Behaviour of Base-Isolated Structures with High Initial Isolator Stiffness

Ajay Sharma, and R.S. Jangid

Abstract**—**Analytical seismic response of multi-story building supported on base isolation system is investigated under real earthquake motion. The superstructure is idealized as a shear type flexible building with lateral degree-of-freedom at each floor. The force-deformation behaviour of the isolation system is modelled by the bi-linear behaviour which can be effectively used to model all isolation systems in practice. The governing equations of motion of the isolated structural system are derived. The response of the system is obtained numerically by step-by-method under three real recorded earthquake motions and pulse motions associated in the near-fault earthquake motion. The variation of the top floor acceleration, inter-story drift, base shear and bearing displacement of the isolated building is studied under different initial stiffness of the bi-linear isolation system. It was observed that the high initial stiffness of the isolation system excites higher modes in base-isolated structure and generate floor accelerations and story drift. Such behaviour of the base-isolated building especially supported on sliding type of isolation systems can be detrimental to sensitive equipment installed in the building. On the other hand, the bearing displacement and base shear found to reduce marginally with the increase of the initial stiffness of the initial stiffness of the isolation system. Further, the above behaviour of the base-isolated building was observed for different parameters of the bearing (i.e. post-yield stiffness and characteristic strength) and earthquake motions (i.e. real time history as well as pulse type motion).

Keywords**—**base isolation, base shear, bi-linear, earthquake, floor accelerations, inter-story drift, multi-story building, pulse motion, stiffness ratio.

I. Introduction

BASE isolation is one of the most widely implemented and accepted seismic protection systems. Seismic base isolation is a technique that mitigates the effects of an earthquake by essentially *isolating* the structure and its contents from potentially dangerous ground motion, especially in the frequency range where the building is most affected. The goal is to simultaneously reduce interstory drifts and floor accelerations to limit or avoid damage, not only to the structure but also to its contents, in a cost-effective manner.

The three basic characteristics of an isolation system are: (1) horizontal flexibility to increase structural period and reduce spectral demands (except for very soft soil sites), (2) energy dissipation (also known as damping) to reduce isolator displacements, and (3) sufficient stiffness at small displacements to provide adequate rigidity for service-level environmental loadings. The horizontal flexibility common to all practical isolation systems serves to uncouple the building from the effects of high frequency earthquake shaking typical of rock or firm soil sites, thus serving to deflect the earthquake energy and significantly reduce the magnitude of the resulting inertia forces in the building. Energy dissipation in an isolation system, in the form of either hysteretic or viscous damping, serves to reduce the displacement response of an isolation system generally resulting in more compact isolators.

Structural response and isolator displacement are two key parameters to decide the characteristics of an isolation system. In near-field area isolator displacement plays pivotal role in governing the design of an isolation system, as large isolator displacements leads failure of isolation system. To check isolator displacement, stiffness of isolation system is increased but such increase adversely affects the structural response, especially floor accelerations. Present study aimed to explore the role of increase of isolation stiffness on structural response of a building. Bi-linear isolation system is selected for the study. The bilinear model, used to express the relation between the shear force and the lateral displacement, can be defined by three parameters: preyield stiffness, postyield stiffness, and characteristic strength. The characteristic strength, Q, is usually utilized to estimate the stability of hysteretic behaviour when the bearing experiences many loading cycles. These three parameters properly reflect the mechanical properties of bearings and provide satisfactory estimations of a bearing's nonlinear behaviour. . The specific objectives of the study are: (i) to investigate the effects of increase of preyield stiffness on structural response, (ii) to analyse the effect of isolation period on structural response and, (iii) to investigate the effects of characteristic strength ratio of isolator on structural response.[1-6]

II. Modelling of Base -Isolated Structure

Figure 1 shows the structural model of an idealized *N*-story shear type structure mounted on the base isolation system. The floors of each story of the superstructure are assumed to be rigid and the force-deformation behaviour of the superstructure is considered to be linear. The isolation system

