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SEISMIC RESPONSE OF STRUCTURE ISOLATED BY R-FBI SYSTEM

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ABSTRACT

Seismic base isolation has become an accepted design technique for buildings to protect against earthquakes. The resilient-friction base isolator (R-FBI) provides a new base isolation system. The response of a planer model of one-storey shear type building isolated by R-FBI system to real earthquake motion under different parametric variations in investigated. The parameters include: time period of the superstructure (as fixed base), mass ratio, and the properties of R-FBI system (i.e. damping, stiffness and coefficient of friction). The responses are compared with those of the corresponding fixed base system in order to investigate the effectiveness of base isolation. It is shown that the R-FBI system is quite effective in reducing the seismic response of isolated structure against earthquake excitation.

INTRODUCTION

The traditional method of providing earthquake resistance to a structure is by increasing its strength as well as energy absorbing capacity. However, during an earthquake many structures have suffered structural and non-structural damages due to inelastic deformations. An alternative method is to isolate the structure by the use of base isolators between the base of the structure and its foundation. These base isolators have two important characteristics: horizontal flexibility and energy absorbing capacity. Horizontal flexibility lowers the fundamental frequency of the structure below the range of frequencies which dominate in general earthquake excitation. Energy absorbing capacity reduces both relative displacements and seismic energy being transmitted to the structure. The effectiveness of various types of base isolation in limiting the earthquake forces in buildings has been demonstrated both experimentally [6,10] and analytically [3,4,7,9]. An excellent review for the earlier works and recent investigations on base isolation is provided in References [1,5].

A variety of base isolation devices including laminated rubber bearing, frictional bearing and roller bearing have been developed. The laminated rubber bearings are one of the most commonly used bearings. Recently, friction-type base isolators have been developed and studied. The most attractive feature of this type of isolator is that the friction force is a natural and powerful energy-dissipation device. The simplest such device is pure-friction, referred to as the P-F system or

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sliding type structure [11.12]. The more advanced devices involve pure-friction elements in combination with laminated rubber bearings. Among the various friction devices, the resilient-friction base isolators (R-FBI) system is common [8].

Herein, the response of one-storey planner model of building isolated by R-FBI system to real ground motion is obtained and analyzed for a parametric study. The objectives of the study are: (i) to investigate the effectiveness of R-FBI system under a set of important parametric variations and (ii) to study the difference between the response behaviour of structure isolated by R-FBI system and linear elastomeric bearings.

STRUCTURAL MODEL

Figure 1 shows the structural system considered, which is an idealized one-storey building model mounted on R-FBI base isolator. The rigid deck mass is supported by massless inextensible columns. The columns are assumed to remain within the elastic range during the earthquake excitation. This is a reasonable assumption, since the purpose of base isolation is to reduce the earthquake effects in such a way that the structure remains within the elastic limits. The two degrees of freedom considered are: lateral displacement of deck (x) and lateral displacement of base isolator (x_b). Further, the isolator is assumed to carry the vertical load without undergoing any vertical deformation.

Description of R-FBI system

The resilient friction base isolator (R-FBI) system was recently proposed by Mostaghel and Khodaverdian [8] as shown in Fig. 2. This base isolator consists of concentric layers of teflon coated steel plates that are in friction contact with each other and contains a central core of rubber. In this base isolator, the interfacial friction force acts parallel with the elastic force in rubber. The rubber core distributes and sliding displacement and velocity along the height of the bearing. The rubber core does not carry any vertical loads and is not vulcanized to the sliding rings. The system provides isolation through the parallel action of friction, damping and restoring force. The R-FBI system is characterized by the parameters: stiffness, damping constant and coefficient of friction. The experimental study for the friction of teflon-steel interface is reported in Reference [2].

