isolated structures. It has been shown that the torsional coupling significantly influences the response of base-isolated structures. Jain and Thakkar (1998) carried out parametric study to understand the behaviour of multi-storeyed base-isolated buildings. In addition, there has also been study for the bi-directional response of sliding systems (Jangid, 1996) and suitability of rolling rods as a base isolation system (Jangid and Londhe, 1998; Jangid, 2000). Recently, Jangid and Kelly (2001) and Rao and Jangid (2001) studied the behaviour of base-isolated structures under near-fault

motions. In spite of several analytical studies, there has not been much attempt towards the fabrication and testing of indigenous base isolation systems in India.

Herein, two base isolation systems, namely the laminated rubber bearing and sliding bearing, are designed and fabricated. Various experimental tests are performed on these bearings for evaluation of their static and dynamic properties. Based on these properties, small-scale models of the isolated steel frame structures are developed. An experimental shake table study of steel frame models with different isolation systems under harmonic excitation is carried out. The experimental responses of isolated and non-isolated models are compared with the corresponding analytical response to validate the mathematical models of the isolation systems. In addition, the analytical response of structural models is also investigated under real earthquake ground motion to demonstrate the effectiveness of isolation systems for controlling the seismic response. It is to be noted that in the past, there have been several experimental studies to demonstrate the effectiveness of seismic isolation and development of isolation systems (Kelly and Hodder, 1982; Kelly and Beucke, 1983; Mokha et al. 1990, 1991; Mostaghel et al. 1992). The present study also aims towards the development of seismic isolation systems and demonstration of effectiveness of base isolation for aseismic design of structures. However, the isolation systems fabricated are based on the existing knowledge of development of bridge bearings in India. Since these bearing are extensively used in India, as a result, the present study will be very useful in developing indigenous isolation systems and its implementation on real structures.



ALL THE DIMENSIONS ARE IN mm.

Fig. 1 Cross-section of the laminated rubber bearings

ISOLATION SYSTEMS

1. Laminated Rubber Bearings

The laminated rubber bearings with steel plates are the most common type of system used for base isolation (refer Figure 1 for the model of the bearing considered for the present study). The basic components of such bearings are steel and rubber plates built in the alternate layers. The steel plates of the bearing are vulcanized to the rubber layers and powdered carbon fillers. Due to the presence of reinforcing steel plates, these bearings are very stiff in the vertical direction. However, the bearings are quite flexible in the horizontal direction. The horizontal flexibility and the damping characteristics of the laminated rubber bearings provide the desired isolation effects in the structure that reduces the transmission of earthquake forces from foundation to superstructure. In the design of laminated rubber bearing, a number of trials are necessary to find out an optimum size of bearing, steel plates and the bearing as a whole. The laminated rubber bearings generally exhibit linear force-deformation behavior

(with some hardening effects at large strains, i.e. 200 percent) and are characterized by their lateral stiffness and viscous damping ratio.

The vertical stiffness of the laminated rubber bearings is expressed by

$$K_v = \frac{E_c A}{t_r} \quad (1)$$

where A is the area of the bearing; t_r is the total thickness of rubber in the bearing; and E_c is the instantaneous compression modulus of the rubber-steel composites.

For a bearing, square in plan, the instantaneous compression modulus (Kelly, 1997) is given by

$$E_c = 6.73 S^2 G \quad (2)$$

where S is the shape factor (i.e. ratio of the loaded area to the force-free area of the rubber layer); and G is the shear modulus of the bearing which is typically dependent on the rubber hardness.

The horizontal stiffness of the laminated rubber bearings is expressed by

$$K_h = \frac{GA}{t_r} \quad (3)$$

Ten models of the laminated rubber bearings with cross-section as shown in Figure 1 and square in plan are fabricated. Several experimental tests were performed to obtain their static and dynamic properties. These tests include: (i) the hardness test (for evaluation of the shear modulus), (ii) the force-deformation behaviour in vertical and horizontal directions, and (iii) the free vibration test for measuring the damping. The hardness of the rubber material of the bearings has been measured by using the Shore-A-Hardness indicator. It has been found to be in the range of 43 to 46 with an average value of 44.5. The corresponding value of the shear modulus, G , of the rubber material with hardness of 44.5 works out to be 0.54 MPa (Freakley and Payne, 1978).

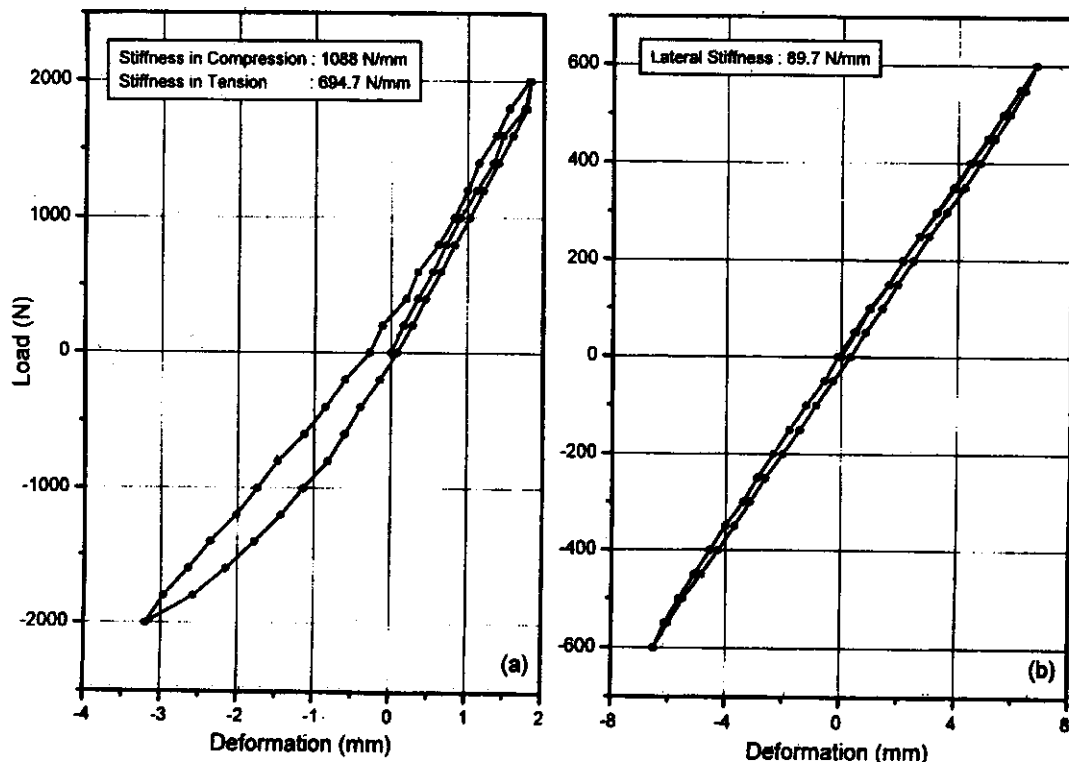


Fig. 2 Experimental force-deformation behaviour of the laminated rubber bearings (a) vertical direction and (b) horizontal direction

A typical force-deformation behaviour in horizontal and vertical directions of the laminated rubber bearings is shown in Figure 2. This figure indicates that the force-deformation behaviour of the bearings can be considered as linear in both directions. The average vertical compression stiffness and horizontal stiffness of the laminated rubber bearings are found to be as 1089.4 N/mm and 46.8 N/mm, respectively. The corresponding analytical vertical and horizontal stiffness of the bearings (expressed by Equations (1) and (3)) provide the values as 1314 N/mm and 45 N/mm which is quite close to the experimental stiffness. The ratio of the average vertical stiffness to the average horizontal stiffness is about 23, which is typical for the small size of the present bearings. For practical rubber seismic isolation bearings, this ratio is of the order of 500 to 2000.