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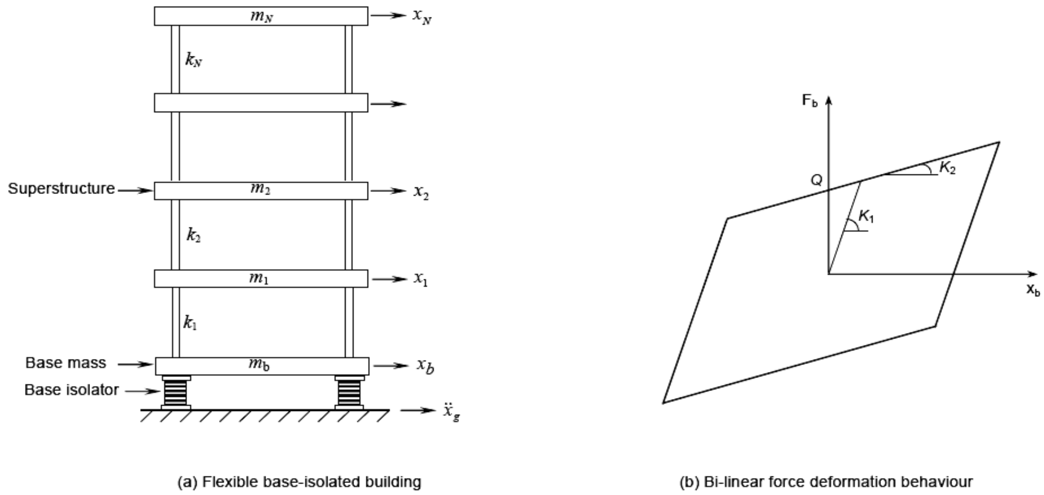

Fig.1. Model of the base-isolated building and isolation system.

installed between the base and foundation of the superstructure and it is modelled by the bi-linear behaviour as shown in Figure 1(b). The base-isolated system is excited by single horizontal component of earthquake ground motion. At each floor and base mass one lateral dynamic degree-of-freedom is considered. The governing equations of motion for fixed-base N-story superstructure model is expressed in matrix form as

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

Where $[M]$, $[K]$ and $[C]$ are the mass, stiffness and damping matrices of the fixed base structure, respectively of the order $N \times N$; $\{x\} = \{x_1, x_2, ..., x_N\}^T$ is the displacement vector of the superstructure; x_j (j = 1, 2, ..., N) is the lateral displacement of the j^{th} floor relative to the base mass; $\{1\} = \{1, 1, 1, ..., 1\}^T$ 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

$$m_b\ddot{x}_b + F_b - c_1\dot{x}_1 - k_1x_1 = -m_b\ddot{x}_g \quad (2)$$

Where m_b is the mass of base raft; F_b is the force mobilised in the isolation system as given in Figure 1(b); and k_1 and c_1 is the stiffness and damping of the first-story of the superstructure, respectively.

Since the force-deformation behaviour of the isolation system considered is non-linear, as a result, the governing equations of motion of the flexible base-isolated structure cannot be solved using the classical modal superposition technique. The seismic response of the system is obtained by solving the governing equations of motion in the incremental form using Newmark's step-by-step method with linear variation of acceleration over small time interval, Δt. A very small time interval for solving the equations of motion is considered especially due to high initial stiffness of the isolation system (i.e. Δt of the order of 0.0001 sec).

III Bi-Linear Modelling of Isolation System

The restoring force of the isolation system, F_b is modelled by the bi-linear model based on three parameters K_1, K_2 and Q as shown in Figure 1(b). The characteristic strength Q is generally estimated from the hysteresis loop of the isolation system which depends upon the yield strength of lead core of the lead-rubber bearings or friction coefficient of the sliding type of system. The characteristic strength of the bearing is normalized with the total weight of the isolated building and expressed by the parameter μ as

$$\mu = \frac{Q}{W} \quad (3)$$

Where $W = (m_b + \sum_{j=1}^{N} m_j)\, g$ is the total weight of the base-isolated building; m_j is the mass of the j^{th} floor; and g is the acceleration due to gravity.