Equations of motion

The mathematical model of the superstructure with R-FBI base isolator is shown in Fig. 3. The system bahaves like a fixed base when there is no sliding in R-FBI system. The criteria for sliding and non-sliding conditions are described later. During the sliding state, the equations of the motion of the system subjected to earthquake excitation are written as [7,8,9]:

$$m\,(\ddot{x} + \ddot{x}_b) + c\,\dot{x} + k\,x = -\,m\,\ddot{x}_g \tag{1}$$

$$m_b \ddot{x}_b + c_b \dot{x}_b + k_b x_b + \mu g (m+m_b) \operatorname{sgn} (\dot{x}_b) - c \dot{x} - k x = - m_b \ddot{x}_g \tag{2}$$

in which m, k and c are the mass, stiffness and damping of the superstructure, respectively; x is the displacement of superstructure relative to base mass; m_b is the mass of base raft or slab; c_b is the damping of R-FBI system; k_b is the stiffness of R-FBI system; sgn denotes the signum function i.e. $\operatorname{sgn}(\dot{x}_b)=\dot{x}_b / |\dot{x}_b|$; x_b is the displacement of base mass relative to the ground; $\ddot{x}_g$ is the ground acceleration due to gravity. The stiffness and damping of the superstructure and isolator can be expressed as :

$$c = 2 \xi m w \tag{3}$$

$$k = m w^2 \tag{4}$$

$$c_b = 2 \xi_b (m+m_b) w_b \tag{5}$$

$$k_b = (m+m_b) w_b^2 \tag{6}$$

in which w and w_b are the natural frequency of the superstructure (considered as fixed base) and base isolation frequency, respectively. ξ and ξ_b are the damping constants of the superstructure and isolator, respectively. The time period of the superstructure (T) and isolator (T_b) are defined as below :

$$T = \frac{2\pi}{w} = 2\pi \sqrt{\frac{m}{k}} \tag{7}$$

$$T_b = \frac{2\pi}{w_b} = 2\pi \sqrt{\frac{m + m_b}{k_b}} \tag{8}$$

The stiffness and damping properties of the superstructure and isolator are determined by assigning appropriate values to the parameters T, T_b, ξ and ξ_b.

Conditions for sliding and non-sliding states

In a non-sliding state, the isolator force (friction+rubber) is greater than the total intertial force generated in the superstructure. Therefore, $\dot{x}_b = \ddot{x}_b = 0$ holds as long as

$$\mu g > \left| \ddot{x}_g + w_b^2 x_b + \frac{m}{m + m_b} \ddot{x} \right| \tag{9}$$

Failure of non-sliding condition given by (9) indicates that occurrence of slip and motion is generated and equation (2) is to be considered in the solution. During sliding, whenever the relative velocity becomes zero, the non-sliding condition given by equation (9) must be checked in order to determine whether the base raft remains in the sliding phase or sticks to the foundation.

Incremental solution procedure

The coupled differential equations of motion (Eqs. 1-2), are solved in incremental form by employing Newmark's β method assuming linear variation for acceleration over the short time interval, δt. For the time intervals during which transition from non-sliding (i.e. x_b changes the sign) to sliding state occured, the time step was reduced to minimize the unbalanced forces created by the numerical approximation to an acceptably small value. The time step, δt for the sliding and non-sliding states is taken as T/100. During the transition phases this time step is subdivided so that at the end of time step the system just reaches to the other phase. The solution of the equations of motion provides the time histories of x and x_b. The time history of the absolute acceleration of the deck is determined by the algebraic addition of $\ddot{x}$, $\ddot{x}_b$ and $\ddot{x}_g$.

NUMERICAL STUDY

The response of the base-isolated system is investigated with respect to the following parameters: time period of the superstructure (T); mass ratio (m_b/m); time period of the isolator (T_b); coefficient of friction of the isolator (μ) ; and damping of the isolator. The effect of these parameters are studied for N00E component of El centro, California earthquake of May, 1940 of duration 30 second. For base isolated structure, the response quantities of interest are the absolute acceleration of superstructure ($\ddot{x} + \ddot{x}_b + \ddot{x}_g$) and the relative displacement of the base mass (x_b). The former is directly proportional to the forces that are exerted on the structure. The latter is a measure of displacement between the base-isolated structure and the ground that is crucial to the design of the isolator. Figures 4 and 5 show the typical time histories of the absolute acceleration of the deck and the base displacement.

In order to study the effectiveness of base isolation, it is convenient to express the response in terms of a ratio rather than plotting their values. For this purpose, response ratio R is defined as :

$$R = \frac{\text{Peak absolute acceleration of the deck for isolated system}}{\text{Peak absolute acceleration of the deck for fixed base system}}$$

The response ratio R is an index of the performance of base isolation system and the value less than 1 indicates that the base isolation is effective.

