SEISMIC RESPONSE OF BUILDINGS ISOLATED BY SLIDING-ELASTOMER BEARINGS SUBJECTED TO BI-DIRECTIONAL MOTION

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SUMMARY

In this paper, nonlinear dynamic analysis of buildings isolated by sliding-elastomer isolation system subjected to bi-directional earthquake motion has been presented. Sliding-elastomer bearing with frictional couple having low coefficient of friction, such as Teflon-stainless steel interface, has been studied. Force-displacement hysteretic behaviour of Teflon-stainless steel interface subjected to bi-directional motion has been simulated using visco-plastic model. Newmark's method in predictor-corrector form has been used for direct integration of coupled equations of motion in staggered fashion. It has been observed that the effect of the bi-axial interaction is considerable in the response of buildings isolated by sliding-elastomer bearing under bi-directional motion.

INTRODUCTION

Sliding-elastomer base isolation system developed by **Gueraud** *et al.***(1985)** under the auspices of Electricite De France (EDF). The component of this system consists of laminated (steel reinforced) neoprene bearing topped by a lead bronze plate which is in frictional contact with stainless steel plate ($\mu = 0.2$) anchored to the structure. The sliding-elastomer base isolator uses essentially an elastomeric bearing and friction couple in series. This system is standardized for nuclear power plants in regions of high seismicity. In this paper, seismic behaviour of buildings isolated by sliding-elastomer isolation system with friction couple, such as Teflon-stainless steel interface, having low coefficient of friction has been studied.

When a building isolated by sliding-elastomer bearing experiences bi-directional motion owing to asymmetry in the structure and /or multidirectional excitation, it becomes difficult to compute the response by conventional rigid-plastic model. Frictional forces developed in the Teflon-stainless steel sliding interface of the sliding-elastomer isolation systems are computed using modified visco-plastic model developed by **Constantinou** *et al.***(1990)**. This model is based on an extensive series of tests on Teflon-stainless steel sliding interface. Strain level in the laminated neoprene bearing of sliding-elastomer bearing (with Teflon-stainless steel frictional couple) is low because of low coefficient of friction. Therefore, hysteretic part of restoring force in the laminated neoprene bearing is not considered.

The solutions of different equations governing the behaviour of non-linear isolation elements are obtained using a close form solution. The implicit-implicit partitioned Newmark's method in predictor-corrector form is used for direct integration of coupled equations of motion in staggered fashion. Comparison of the displacement and acceleration histories show that the effect of the bi-axial interaction is considerable in the response of buildings isolated by sliding-elastomer bearing under bi-directional motion.

NONLINEAR HYSTERETIC MODEL OF ISOLATION SYSTEM

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Relative bearing displacements and velocities in the X and Y directions with respect to the ground are designated by u_{b1}, u_{b3} and $\dot{u}_{b1}$, $\dot{u}_{b3}$ respectively. The isolation bearings are considered to be rigid in the vertical direction. Therefore, the instantaneous direction of the displacement θ_b and the velocity $\dot{u}_b$ are given by

$$\theta_b = \tan^{-1}\left(\frac{\dot{u}_{b3}}{\dot{u}_{b1}}\right) \tag{1}$$

$$\dot{u}_b = \left(\dot{u}_{b1}^2 + \dot{u}_{b3}^2\right)^{1/2} \tag{2}$$

The direction of the resultant force developed at the bearing is opposite to the direction of the motion. The forces mobilized in the sliding interface are expressed as:

$$f_1 = \mu_s W z_1 \tag{3a}$$

$$f_2 = 0 \tag{3b}$$

$$f_3 = \mu_s W z_3 \tag{3c}$$

where W is the total load at the frictional interface z_1 and z_3 are the hyteretic dimensionless constants in the X and Y directions respectively and μ_s is the coefficient of the sliding friction, which depends on the bearing pressure and the instantaneous sliding velocity at the sliding interface.

The contribution of the torsional moment, which develops at the bearing owing to the total torque exerted to the superstructure supported by the bearings, is insignificant. Therefore, z_2 is considered to be equal to zero.

Equation (3) is identical to the Coulomb's friction force model. Here, *sign* function is replaced by z and it takes values of ±1 during the sliding (yielding) phase. During non-sliding (elastic) phase, the absolute value of z is less than unity.