The post-yield stiffness of the isolation system is designed in such a way to provide the specific value the isolation period, T_b expressed as

$$T_b = 2\pi\sqrt{\frac{(W/g)}{K_2}} \quad (4)$$

The elastic stiffness K_1 is selected as a multiple of K_2 and expressed by the factor κ defined by

$$\kappa = \frac{K_1}{K_2} \quad (5)$$

Thus, the modelling of base isolation system requires the specification of the three parameters i.e. μ, T_b, and κ.

IV NUMERICAL STUDY

The seismic response of the base-isolated building is obtained under various recorded earthquake ground motions and pulse type motion. For the present study, a five-story building is selected to investigate the influence of the high initial stiffness of the isolation system. The properties of the building considered are: $m_1 = m_2 = m_3 = m_4 = m_5 = m_b$ (i.e. same mass at all floors and base raft locations). The inter-story stiffness of different floors is taken as $k_1 = 15k$, $k_2 = 14k$, $k_3 = 14k$, $k_4 = 9k$ and $k_5 = 5k$. The value of k is selected to provide the fundamental time period of fixed base superstructure as 0.4 sec. The five natural frequencies of the superstructure with fixed base measured in rad/sec are 15.71, 38.48, 60.84, 83.12 and 105.37. The damping matrix of the superstructure is constructed by assuming the modal damping ratio of 0.02 in all modes of vibration.

In the present study, three recorded earthquake motions are used namely N00E component of the 1989 Loma Prieta earthquake (recorded at Los Gatos Presentation Centre), N90E component of 1994 Northridge earthquake (recorded at Sylmar Station) and N00E component of 1995 Kobe earthquake (recorded at JMA). The peak ground accelerations (PGA) of Loma Prieta, Northridge and Kobe earthquake motions are 0.57g, 0.6g and 0.83g, respectively. For the base-isolated building, the response quantities of interest are the top floor absolute acceleration (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 forces 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. In addition, the effects of isolation system parameters are also studied on the inter-story drift and base shear of the base-isolated building.

Figure 2 shows the time variation of the top floor absolute acceleration structure under Northridge, 1994 earthquake motion. The response is shown for different values of κ with fixed value of μ=0.075 and T_b = 2.5 sec. The figure indicates that the top floor acceleration increases with the increase of the initial stiffness of the isolation system. The increase in the acceleration is arising from the contribution of high frequencies. The corresponding FFT analysis of the top floor acceleration for different κ values clearly indicates that there is significant contribution from high frequencies in the top floor acceleration for higher values of κ (refer Figure 3).

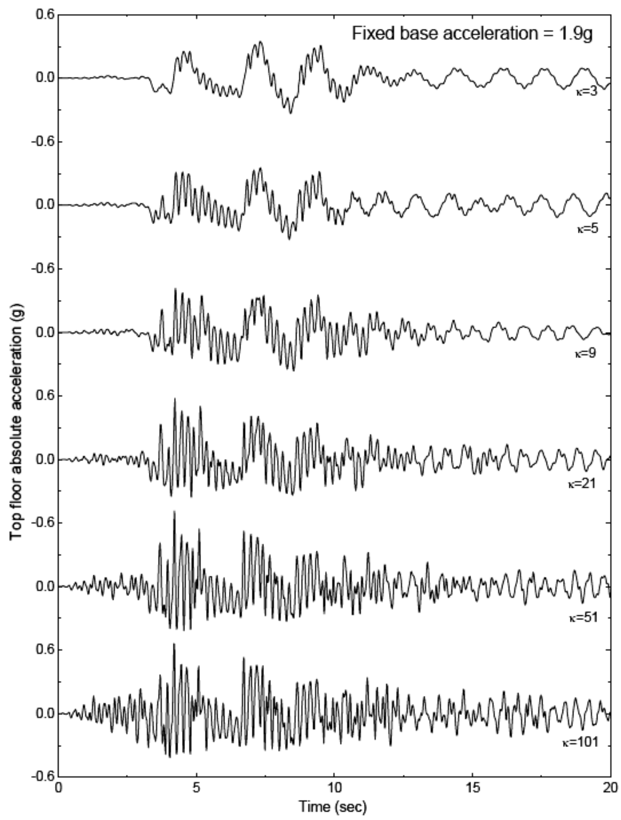

Fig. 2. Time variation of the top floor absolute acceleration for different stiffness ratio, κ under Northridge, 1994 earthquake motion (T_b = 2.5 sec and μ = 0.075).