Effect of superstructure time period (T)

In fig. 6, the variation of R is plotted against T for μ = 0, 0.05, 0.1 and 0.15. As μ increases, the ratio R increases showing that the presence of high friction coefficient reduces the effectiveness of base isolation. Also, as T increases, R increases indicating that the base isolation is less effective for a flexible superstructure as compared to stiff superstructure. For the case when μ = 0 (i.e. the force deformation behaviour the isolator system is linear), base isolation provides maximum effectiveness in reducing the absolute acceleration of the superstructure in the range T < 1 sec. Althrough μ cannot be zero for R-FBI system, the above result signifies that the linear elastomeric bearing may be more effective than R-FBI system in reducing the response of relatively stiff superstructure. Further, for higher value of μ (>0.1), it is observed that the base isolated system behaves almost like a fixed base system for relatively flexible superstructure (T > 1.2 sec).

In Fig. 7, the variation of base displacement is plotted against T. Figure clearly shows that the base displacement is significantly reduced because of the presence of friction in the isolator.

For further parametric studies, the two values of μ, i.e., 0 and 0.1 are considered. The difference between the parametric behaviours of the two cases essentially shows the effect of friction element on the response and indicates the difference between the isolation characteristics provided by linear elastomeric bearings and R-FBI systems.

Effect of mass ratio (m_b/m)

In Fig. 8, R is plotted against m_b/m for T = 0.5 and 1 sec and μ = 0 and 0.1. The ratio R remains insensitive to the variation of mass ratio for μ = 0. However, for R-FBI system (with μ = 0.1), it increases with the increase in m_b/m ratio. This is expected since for higher values of mass ratio (due to increase of limiting force = μ g time total mass) system remains to stick condition for most of the time. As a result, more acceleration is transmitted to the superstructure and therefore, the effectiveness of isolation is reduced.

Figure 9 shows the variation of base displacement against m_b/m. It is observed from the figure that base displacement is insensitive to the variation of mass ratio. Further, the difference between the base displacement for T = 0.5 and 1 sec is not significant. However, it is again seen that the presence of friction elements in the isolator system reduces the base displacement significantly (compare between μ = 0 and 0.1).

Effect of isolator time period (T_b)

Figure 10 shows the variation of R against T_b for T = 0.5 and 1 sec. when μ = 0, the ratio R decreases with increase in the isolator time period showing more effectiveness of base isolation. Note that when

T_b = 0.5 sec, the ratio R becomes greater than unity showing ineffectiveness of base isolation. This is expected since a very stiff isolator transmits more acceleration into the superstructure as compared to flexible isolator. The ratio R for μ = 0.1 remains almost insensitive to the variation of T_b.

In Fig. 11, the variation of the base displacement is plotted against T_b. The base displacement for μ = 0.1 is significantly less and remains almost constant for all values of T_b. However, for μ = 0, the base displacement generally increases with the increase in T_b. The differense between the base displacements for T = 0.5 and 1 sec is not significant.

Effect of damping constant of isolator, ξ_b

In order to study the effect of additional viscous damping on the response of base-isolated structure, the damping constant, ξ_b was varied from 2 to 20 %. Figure 12 shows the variation of the ratio R against ξ_b. R decreases mildly with the increase in ξ_b for T_b = 2 sec and μ = 0. However, for μ = 0.1, it remains insensitive to the variation of ξ_b. This is because of the fact that the energy dissipation due to friction is more dominant than the dissipation of energy due to additional damping (due to rubber).

Figure 13 shows the variation of base displacement against ξ_b. The base displacement decreases with the increase in ξ_b when μ = 0. However, for μ = 0.1, the base displacement remains insensitive to the variation of ξ_b.

CONCLUSIONS

The response of a one-storey building isolated by R-FBI system to real ground motion is analyzed for parametric study. The responses of the isolated structure are compared with those of the same structure with fixed base in order to investigate the effectiveness of base isolation under different conditions. From the trends of the results, the following conclusions may be drawn:

(1) Effectiveness of base isolation decreases with the increase in the superstructure time period.