On the basis of extensive experimental work **Constantinou** *et al.*(1990) modelled the coefficient of the sliding friction by the following expression:

$$\mu_s = \mu_{\max} - \Delta\mu \ \exp\left(-a\left|\dot{u}_b\right|\right) \tag{4}$$

where, $\mu_{\max}$ is the maximum coefficient of friction at high velocity of sliding, $\Delta\mu$ is the difference between the $\mu_{\max}$ and the sliding value at very low velocity and a is a constant which takes care of variation of the bearing pressure at the sliding interface.

The dimensionless hysteretic constants z_1 and z_3 can be calculated from the following coupled differential equations: (**Park** *et al.***1986**)

$$Y\dot{z}_1 + \gamma\left|\dot{u}_{b1}z_1\right|z_1 + \beta\dot{u}_{b1}z_1^2 + \gamma\left|\dot{u}_{b3}z_3\right|z_1 + \beta\dot{u}_{b3}z_1 z_3 - A\dot{u}_{b1} = 0 \tag{5a}$$

$$Y\dot{z}_3 + \gamma\left|\dot{u}_{b3}z_3\right|z_3 + \beta\dot{u}_{b3}z_3^2 + \gamma\left|\dot{u}_{b1}z_1\right|z_3 + \beta\dot{u}_{b1}z_1 z_3 - A\dot{u}_{b3} = 0 \tag{5b}$$

where, γ, β and A are the dimensionless constants which govern the general shape of the hysteresis loop and Y represents a displacement quantity. It has been observed that when $A = 1$ and $\beta+\gamma = 1$ the model of equation (5) reduces to a model of visco-plasticity and in this case Y represents the yield displacement.

Equations (5a) and (5b) are extensions of equation for the one dimensional hysteretic restoring force. The variables in equations (5a) and (5b) are expressed as:

$$z_1 = z\ \cos\theta_b\ ,\quad z_3 = z\ \sin\theta_b\ ,\quad u_{b1} = u_b\ \cos\theta_b\ ,\quad u_{b3} = u_b\ \sin\theta_b \tag{6}$$

in which u_b and z are the resultant uniaxial displacement and hysteretic dimensionless constant respectively. Substituting equation (6) into (5) and subsequent simplification results in following equation:

$$Y\dot{z} + \gamma|\dot{u}_b z|z + \beta\dot{u}_b z^2 - A\dot{u}_b = 0 \tag{7}$$

Considering the signs of $\dot{u}_b$ and z in equation (7) are the same, the equation simplifies to the form:

$$\frac{dz}{dt} + z^2\left(\frac{\dot{u}_b}{Y}\right) - \frac{\dot{u}_b}{Y} = 0 \tag{8}$$

The explicit solution of equation (8) is given as:

$$z = \tanh\left(\frac{\dot{u}_b}{Y}\right) \tag{9}$$

In the present study, the hysteretic dimensionless constant z is calculated from equation (9) and then z_1 and z_3 with proper signs are calculated using equation (6) and these values are used in turn to compute the hysteretic component of restoring force using equations (3a) to (3c).

VERIFICATION OF HYSTERETIC MODEL

For verification of the hysteretic model discussed in the preceding section, simulated hysteresis loops are compared with the experimental results obtained from the bi-directional tests carried out by **Mokha** *et al.***(1993)**. The bi-directional motion is given by:

$$u_{b1} = u_m\ \sin\omega t \tag{10a}$$

$$u_{b3} = u_m \sin 2\omega t \tag{10b}$$

in which ω = 1.57 rad/sec and u_m = 14.65 mm and 29.3 are considered for the tests. Figure 1 shows the bi-axial hysteretic behaviour of the Teflon-stainless steel interfaces – both the simulated loops obtained in the present study and experimental observation of Test 3 and Test 6 performed by **Mokha** *et al.***(1993)** in the X and Y directions. The out of phase sinusoidal excitations represented by equation (10) are considered as inputs in the X and Y directions. For simulation of hysteretic behaviour: $\Delta\mu$ = 0.0811; $\mu_{\max}$ = 0.12; a = 0.01578 sec/mm in the direction parallel to layer and $\Delta\mu$ = 0.094; $\mu_{\max}$ = 0.14; a = 0.017874 sec/mm in the direction perpendicular to layer are considered. The bearing pressure in the interface was 3.44736 Pa. In Test 3, peak displacements in the X and Y directions are 45.491 mm and 43.8912 mm respectively with frequency of 0.5 rad/sec, while in Test 6, the peak displacements in X and Y directions are 45.1866 mm and 43.8912 mm respectively with a frequency of 2.22 rad/sec. Both simulated loops and experimental loops in X and Y directions are found to in good agreement.