For low values of κ (i.e. soft isolator) the top floor acceleration is mainly dominated by the isolation frequency (0.4 Hz) with some contribution from the first mode of the superstructure. However, for higher values of the stiffness ratio κ (i.e. isolator with high initial stiffness) the contribution from the isolation mode is decreased but increased from high frequencies spread over wider range. Thus, the high initial of the isolation system excites the higher modes of the base-isolated structure and generate floor accelerations. Such behaviour of the base-isolated building, especially supported on the sliding isolation systems, can be detrimental to the sensitive equipment installed in the building. The time variation of corresponding bearing displacement for the different values of κ is shown in Figure 4. It is observed that the peak bearing displacement decreases marginally with the increase of the initial stiffness of the isolation system. The FFT analysis of the bearing displacement (refer Figure 5) indicates that the bearing displacement is contributed mainly by the isolation frequency 0.4 Hz (i.e. 2.5 sec period). The corresponding force-deformation loop of the isolation system for different κ values is shown in Figure 6.

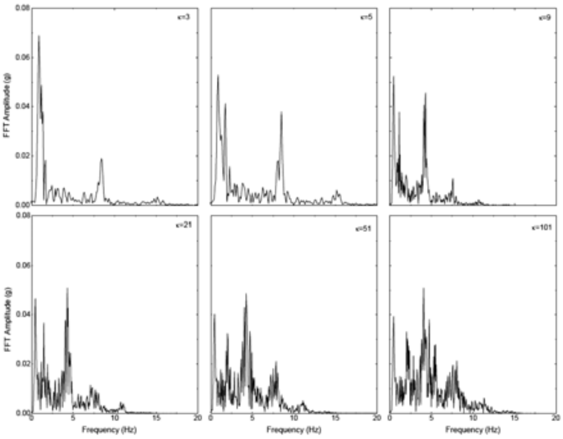

Fig. 3. Plot of the FFT amplitude of the top floor absolute acceleration for different stiffness ratio, κ under Northridge, 1994 earthquake motion (T_b = 2.5 sec and μ = 0.075).

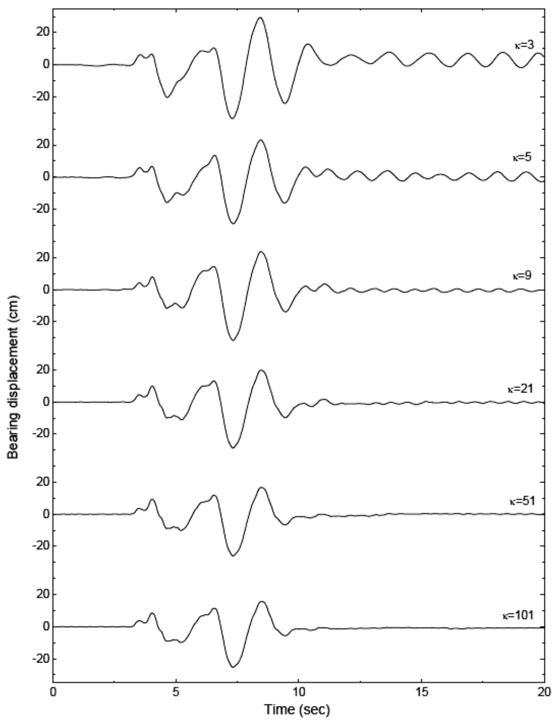

Fig. 4. Time variation of the bearing displacement for different stiffness ratio, κ under Northridge, 1994 earthquake motion (T_b = 2.5 sec and μ = 0.075).