(2) The effectiveness of base isolation decreases with the increase of coefficient of friction and mass ratio (m_b/m).

(3) The effectiveness of base isolation remains insensitive to the variation of the isolator time period.

(4) The parametric behaviours of the structure isolated by R-FBI system are distinctly different than those isolated by linear elastomeric bearings because of the presense of friction elements

in the former.

(5) The presence of friction elements in R-FBI system tends to reduce the base displacement.

(6) The additional viscous damping upto a range of 20% does not significantly influences the response characteristics of the structure isolated with R-FBI having a coefficient of friction=0.1.

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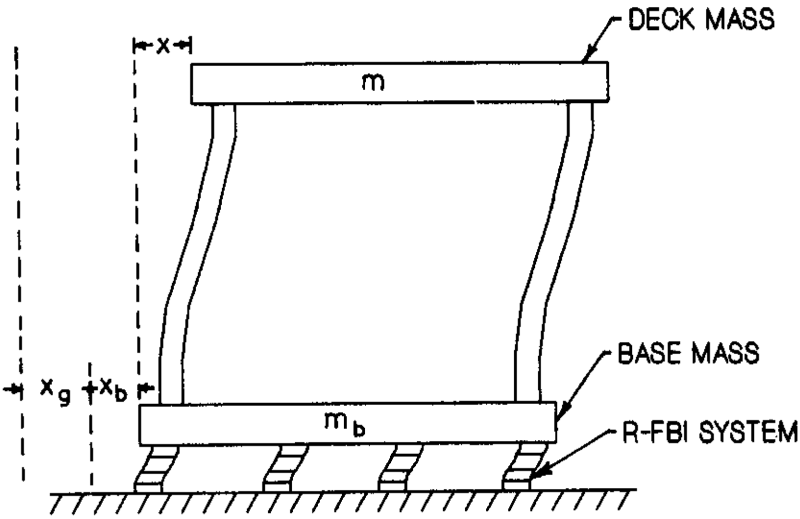

Fig. 1 Structural Model

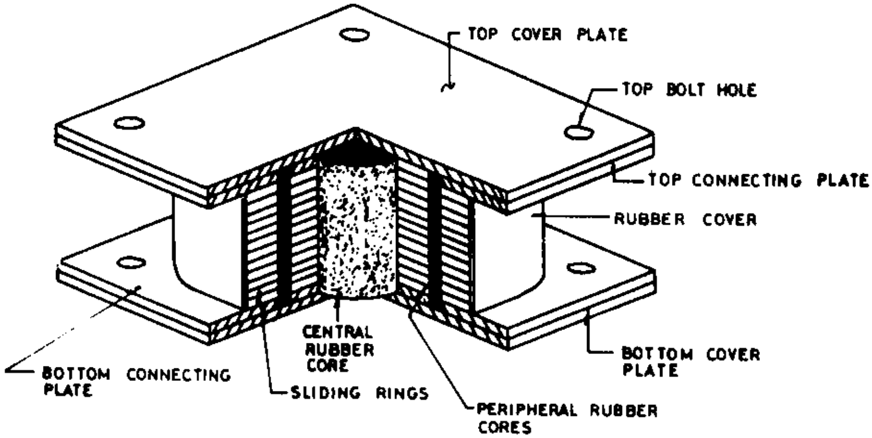

Fig. 2 R-FBI bearing

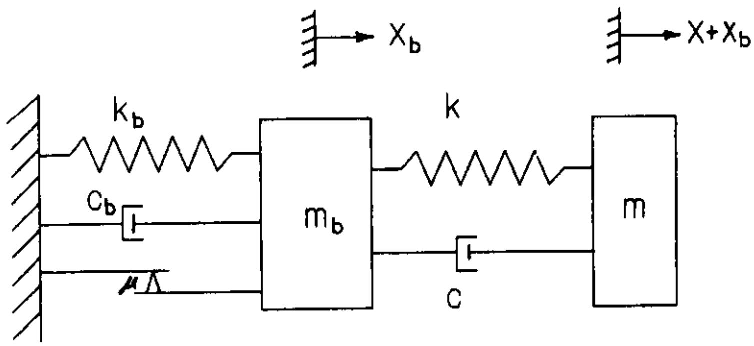

Fig. 3 Mathematical model of the building with R-FBI system.