In order to determine the viscous damping of the laminated rubber bearings, a setup consisting of the four bearings supporting a specified mass has been built. The supporting mass is kept equal to the corresponding mass of the steel frame models to be isolated by these bearings. The system was excited in horizontal direction using the hammer, and the free vibration response has been recorded with the help of FFT Analyzer. The average damping ratio is found to be 5 percent of the critical. This damping value is relatively low for the practical design of the isolation systems. It may be noted that it is generally difficult to achieve higher damping in laminated rubber bearings, unless special rubber ingredients are used, thus called high damping rubber bearings; or a lead core is included inside the bearing, thus called lead-rubber bearings; or a supplemental damping device, such as viscous, friction, or yielding steel, is used.

2. Sliding Bearings

A significant amount of the recent research in base isolation has focused on the use of sliding/frictional elements to concentrate flexibility of structural system and to add damping to the isolated structure. The advantages of sliding type system over conventional rubber bearings are (i) the friction force developed at the base is proportional to the mass supported by that bearing implying that there is no eccentricity between the center of mass of the superstructure and the center of stiffness (therefore, if the mass distribution is different from that assumed in the original design, the effects of torsion at the base are diminished), (ii) the frictional isolators do not have any unique natural frequency, and therefore, those dissipate the seismic energy over a wide range of frequency input without the risk of resonance with the ground motion and (iii) the frictional type of system ensures a maximum acceleration transmissibility equal to maximum frictional force.

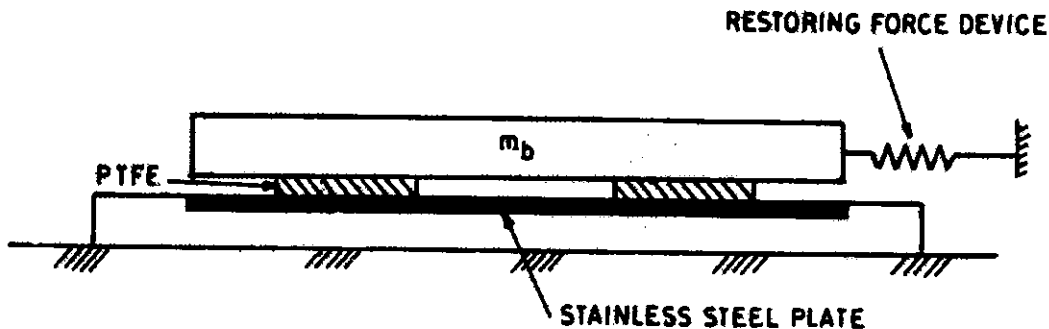


Fig. 3 PTFE bearings for the sliding isolation system

For the present study, two sets of the sliding systems are developed using the Poly Tetra Fluoro Ethylene (PTFE) typically used for the bridge bearings. The system developed is shown in Figure 3. It consists of four PTFE bearings (size 195 mm $\times$ 195 mm) attached to the steel plate which slides over a stainless steel plate (850 mm $\times$ 800 mm). These bearings are generally characterized by their coefficient of friction (μ) which is generally dependent on the pressure (lower for higher pressure) and sliding velocity. A test on these bearings for evaluation of the static friction coefficient is conducted and the friction coefficient of the bearings is found to be about 7 percent. The vertical contact pressure applied on the bearing was about 10 kN/m².