EQUATIONS OF MOTION

In this study, the superstructure is assumed to be a three dimensional multi-storey elastic shear frame with three degree of freedom (dof) per floor. This three dof are two translational motion in X and Y directions respectively and a rotation about z axis. Figure 2 shows the structural model of a three storey shear frame building. The three dof are associated with the centre of mass of each floor and the base. The floors and the base are assumed to be infinitely rigid in its plane. The centre of mass of all floors and the base are assumed to be on the same vertical axis. The asymmetry in floor plan (if any) is identical for all the floors.

The governing equations of motion of elastic superstructure for 3-D model of isolated multi-storey shear building are expressed as:

$$\mathbf{M\ddot{u}} + \mathbf{C\dot{u}} + \mathbf{Ku} = \mathbf{MR\ddot{u}_{bt}} \tag{11}$$

where, **M**, **C** and **K** are mass matrix, damping matrix and stiffness matrix of size NxN of the superstructure, defined as in **Kan and Chopra(1977)**, N is three times number of the floors and **R** is the matrix of size Nx3 of earthquake influence coefficient. Here, $\mathbf{\ddot{u}}$, $\mathbf{\dot{u}}$ and $\mathbf{u}$ represent the floor acceleration, velocity and displacement vectors (Nx1) relative to the base, $\mathbf{\ddot{u}_{bt}}$ is the absolute base acceleration.

The equations of motion of the base for sliding-elastomer isolation system are given as:

$$\mathbf{M_b\ddot{u}_b} + \mathbf{C_b\dot{u}_b} + \mathbf{K_b u_b} = \mathbf{M_b}\left(\mathbf{\ddot{u}_g} + \mathbf{\ddot{u}_s}\right) - \mathbf{R^T M\ddot{u}} \tag{12a}$$

$$\mathbf{\ddot{u}_s} = -\mathbf{\ddot{u}_g} - \mathbf{\ddot{u}_b} - \left(\frac{1}{m_t}\right)\mathbf{f} - \left(\frac{1}{m_t}\right)\mathbf{R^T M\ddot{u}} \tag{12b}$$

where, $\mathbf{M_b}$ is the diagonal mass matrix (3x3) and each of the diagonal elements is having a value m_t (total mass), $\mathbf{C_b}$ is the damping matrix (3x3) of viscous isolation elements, $\mathbf{K_b}$ is the stiffness matrix (3x3) of laminated neoprene bearing. $\mathbf{\ddot{u}_b}$, $\mathbf{\dot{u}_b}$ and $\mathbf{u_b}$ are the acceleration, velocity and displacement vectors (3x1) of laminated neoprene bearing of the isolation system and , $\mathbf{\ddot{u}_s}$, $\mathbf{\dot{u}_s}$ and $\mathbf{u_s}$ are sliding acceleration, velocity and displacement vectors (3x1) of the isolation system. Here, **f** is the vector (3x1) containing forces mobilized in the frictional interface. The absolute base acceleration $\mathbf{\ddot{u}_{bt}}$ is given as:

$$\mathbf{\ddot{u}_{bt}} = \mathbf{\ddot{u}_g} + \mathbf{\ddot{u}_b} + \mathbf{\ddot{u}_s} \tag{13}$$

$$m_t = m_b + \sum_{i=1}^{Nf} m_i \tag{14}$$

The implicit-implicit partitioned Newmark's method in predictor-corrector form is used for direct integration of individual coupled equations of motion in staggered fashion [**Zienkiewicz** *et al.*(**1988**)]. The solution of differential equations governing behaviour of non-linear isolation elements, which are essentially very stiff, are obtained by using the close form solution as discussed in the preceding section.

SAMPLE RESPONSES AND DISCUSSION

In this section, the response of 3D model of a three storey r.c. building, isolated by sliding-elastomer bearing, subjected to Koyna Earthquake (1967) with longitudinal component in X direction and transverse component in Y direction are computed using solution technique discussed in the preceding sections. A three storeyed symmetrical building (2225 kN) has been considered for response calculation. The natural frequency of the building (fixed base) are as ω_1 = 20.62 rad/sec, ω_2 =57.08 rad/sec and ω_3 = 87.07 rad/sec. The stiffness of the elastomeric bearing of the isolation system = 2,225 kN/mm. The properties of Teflon-stainless steel frictional couple considered were: $\mu_{\max}$ = 0.1193, $\Delta\mu$ = 0.0927, a = 0.023622 sec/mm and Y = 0.02 mm for both direction.