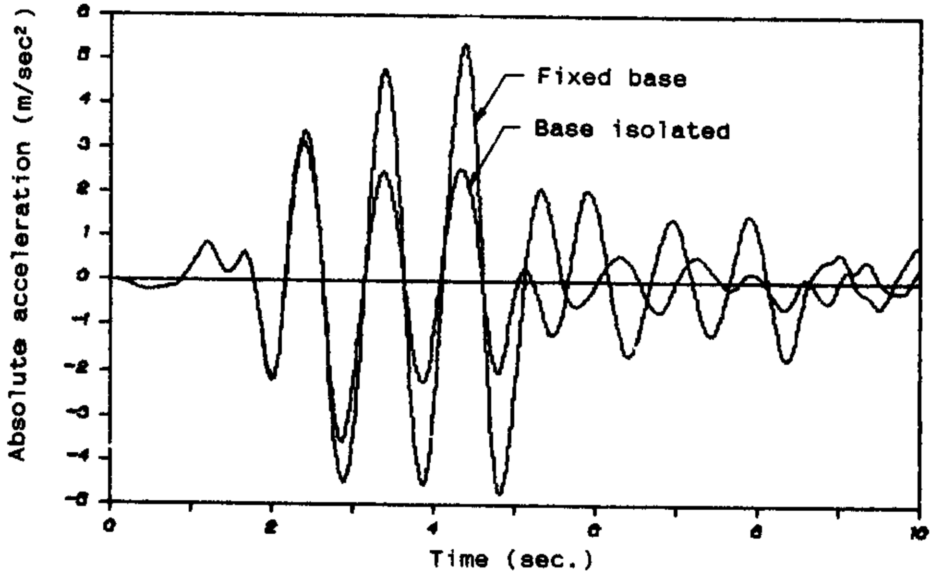

Fig. 4 Time variation of absolute acceleration of the deck: T = 1 sec., m_b/m = 1.5, T_b = 2 sec., μ = 0.1 and ξ_b = 0.1

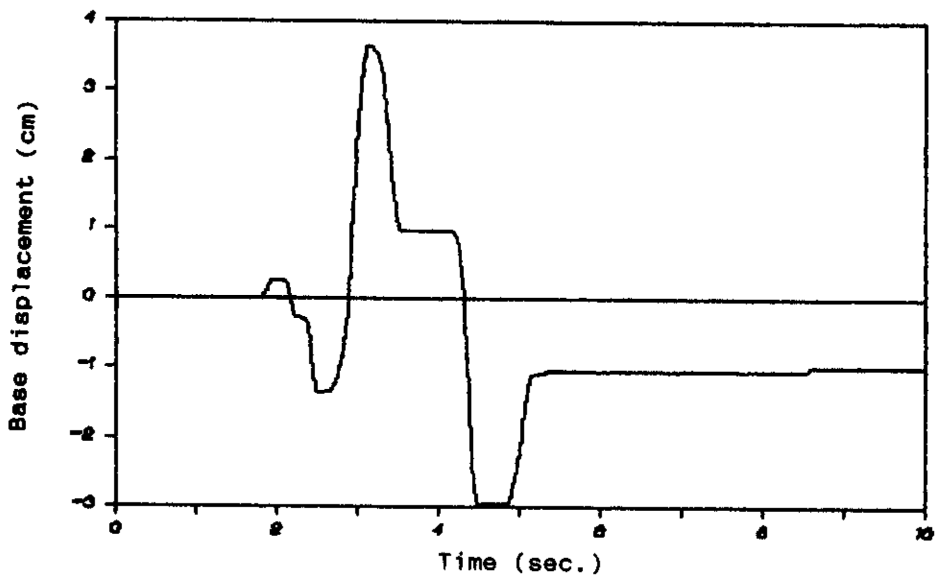

Fig. 5 Time variation of base displacement: T = 1 sec., m_b/m = 1.5, T_b = 2 sec, μ = 0.1 and ξ_b = 0.1