It is observed from the Figure 6 that the maximum base shear in the isolated structure marginally decreases with the increase of the initial stiffness of the isolation system. Thus, the high initial stiffness of the isolation system increases the floor accelerations in the base-isolated structure even if the base shear is low.

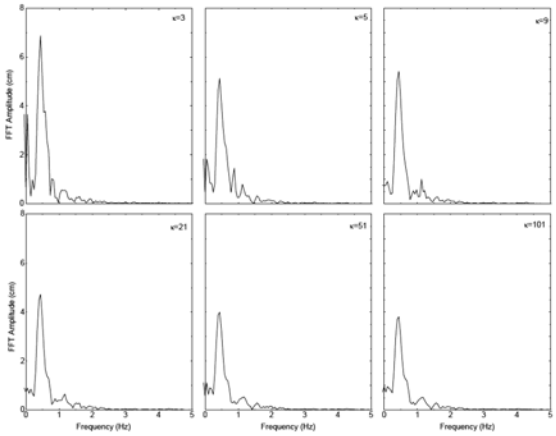

Fig. 5. Plot of the FFT amplitude of the bearing displacement for different stiffness ratio, κ under Northridge, 1994 earthquake motion (T_b = 2.5 sec and μ = 0.075).

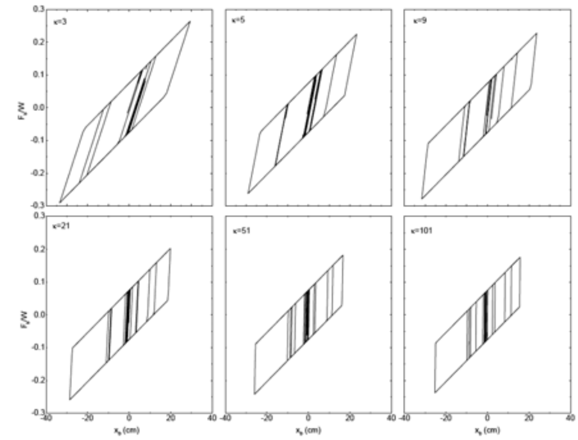

Fig. 6. Plot of force-deformation loops for different stiffness ratio, κ under Northridge, 1994 earthquake motion (T_b = 2.5 sec and μ = 0.075).

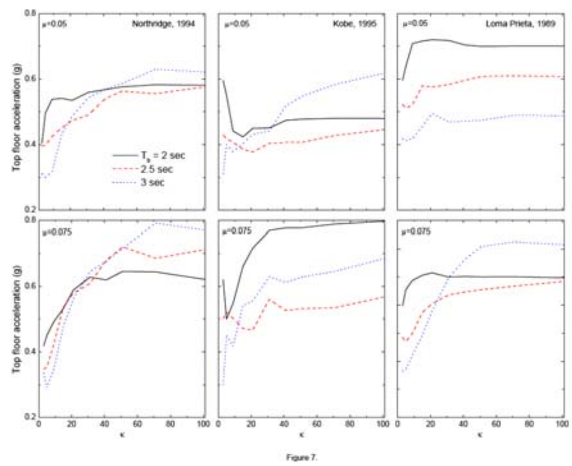

Fig. 7. Variation of the peak top floor absolute acceleration against the stiffness ratio, κ under different earthquake motions.

Figure 7 shows the variation of the peak top floor absolute acceleration against the stiffness ratio, κ under different earthquake motions. The top floor acceleration is plotted for three periods of isolation (i.e. T_b = 2, 2.5 and 3 sec) and two values of the characteristic strengths (i.e. $\mu = 0.05$ and 0.75). As expected, the peak top floor acceleration increases significantly with the increase of the initial stiffness of the isolation system. This effect is found to be more pronounced for flexible isolation systems as compared with the relatively stiff isolation systems (compare the response for $T_b = 2$ with that for $T_b = 3$ sec). Further, the increase in the top floor acceleration due to high initial stiffness of the isolator are found to be severe for the isolation system with high characteristic strength as compared to that with low characteristic strength. Similar effects of high initial stiffness of the isolator on the middle-story drift are depicted in Figure 8 where the inter-story drift increases with the increase of the initial isolator stiffness.