Figure 3(a) and (b) show the relative base displacement history, the absolute acceleration history in the X direction of the structure isolated by the sliding-elastomer bearing subjected to only longitudinal component of Koyna earthquake. Figure 4(a) and (b) show the relative base displacement histories and absolute roof acceleration histories in the X and Y directions of the isolated structure supported on the sliding-elastomer bearing subjected to bi-directional Koyna motion. Comparison of the displacement and the acceleration histories in the X direction as shown in Figures 3 and 4, confirms that substantial biaxial interaction exists in the response of the building.

CONCLUSIONS

Base isolated structure experiences bi-directional motion due to asymmetry in structure and /or due to bi-directional excitation. In this paper, a simple yet accurate method of nonlinear dynamic analysis of buildings isolated by sliding-elastomer bearing subjected to bi-directional earthquake excitation has been presented. On the basis of the study carried out in this paper following conclusions can be drawn:

- Experimental force-displacement hysteresis loops of Teflon-stainless steel frictional couple, reported in the literature, subjected to bi-directional motion and simulated force-displacement hysteresis loops obtained in the present study are found to be good agreement.

- In force-displacement hysteresis loops, simulated using visco-plastic model, there is no discontinuity. Therefore, this model is suitable for computation of response of the isolated system subjected to bi-directional motion.

- Comparison of the displacement and acceleration histories show that the effects of the bi-axial interaction is considerable in the response of buildings isolated by sliding-elastomer bearing under bi-directional motion.

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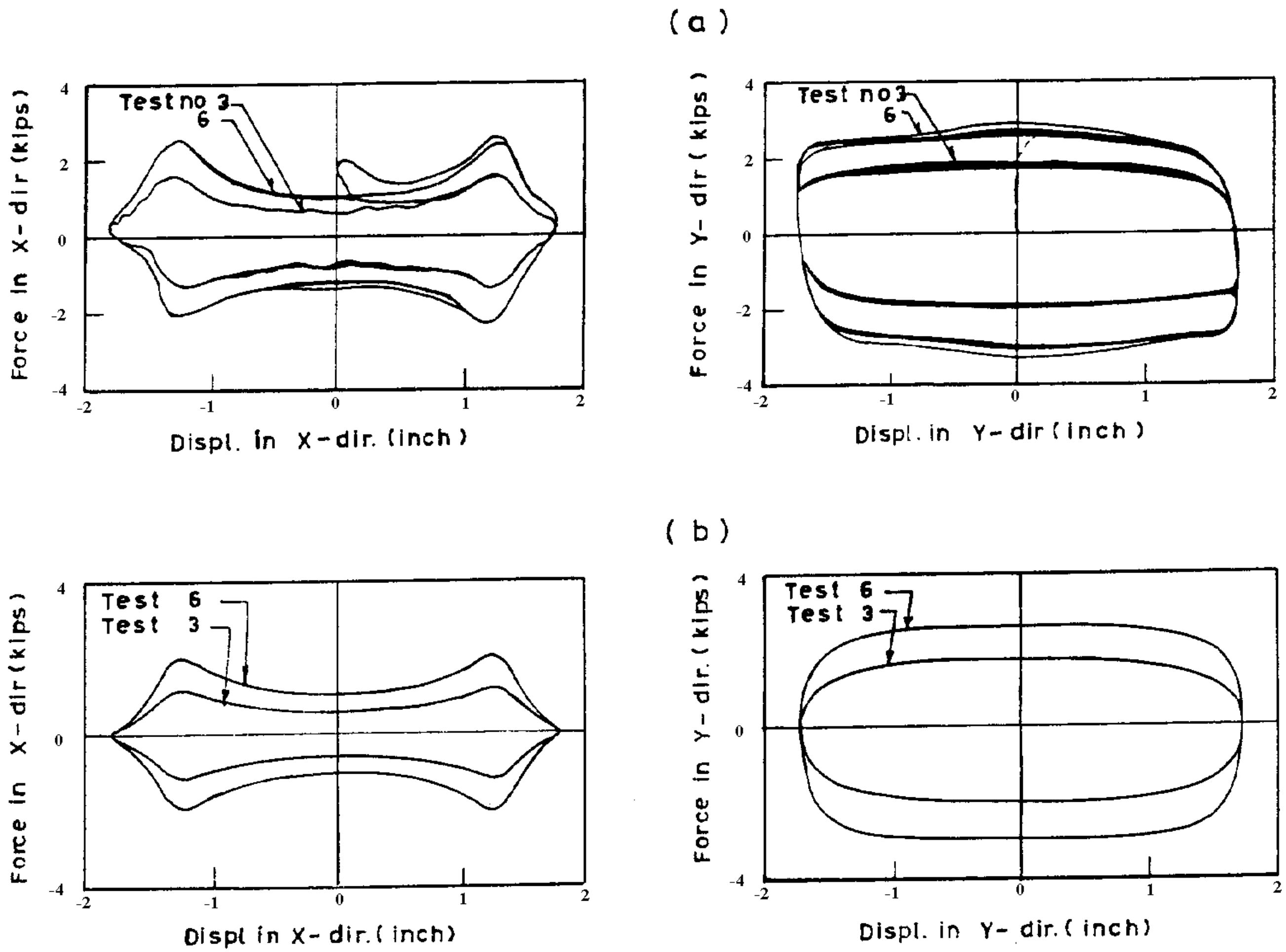