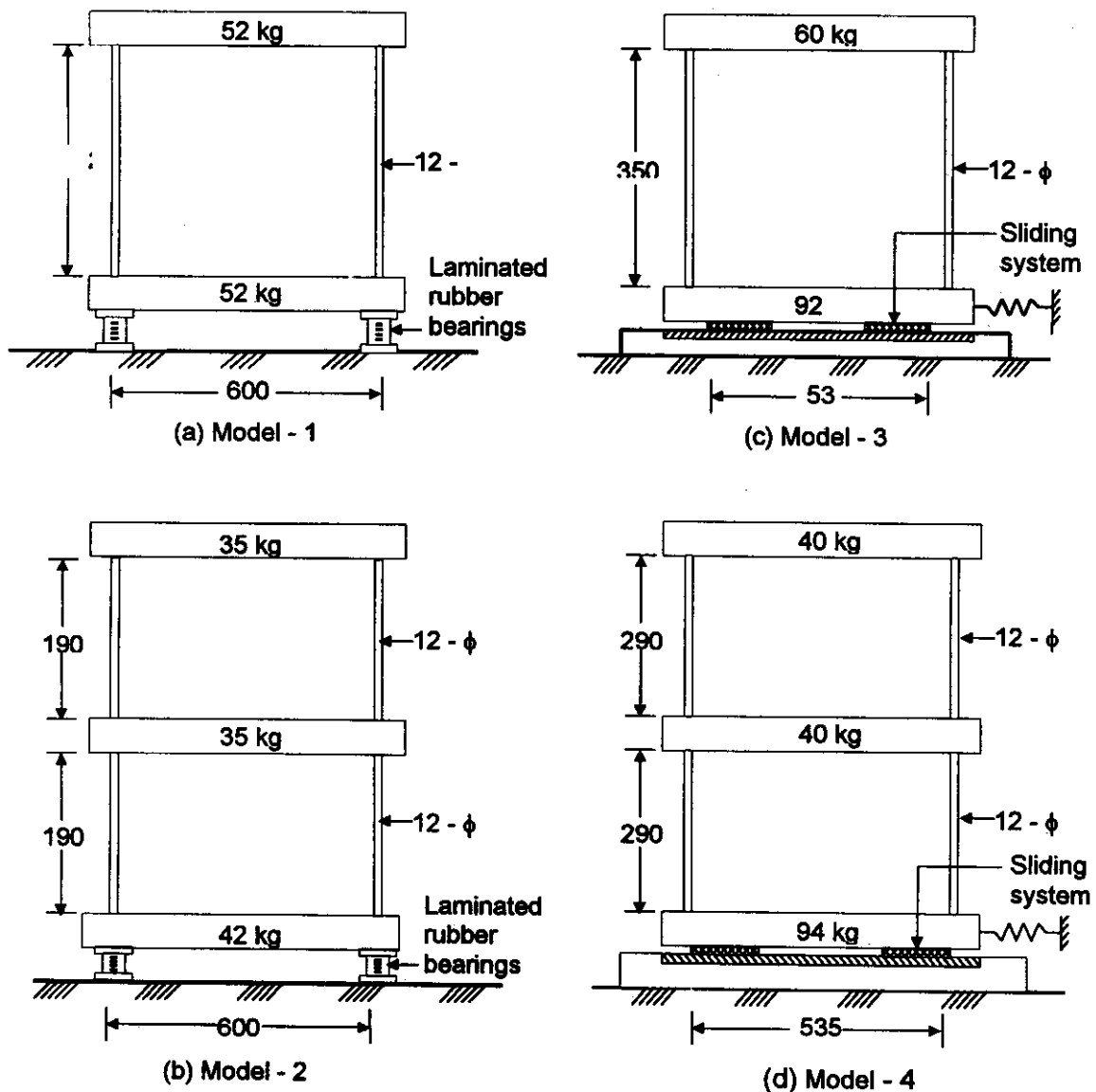


Fig. 4 One and two-storey steel frame models with different isolation systems

ISOLATED STRUCTURAL MODELS

Four models of one and two-storey steel frames isolated by the laminated rubber bearings and sliding bearings are developed as shown in Figure 4. Superstructure consists of steel plates supported by the four steel rods of 12 mm diameter. The steel rods and plates of the model replicate the columns and floors of real building, respectively. For a specified mass of the steel plates, the length of the steel rods was worked out to provide a specific fundamental time period of the superstructure in comparison to the period of the isolated structure. The superstructure has been designed for a fundamental period of about 0.05 sec (20 Hz) and 0.1 sec (10 Hz) for the laminated rubber and sliding bearings, respectively, for both one and two-storey frames assuming the steel plate to be rigid. However, the flexibility of the steel plates will elongate the period beyond the above-specified values. The simple PTFE bearings do not have restoring force; as a result, these bearings will undergo large base displacements (which have practical limitations) under earthquake excitation. The restoring force device used with these bearings consisted of horizontal cantilever beams made of the steel rods. Such an arrangement was quite satisfactory for the experimental

study but may not be feasible in practice. The stiffness of cantilever beams is adjusted such that it provides the required period of isolation. The scaling factor of structural models is of the order of $1/20$. The fundamental frequency of the scaled models is higher as compared to the actual structures (i.e., the fundamental period of the structure isolated by the laminated rubber bearing should be of the order of 2 sec whereas it is 0.15 sec in the scaled model).

ANALYTICAL MODELLING OF STRUCTURAL MODELS

The various assumptions made for analytical modeling of the isolated structural models are as follows:

1. The steel rods in the superstructure remain elastic during the base excitation. This is a reasonable assumption, since the purpose of base isolation is to reduce the earthquake effects in such a way that the superstructure remains within the elastic limit.
2. The coefficient of friction of the sliding bearing remains constant throughout the motion of the structure (i.e., the friction coefficient is independent of velocity and pressure).
3. The force-deformation behaviour of the laminated rubber bearings is considered to be linear.
4. The force-deformation behaviour of the restoring force device used for the sliding bearings is also taken as linear. However, the associated damping of the restoring force device is neglected.
5. The damping in various elements (i.e. steel rods of the superstructure and laminated rubber bearings) of structural systems is considered in form of equivalent viscous damping ratios obtained from the free vibration measurements.
6. No overturning or tilting will occur in the superstructure during the sliding phase of motion.
7. At each floor and base mass, one lateral dynamic degree-of-freedom is considered.

The above assumptions will lead to the mathematical model of the isolated steel frame structural models as shown in Figure 5. This model is applicable for both types of isolation systems.

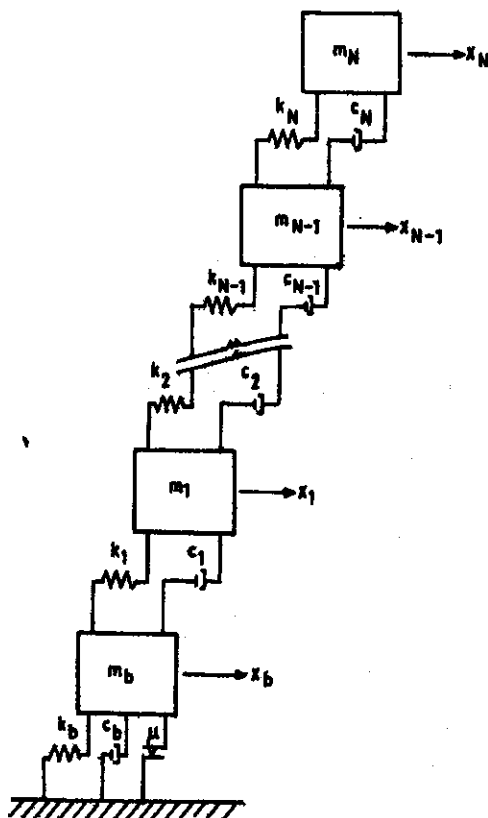


Fig. 5 Analytical model of structure supported on the isolation system

1. Governing Equations of Motion

The governing equations of motion for the fixed-base N -storey steel frame model shown in Figure 5 are expressed as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = -[M]\{1\} \ddot{x}_g \quad (4)$$

where $[M]$, $[K]$ and $[C]$ are the mass, stiffness and damping matrices of the fixed-base structure, respectively, of the order $N \times N$; $\{x\} = \{x_1, x_2, \dots, x_N\}^T$ is the displacement vector of the superstructure; x_j ($j = 1, 2, \dots, N$) is the lateral displacement of the j th floor relative to the base mass; $\{1\} = \{1, 1, 1, \dots, 1\}^T$ is the influence coefficient vector; and $\ddot{x}_g$ is the ground acceleration. Note that the damping matrix of the superstructure, $[C]$ is not known explicitly. It is constructed by assuming the modal damping ratio which is kept constant in each mode of vibration.

The governing equation of motion of the base mass is expressed by

$$m_b \ddot{x}_b + c_b \dot{x}_b + k_b x_b + F_x - c_1 \dot{x}_1 - k_1 x_1 = -m_b \ddot{x}_g \quad (5)$$

where m_b is the mass of base raft; c_b and k_b are the damping and stiffness of the isolation system, respectively; F_x is the mobilised frictional force of the system; k_1 and c_1 are the stiffness and damping of the first-storey of the superstructure, respectively.

The lateral stiffness (k_b) and viscous damping constant (c_b) of the laminated rubber bearings are expressed in terms of the isolation period and damping ratio by

$$c_b = 2\xi_b (m_b + \sum_{i=1}^N m_i) \omega_b \quad (6)$$

$$k_b = (m_b + \sum_{i=1}^N m_i) \omega_b^2 \quad (7)$$

where ξ_b is the damping ratio of the laminated rubber bearings; m_i is the mass of the i th floor of the superstructure; $\omega_b = 2\pi/T_b$ is the base isolation frequency; and T_b is the period of base isolation. Note that for the sliding bearings, k_b denotes the stiffness of the restoring force device which is designed in accordance with Equation (7) to provide a specified period of isolation.

The limiting value of the frictional force, F_x to which the sliding bearings isolating the multi-storey steel frame model can be subjected in a particular direction, is expressed as

$$F_x = \mu (m_b + \sum_{i=1}^N m_i) g \quad (8)$$

where μ is the friction coefficient of the sliding bearing; and g is the acceleration due to gravity.