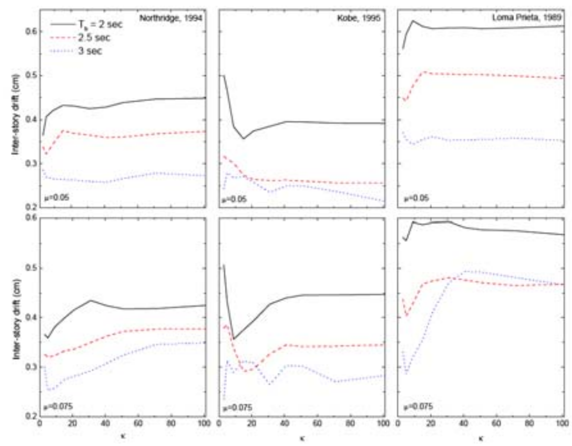

Fig. 8. Variation of the peak bearing displacement against the stiffness ratio, κ under different earthquake motions.

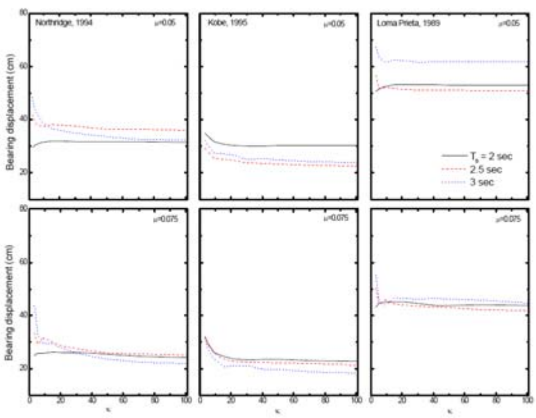

Fig. 9. Variation of the peak middle-story drift against the stiffness ratio, κ under different earthquake motions.

Figures 9 and 10 show the variation of the peak bearing displacement and base shear against the ratio, κ, respectively. The comparison of the response for different values of T_b and μ indicates that the bearing displacement as well as base shear decreases marginally with the increases of the initial stiffness isolation system. Thus, the high initial stiffness of the isolation system may not reduce the bearing displacement much but can increase the floor accelerations and story drift significantly.

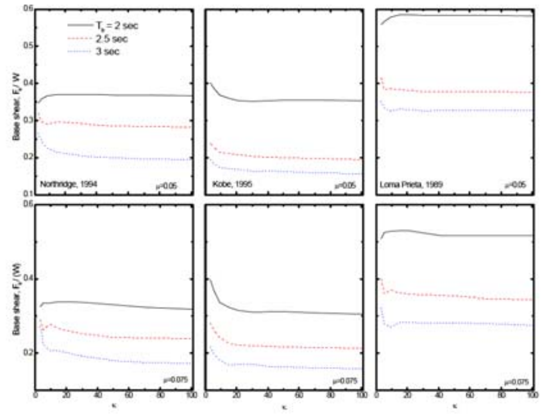

Fig. 10. Variation of the peak base shear against the stiffness ratio, κ under different earthquake motions.

V Response under Pulse Type Motion

In recent years, there had been considerable interest in studying the response base-isolated building under recorded near-fault earthquake motion [6-7]. These ground motions contain one or more displacement pulses with peak velocities of the order of 0.5 m/sec and durations in the range of 1 to 3 sec. Such pulses have a large impact on the isolation system with a period in this range and lead to a large isolator displacement. It will be interesting to study the effects of high initial stiffness of the isolator on the peak response of base-isolated building under pulse type earthquake motion.