Fig.1 Biaxial Hysteretic Behaviour of Teflon-Stainless Steel Frictional Couple
(a) Experimental Loops in X and Y Directions [Mokha *et al.*(1993)]
(b) Simulated Loops in X and Y Directions

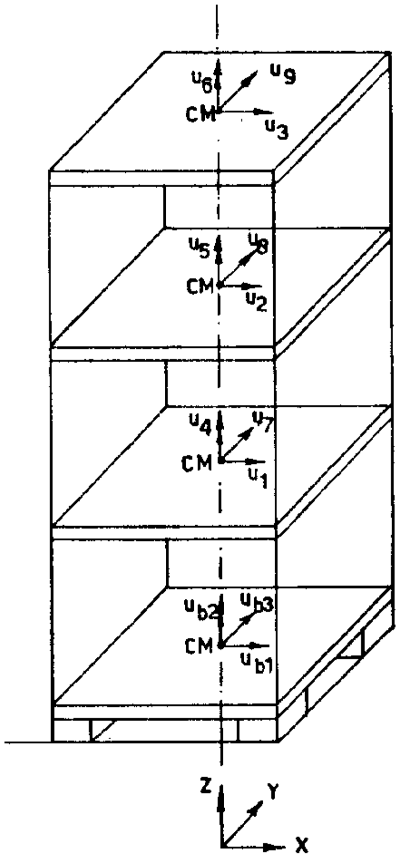
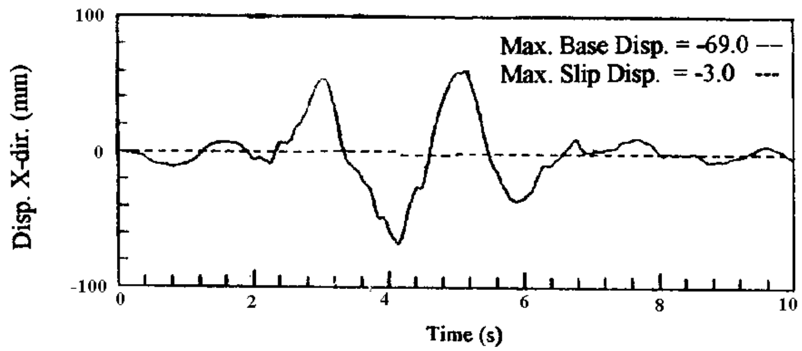
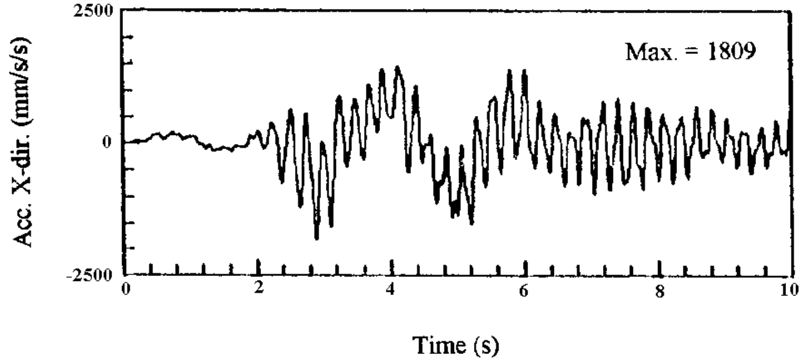