2. Solution of Equations of Motion

The dampings in the isolation system and superstructure are different in nature, and the frictional force mobilized in the sliding system is non-linear function of the system response; therefore, the response of isolated structural system cannot be obtained by using the classical modal superposition technique. However, the equations of motion can be solved in the incremental form by using the step-by-step method. For the present study, Newmark's method has been chosen for the solution of governing differential equations, while assuming a linear variation of acceleration over a small time interval. For the structure with sliding bearings, the conditions for sliding and non-sliding phases are duly checked at the end of each time step. The system remains in the non-sliding phase ($\dot{x}_b = \ddot{x}_b = 0$) if the frictional force mobilized at the interface of sliding bearings is less than the limiting frictional force (i.e., $|F_x| < F_x$). However, the system starts sliding ($\dot{x}_b \neq \ddot{x}_b \neq 0$) as soon as the frictional force attains the limiting

frictional force (i.e., $|F_x| = F_s$). During the sliding phase, whenever the relative velocity of the base mass becomes zero (i.e., $\dot{x}_b = 0$), the phase of the motion had been checked in order to determine whether the system remains in the sliding phase or sticks to the foundation.

For the present study, a specific computer code is written to obtain the response of isolated structural models to harmonic and earthquake excitations. However, the computer software 3D-BASIS (Nagarajaiah et al., 1991) is also available for the non-linear analyses of three-dimensional base-isolated structures.

Table 1: Properties of Isolated Steel Frame Models

Properties	Model - 1	Model - 2	Model - 3	Model - 4
Fundamental time period of superstructure, T_s (sec)	0.053	0.064	0.1	0.111
Superstructure damping, ξ_s (per cent)	2	2	2	2
Number of storeys (N)	1	2	1	2
Mass ratio (m_b/m)	1	1.2	1.53	2.35
Period of isolation, T_b (sec)	0.152	0.145	0.456*	0.488*
Isolation damping, ξ_b (per cent)	5	5	-	-
Friction coefficient (μ)	-	-	0.07	0.07

(* the restoring force device provides isolation period)

3. System Parameters of Structural Models

The model of the isolated structural system (refer Figure 5) can be completely characterized by the parameters, namely, the fundamental time period of the superstructure with fixed base (T_s), the damping ratio of the superstructure (ξ_s), number of stories in the superstructure (N), the ratio of base mass to the superstructure floor mass (m_b/m), the period of base isolation (T_b), damping ratio of the isolation system (ξ_b), and the coefficient of friction (μ). The values of these parameters for different models obtained from several experimental tests are shown in Table 1. These parameters are used for finding out the analytical response of the structural models under different base excitations. The fundamental time periods and the damping ratios of the superstructures are obtained from the free vibration tests by using the FFT Analyzer. As expected, the fundamental time periods of the superstructures are elongated due to the flexibility of the steel plates (the theoretical fundamental time periods of the Models-1, -2, -3 and -4 are 0.05, 0.05, 0.1 and 0.1, respectively). Further, this effect is more pronounced for the superstructure with two storeys in comparison to the single-storey models.

SHAKE TABLE STUDY

In this section, shake table tests of different models under harmonic base acceleration are discussed. The harmonic base excitation is expressed as $\ddot{x}_g = a_0 \sin(\omega t)$ (where a_0 = amplitude of the harmonic acceleration; ω = harmonic excitation frequency; and t = time variable). The amplitude of harmonic acceleration was taken as 20 percent of gravity and kept constant for all frequencies of excitation (in the range of 1 to 35 Hz). For the base-isolated structures, the response quantities of interest are the top floor absolute acceleration of the superstructure (i.e., $\ddot{x}_a = \ddot{x}_N + \ddot{x}_b + \ddot{x}_g$) and the relative base displacement (x_b). The absolute acceleration is directly proportional to the force exerted in the superstructure due to earthquake ground motion. On the other hand, the relative base displacement is crucial from the design point of view of the isolation system. At the top floor of each model, three sensors are placed to measure the absolute acceleration. Similarly, three other sensors are placed at the base of isolated system for measuring the absolute base displacement (relative base displacement can be obtained analytically after validating the mathematical model of the system). An additional sensor was put to monitor the

acceleration of the shake table. The experimental response of the structural models is compared with the corresponding analytical response to validate the mathematical model of the superstructure and isolation systems. The response of the isolated system is also compared with the corresponding response of fixed base (referred as non-isolated) system to investigate the effectiveness of base isolation. In addition, the effects of re-centering device on the response of the structures isolated by sliding bearings are also investigated. It is to be noted that due to the small size of the existing shake table, the structural models and isolation bearings used in the study are very small, and do not represent the actual size of the bearings used in the practice. However, the results of the experimental study nonetheless demonstrate the general benefits of seismic isolation.