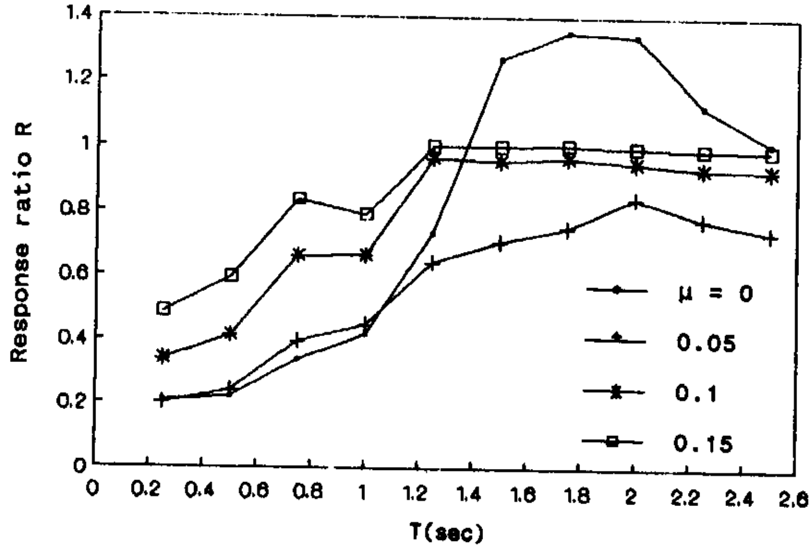

Fig. 6 Plot of response ratio R against time period T. for T_b = 2 sec, m_b/m = 1.5 and ξ_b = 0.1

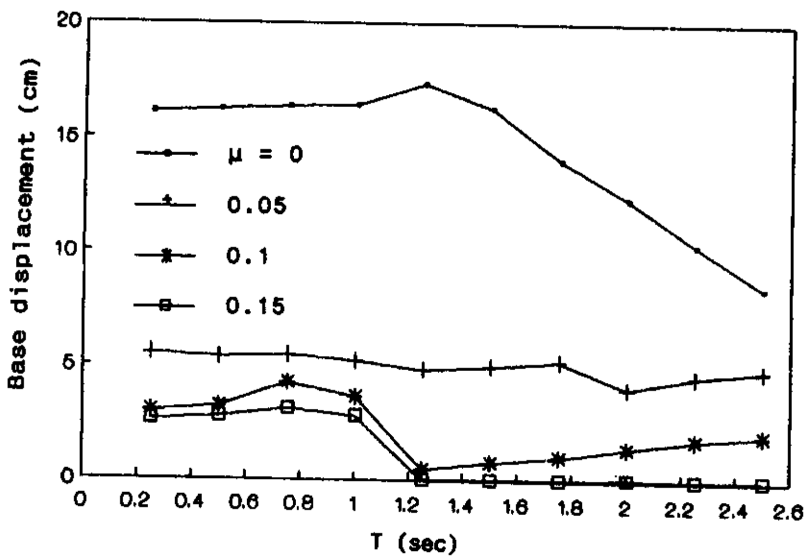

Fig. 7 Variation base displacement against time period T. for T_b = 2 sec, m_b/m = 1.5 and ξ_b = 0.1

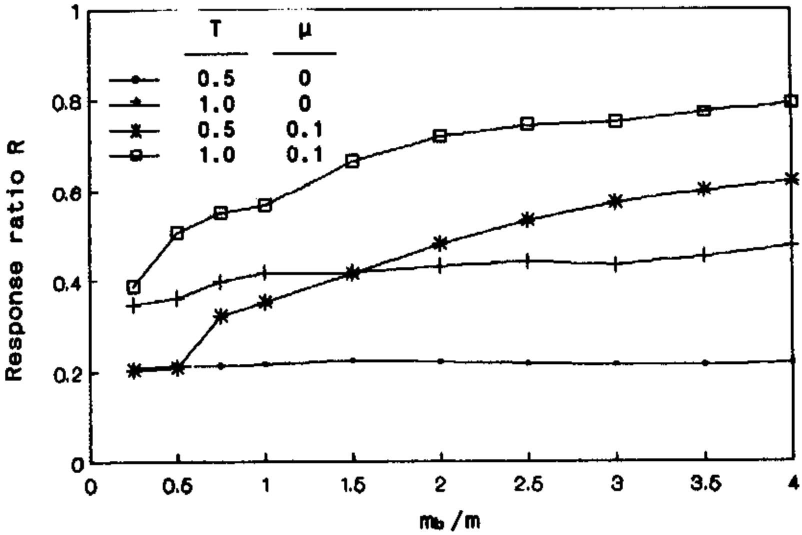

Fig. 8 Plot of response ratio R against mass ratio m_b/m. for T_b = 2 sec and ξ_b = 0.1