Fig.2 Structural Model (3D) of a Three Storeyed Building

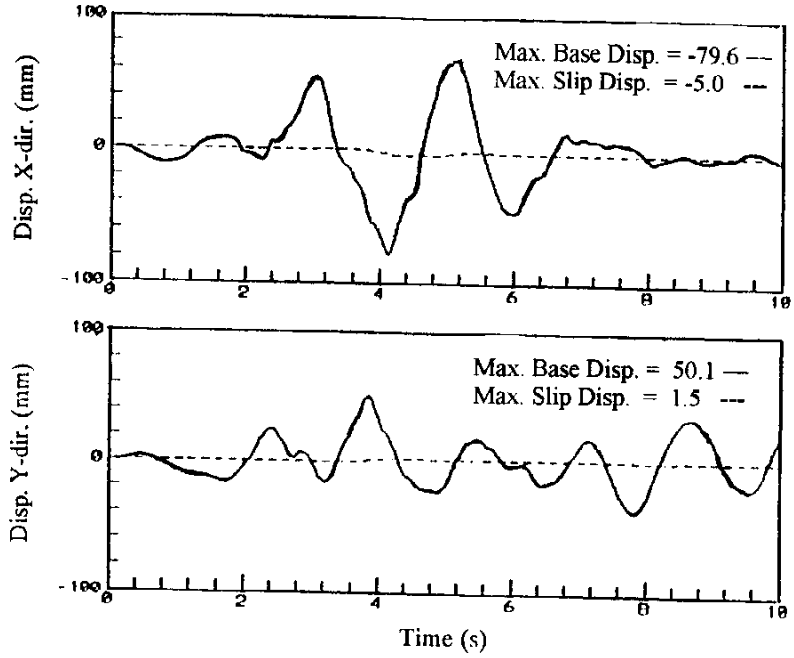


(a) Relative Base Displacement History in X-Dir.

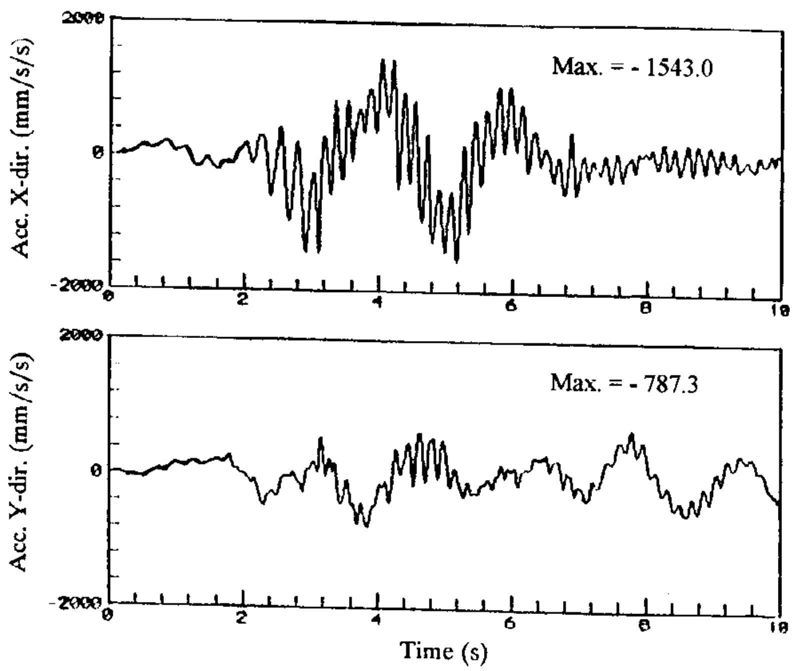


(b) Absolute Roof Acceleration History in Y-Dir.

Fig.3 Response of the Base Isolated Building Subjected to Unidirectional Koyna (L) Earthquake Motion



(a) Relative Base Displacement History in X and Y-dir



(b) Absolute Roof Acceleration History in X and Y-dir

Fig.4 Response of the Base Isolated Building Subjected to Bi-directional Koyna Earthquake Motion