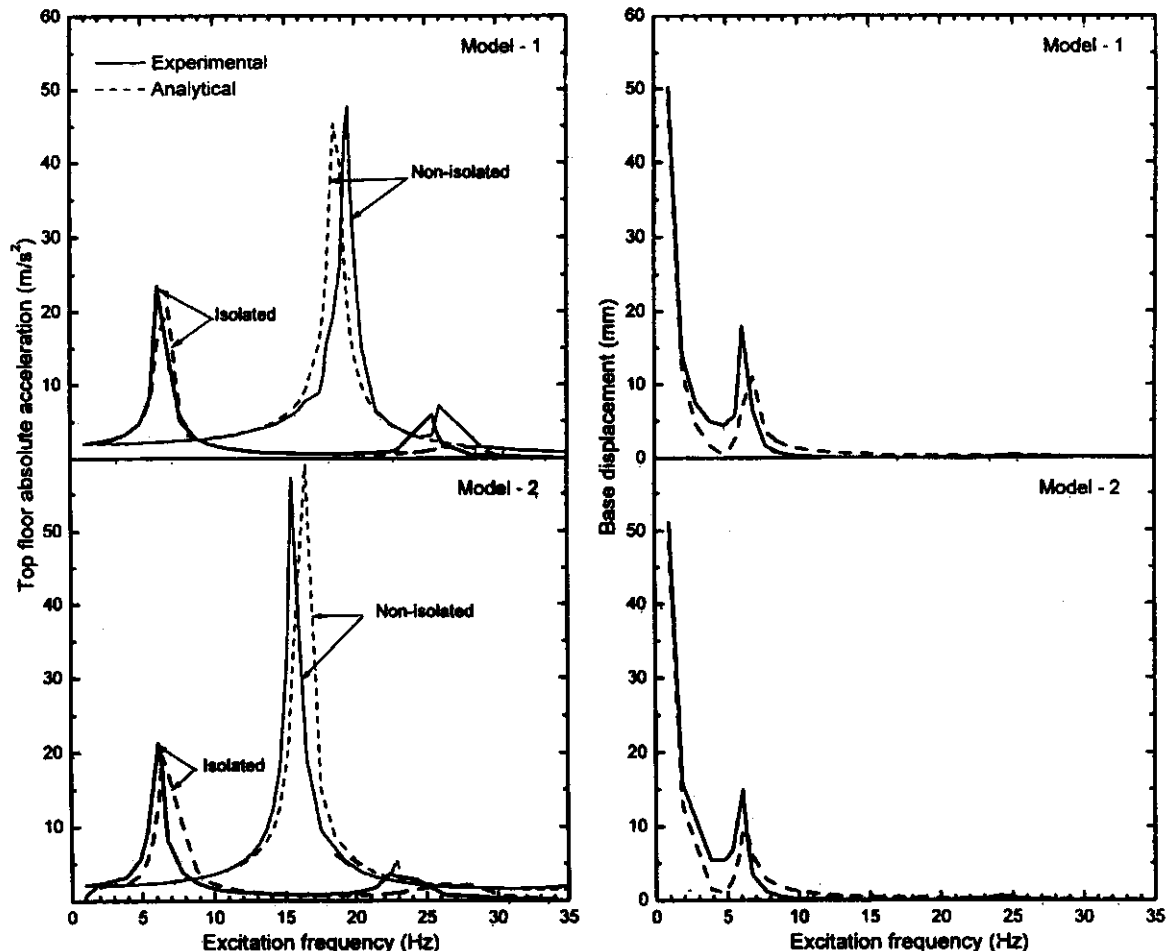


Fig. 6 Experimental and analytical response of structural models isolated by laminated rubber bearings under harmonic excitation

Figure 6 shows the comparison of experimental and analytical responses of structural models isolated by the laminated rubber bearings against different harmonic excitation frequencies. The figure indicates that there is a good agreement between the experimental and analytical responses of the structural models. The superstructure acceleration of the isolated structures is relatively less in comparison to that of the non-isolated system (for both Models-1 and -2), indicating that the isolation is quite effective in reducing the dynamic response of the system. It is to be noted that there is an increase in the top floor acceleration for both isolated and non-isolated conditions of Model-1 in the vicinity of excitation frequency of 25 Hz. This took place due to accidental torsion in the model, and resonance was observed between the harmonic excitation frequency and the torsional frequency of the model. As a result, the experimental response of the system has increased due to coupling between lateral and torsional displacements of the system.

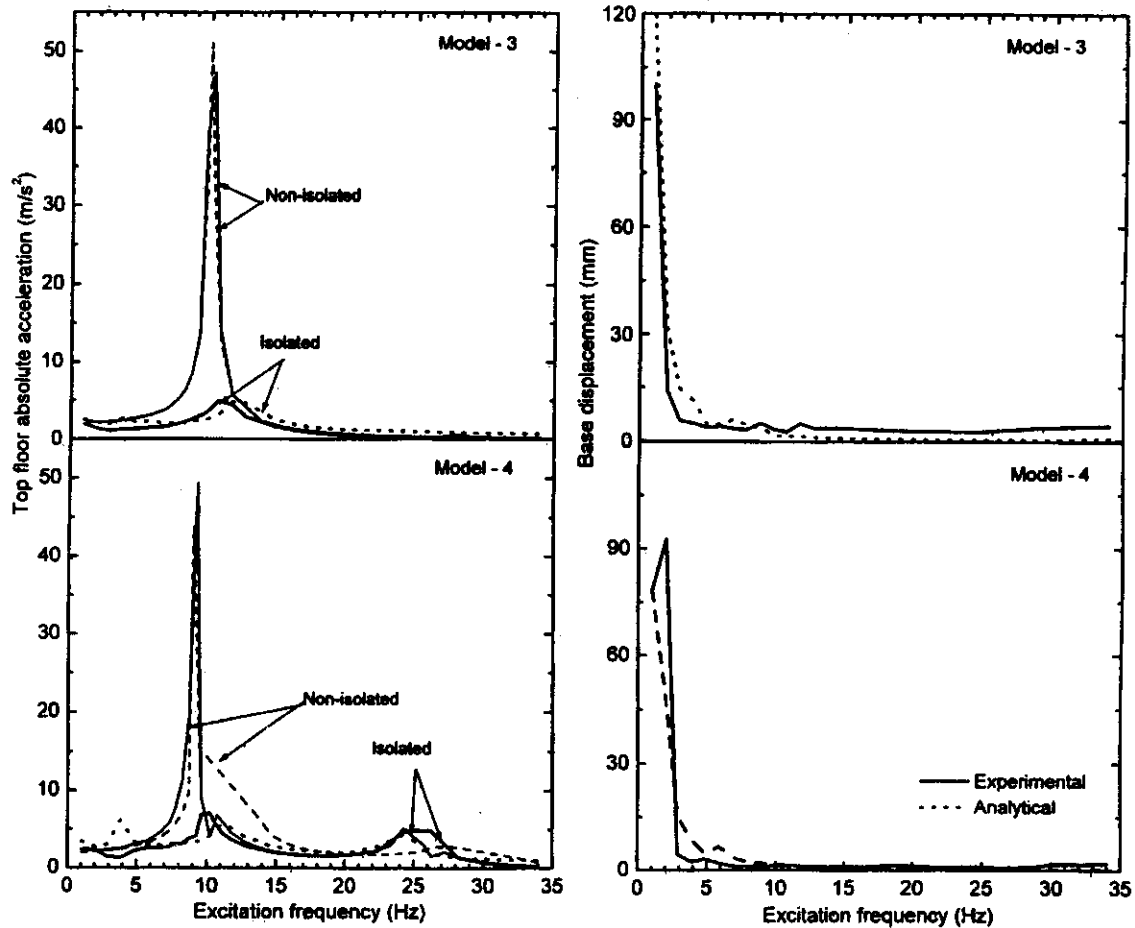


Fig. 7 Experimental and analytical response of structural models isolated by sliding bearings without restoring force device under harmonic excitation

The variation of top floor acceleration and base displacement against harmonic excitation frequency is shown in Figures 7 and 8 for the sliding bearings with and without restoring force device, respectively. There is a significant reduction in the response of isolated system, implying that the sliding bearings are quite effective for reducing the dynamic response of the system. The presence of restoring force along with sliding bearings reduces the base displacement without additional transmission of superstructure acceleration. Thus, the pure-friction sliding systems should be associated with restoring force device to control the base displacement.

RESPONSE UNDER REAL EARTHQUAKE MOTION

In order to study the behaviour of designed isolated structural models, their response is investigated under a real earthquake ground motion. The N00E component of El Centro, 1940 earthquake ground motion is considered with appropriate time scaling factors (since the small-scale models do not reflect the actual frequency real structure). The scaling factors of 10 and 5 are considered for the models isolated by the laminated rubber bearings (i.e., Models-1 and -2) and sliding bearings (i.e., Models-3 and -4), respectively. Figure 9 shows the time variations of top floor absolute acceleration ($\ddot{x}_a$) and relative base displacement (x_b) of Models-1 and -2. Significant reductions are seen in the absolute superstructure acceleration for both models, confirming the effectiveness of base isolation in reducing the seismic response of structures. Further, there is not significant difference between the response of both models. This is due to the fact that both the systems are linear and that their dynamic properties are almost identical (refer Table 1). Note that the low relative displacement of the isolated structural model is due to

scaling factor used in the earthquake ground motion. For example, if the time period of the structural models is scaled corresponding to real structure (i.e., increase 10 times for models isolated by the laminated rubber bearings), then the absolute acceleration of the systems will remain the same but the displacement will be increased to 100 times. Further, similar effects of isolation under earthquake motion are depicted in Figures 10 and 11 for structural models with sliding bearings with and without restoring force device, respectively. These figures indicate clearly the effectiveness of sliding bearings for reducing earthquake response and restoring force device in controlling the base displacement. Since the dynamic properties of Models-3 and -4 are almost identical, the variation of top floor absolute acceleration is almost same for both models. However, there is significant difference in the variation of sliding base displacement. This is due to the fact that the sliding base displacement is quite sensitive to the initial condition at the sliding and non-sliding phases of the system (Iura et al., 1992).