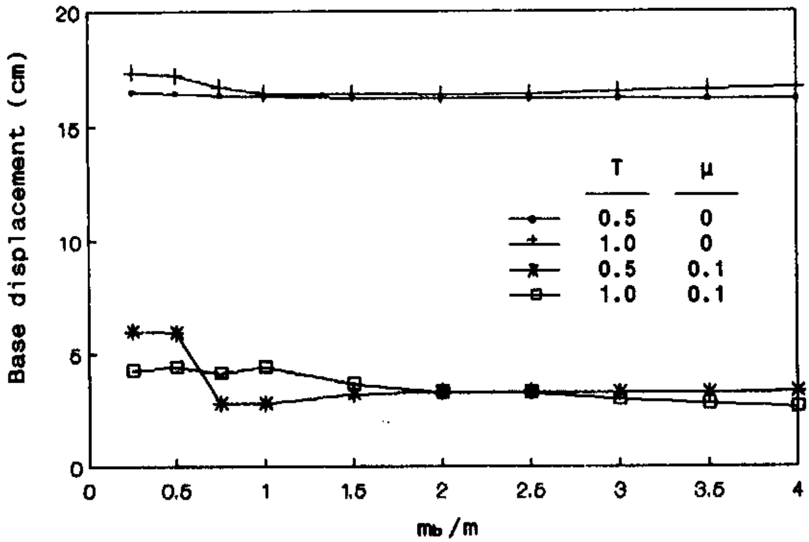

Fig. 9 Variation base displacement against mass ratio m_b/m. for T_b = 2 sec and ξ_b = 0.1

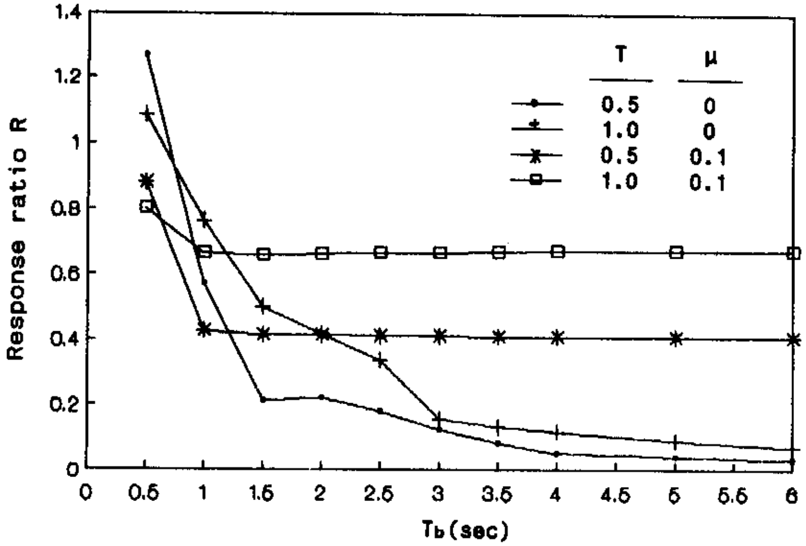

Fig. 10 Plot of response ratio R against time period of isolator. for m_b/m = 1.5 and ξ_b = 0.1