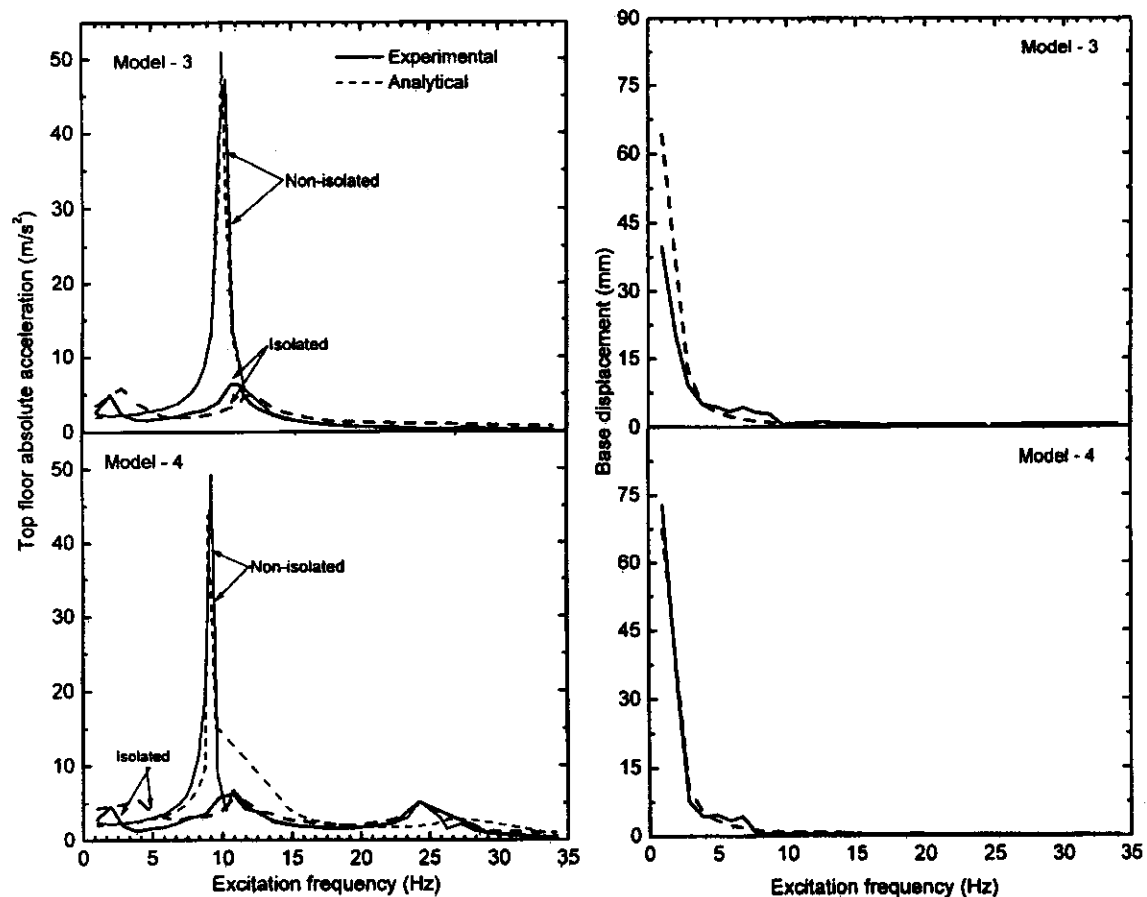


Fig. 8 Experimental and analytical response of structural models isolated by sliding bearings with restoring force device under harmonic excitation

CONCLUSIONS

Two base isolation systems, namely the laminated rubber bearings with steel plates and sliding bearings, are designed and fabricated. These bearings are tested for evaluation of their static and dynamic properties. Based on these properties of the bearings, small-scale models of the isolated one and two-storey steel frame structures are developed. An experimental shake table study of these models with different isolation devices has been carried out. The models were subjected to harmonic base acceleration of fixed amplitude (i.e. 0.2g) with varying frequencies (in the range of 1 to 35 Hz). The experimental response of the isolated and non-isolated models is compared with the corresponding analytical response to validate the mathematical model of the isolation systems. Further, in order to study the effectiveness of isolation system, the response of isolated structure is compared with the corresponding response for fixed base. From the trends of the results of the present study, following conclusions may be drawn:

1. The force-deformation behaviour of developed small-scale laminated rubber bearings is found to be almost linear in both horizontal and vertical directions. The ratio of the average vertical to horizontal stiffness of the laminated rubber bearings is of the order of 23.
2. There was a good agreement between experimental and analytical stiffness of the laminated rubber bearings in both vertical and horizontal directions.
3. The damping in the laminated rubber bearings is found to be of the order of 5 percent whereas the friction coefficient of the sliding bearing is found to be about 7 percent.
4. The top floor acceleration of isolated structural models is found to be less in comparison to the corresponding acceleration without isolation system. Thus, the isolation system is effective in reducing the dynamic response of the system.
5. There was a good agreement between the experimental and analytical responses of the structural models. The proposed mathematical model can be used for calculation of analytical response of the isolated structure under real earthquake excitations.
6. The presence of restoring force device along with the sliding bearing reduces the base displacement without transmission of additional superstructure acceleration. Thus, the pure-friction sliding bearings should be associated with the restoring force device to control the base displacements which have practical limitations.

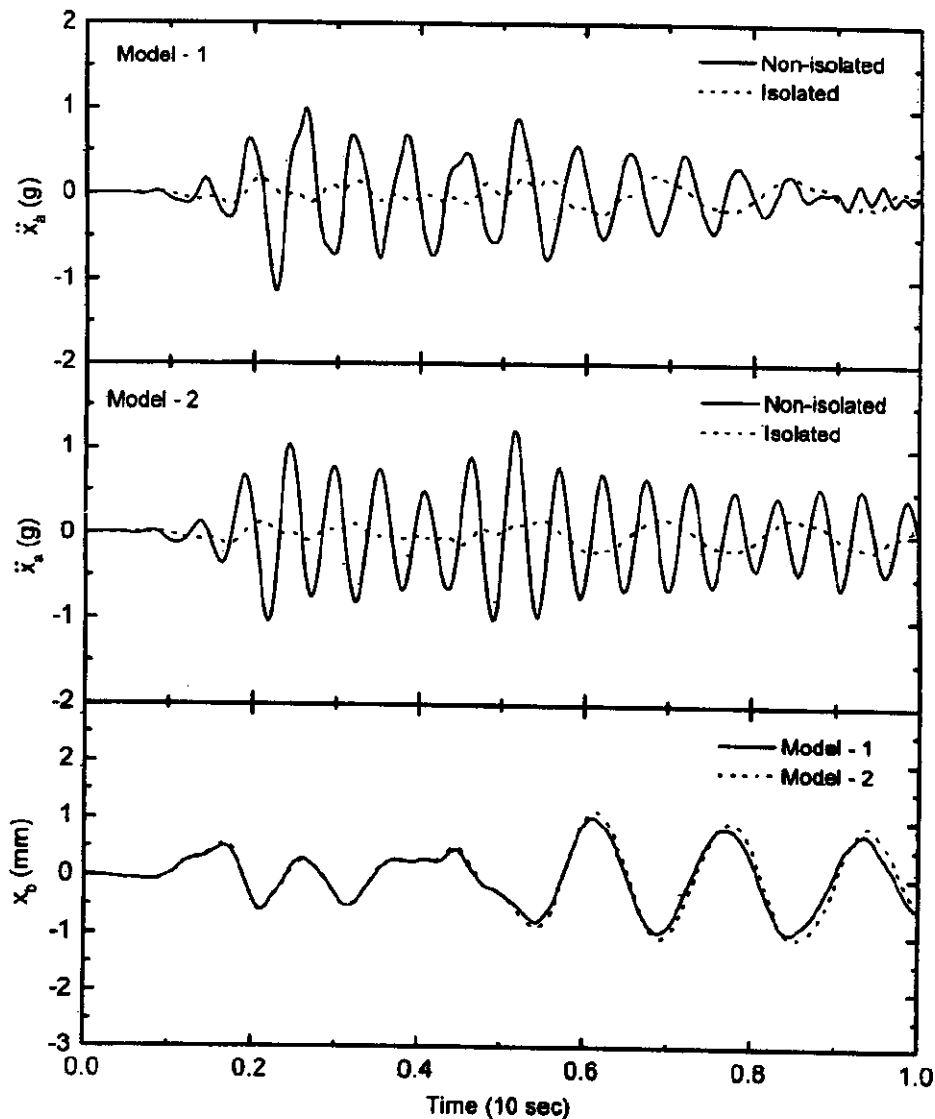


Fig. 9 Earthquake response of structural models isolated by the laminated rubber bearings

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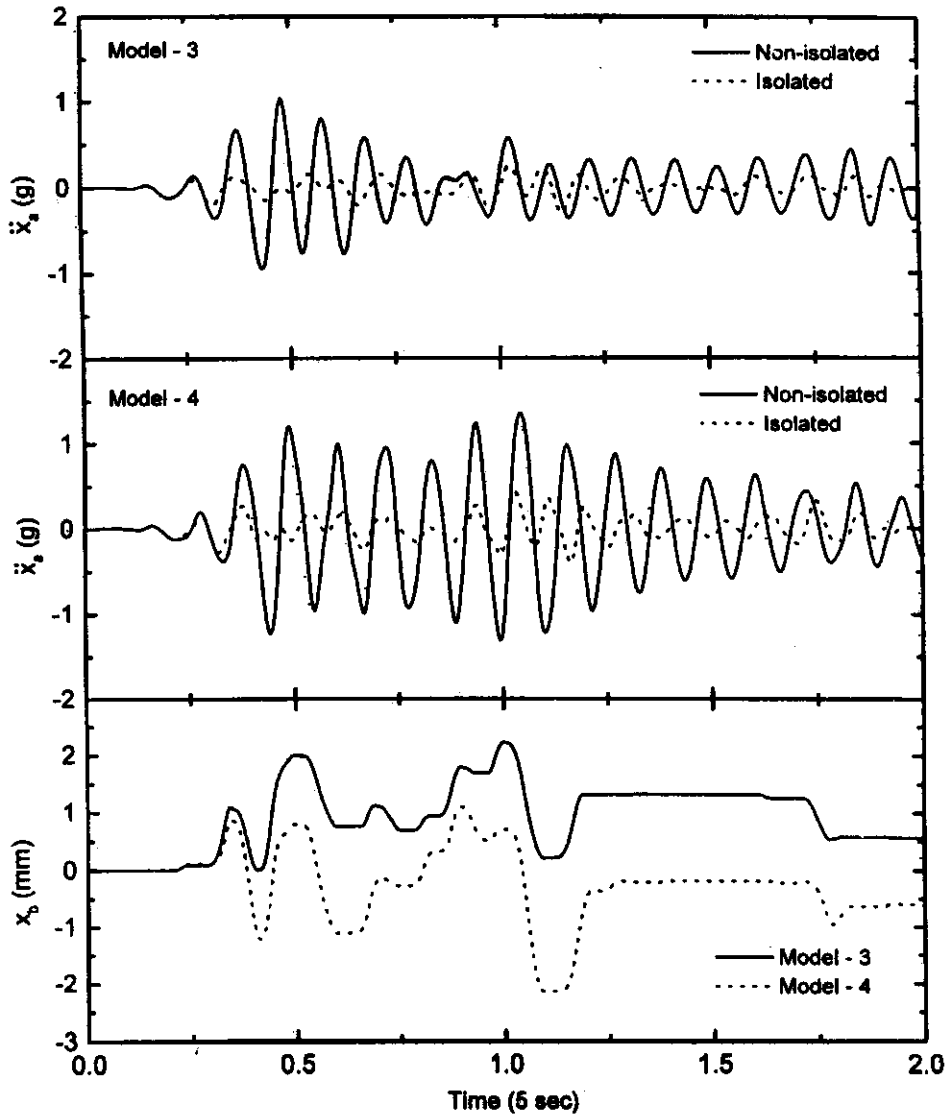


Fig. 10 Earthquake response of structural models isolated by the sliding bearings without restoring force device

REFERENCES

1. Buckle, I.G. and Mayes, R.L. (1990). "Seismic Isolation: History, Application and Performance-A World Overview", *Earthquake Spectra*, Vol. 6, No. 2, pp. 161- 202.
2. Freakley, P.K. and Payne, A.R. (1978). "Theory and Practice of Engineering with Rubber", Applied Science Publishers Ltd., London, U.K.
3. Iura, M., Matsui, K. and Kosaka, I. (1992). "Analytical Expression for Different Modes in Harmonic Motion of Sliding Structures", *Earthquake Engineering and Structural Dynamics*, Vol. 21, pp. 757-769.