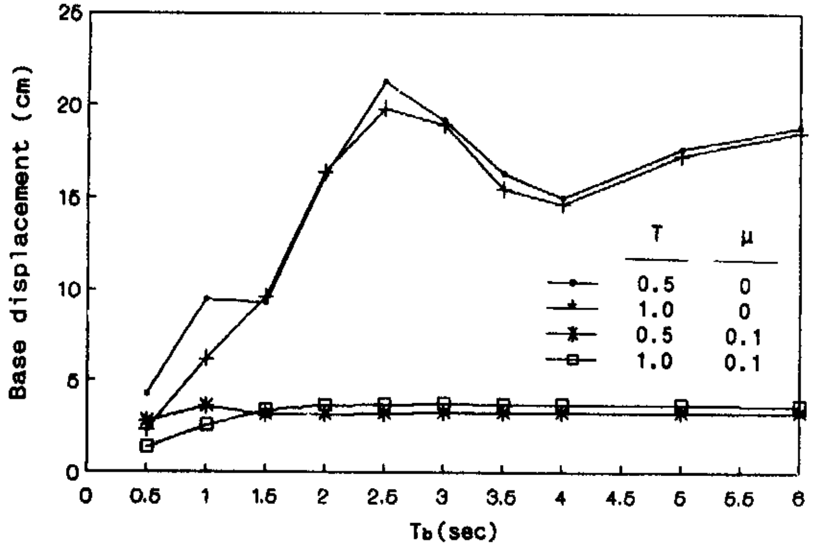

Fig. 11 Variation base displacement against time period of isolator for m_b/m = 1.5 and ξ_b = 0.1

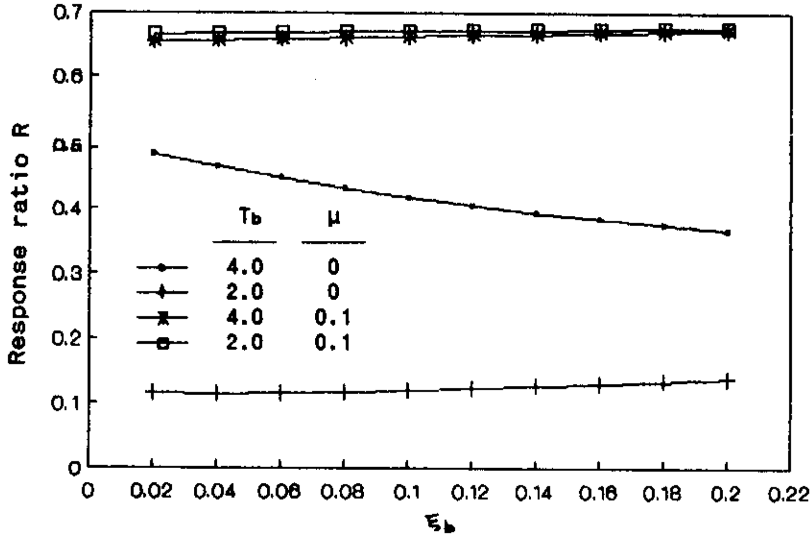

Fig. 12 Plot of response ratio R against damping of isolator. for T = 1 sec and m_b/m = 1.5

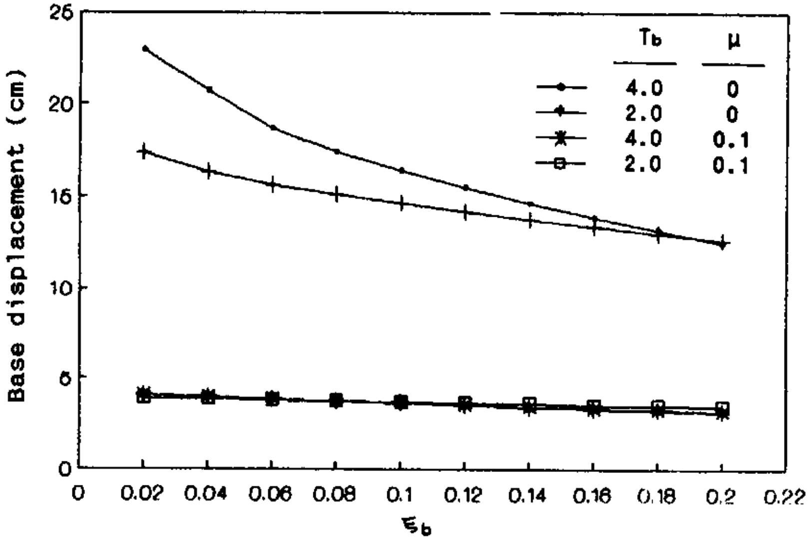

Fig. 13 Variation base displacement against damping of isolator. for T = 1 sec and m_b/m = 1.5