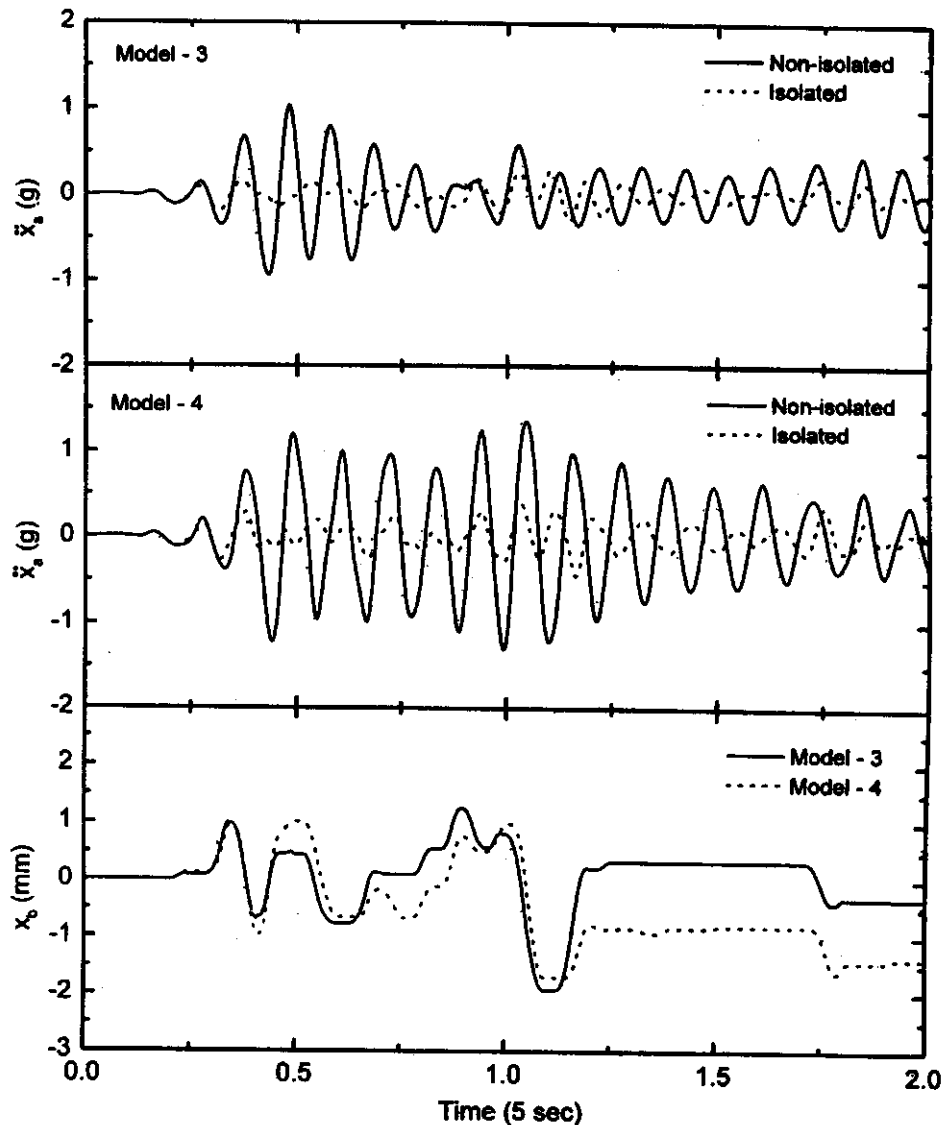


Fig. 11 Earthquake response of structural models isolated by the sliding bearings with restoring force device

4. Jain, S.K. and Thakkar, S.K. (1998). "Response Control of Buildings with Rubber Bearings", *International Journal of Structures*, Vol. 18, No. 2, pp. 109-125.
5. Jangid, R.S. and Datta, T.K. (1994). "Non-Linear Response of Torsionally Coupled Base Isolated Structure", *Journal of Structural Engineering, ASCE*, Vol. 120, pp. 1-22.
6. Jangid, R.S. and Datta, T.K. (1995a). "Seismic Behaviour of Base Isolated Building - A-State-of-the-Art-Review", *Journal of Structures and Buildings*, Vol. 110, pp. 186-203.
7. Jangid, R.S. and Datta, T.K. (1995b). "The Stochastic Response of Asymmetric Base Isolated Buildings", *Journal of Sound and Vibration*, Vol. 179, pp. 463-473.
8. Jangid, R.S. (1996). "Seismic Response of Sliding Structures to Bi-Directional Earthquake Excitation", *Earthquake Engineering and Structural Dynamics*, Vol. 25, pp. 1301-1306.
9. Jangid, R.S. and Londhe, Y.B. (1998). "Effectiveness of Elliptical Rolling Rods for Base-Isolation", *Journal of Structural Engineering, ASCE*, Vol. 124, pp. 469-472.
10. Jangid, R.S. (2000). "Stochastic Seismic Response of Structures Isolated by Rolling Rods", *Engineering Structures*, Vol. 22, pp. 937-946.
11. Jangid, R.S. and Kelly, J.M. (2000). "Torsional Displacements in Base-Isolated Buildings", *Earthquake Spectra*, Vol. 16, pp. 443-454.

12. Jangid, R.S. and Kelly, J.M. (2001). "Base Isolation for Near-Fault Motions", *Earthquake Engineering and Structural Dynamics*, Vol. 30, pp. 691-707.
13. Kelly, J.M. and Hodder, S.B. (1982). "Experimental Study of Lead and Elastomeric Dampers for Base Isolation System in Laminated Neoprene Bearings", *Bulletin of the New Zealand National Society for Earthquake Engineering*, Vol. 15, No. 2, pp. 53-67.
14. Kelly, J.M. and Beucke, K.E. (1983). "A Frictional Damped Base Isolation System with Fail-Safe Characteristics", *Earthquake Engineering and Structural Dynamics*, Vol. 11, pp. 33-56.
15. Kelly, J.M. (1986). "A Seismic Base Isolation: Review and Bibliography", *Soil Dynamics and Earthquake Engineering*, Vol. 5, pp. 202-216.
16. Kelly, J.M. (1997). "Earthquake-Resistant Design with Rubber", 2nd Edition, Springer-Verlag, London, U.K.
17. Mokha, A., Constantinou, M.C. and Reinhorn, A.M. (1990). "Teflon Bearings in Base Isolation I: Testing", *Journal of Structural Engineering, ASCE*, Vol. 116, pp. 438-454.
18. Mokha, A., Constantinou, M.C. and Reinhorn, A.M. (1991). "Experimental Study of Friction-Pendulum Isolation System", *Journal of Structural Engineering, ASCE*, Vol. 117, No. 4, pp. 1201-1217.
19. Mostaghel, N., Kelly, J.M. and Clark, P.W. (1992). "Stability of R-FBI Bearings: Analysis and Experiment", *Earthquake Spectra*, Vol. 8, pp. 259-278.
20. Naeim, F. and Kelly, J.M. (1999). "Design of Seismic Isolated Structures", John Wiley, NY, U.S.A.
21. Nagarajaiah, S., Reinhorn, A.M. and Constantinou, M.C. (1991). "Non-Linear Dynamic Analysis of Three Dimension Base Isolated Structures (3D-BASIS)", Report No. NCEER-91-005, State University of New York, Buffalo, NY, U.S.A.
22. Rao, P.B. and Jangid, R.S. (2001). "Performance of Sliding Systems under Near-Fault Motions", *Nuclear Engineering and Design*, Vol. 203, pp. 259-272.
23. Qamaruddin, M., Arya, A.S. and Chandra, B. (1986a). "Seismic Response of Brick Buildings with Sliding Substructures", *Journal of Structural Engineering, ASCE*, Vol. 112, pp. 558-572.
24. Qamaruddin, M., Rasheeduzzafar, Arya, A.S. and Chandra, B. (1986b). "Seismic Response of Masonry Buildings with Sliding Substructures", *Journal of Structural Engineering, ASCE*, Vol. 112, pp. 2001-2011.