Figure 11 shows the variation of the peak top floor absolute acceleration, middle-story drift and the bearing displacement against the stiffness ratio, κ under the 3.2 sec duration pulse motion. This pulse having the peak velocity of 0.7 m/sec is associated in the normal component of 1979 Imperial Valley earthquake recorded at Array # 5[1]. The responses under pulse motion are shown for three values of isolation period (i.e. T_b = 2, 2.5 and 3 sec) and μ=0.05. As observed earlier, both the top floor acceleration and inter-story drift also increases with the increase of the initial stiffness of the isolation system under pulse type motion. On the other hand, the peak bearing displacement decreases with the increase of the initial stiffness of the isolator. Similar effects of the high initial stiffness of the isolation system on the peak response of base-isolated building are depicted in Figure 12 under the pulse motion associated in the normal component of 1994 Northridge earthquake recorded at Rinaldi station.

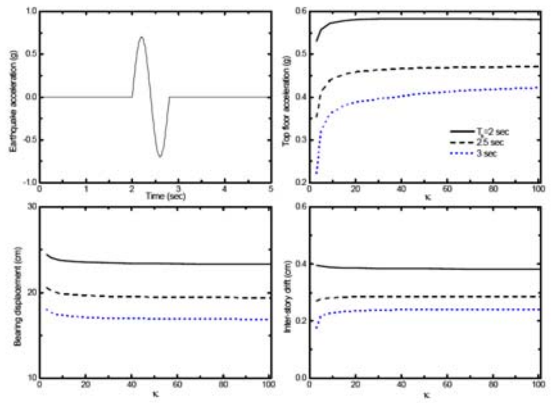

Fig. 11. Variation of the top floor acceleration, middle-story drift and the bearing displacement against the stiffness ratio, κ under the pulse associated in Imperial Valley, 1979 earthquake recorded at Array # 5 (μ = 0.05).

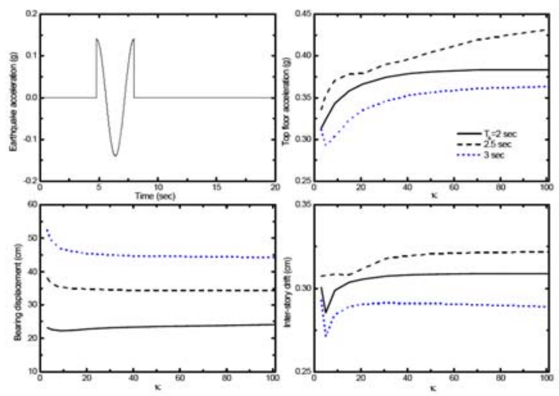

Fig. 12. Variation of the top floor acceleration, middle-story drift and the bearing displacement against the stiffness ratio, κ under the pulse associated in Northridge, 1994 earthquake recorded at Rinaldi station (μ = 0.05).

VI Conclusions

Analytical seismic response of multi-story building supported on base isolation system is investigated under real earthquake and pulse type motion. The force-deformation behaviour of the isolation system is modelled by the bi-linear behaviour. The response of the isolated building is obtained numerically by step-by-method and compared with the different values of the initial stiffness of the isolation system. The variation of top floor acceleration, inter-story drift, base shear and bearing displacement of the isolated building is studied under different system parameters to investigate the effects of high initial stiffness of the isolator. From the trends of the results of the present study, the following conclusions may be drawn:

1. The floor accelerations and inter-story drifts are found to be increased significantly with the increase of the initial stiffness of the isolation system. Such behaviour of the base-isolated building especially supported on the sliding isolation systems can be detrimental to the sensitive equipment installed in the building.
2. The high initial stiffness of the isolation system excites the higher modes of the base-isolated structure and generates floor accelerations. The increase in the floor accelerations is arising from the high frequencies spread over a wider range in the vicinity of higher modes of superstructure.
3. The bearing displacement and base shear found to be decrease marginally with the increase of initial of the isolation system. Thus, due to the high initial isolator stiffness the floor accelerations are increased even if the base shear is low.
4. The increase in the floor accelerations due to the high initial isolator stiffness are found to be more pronounced for the isolation system with low-post yield stiffness and high characteristic strength.
5. The increase in the floor accelerations due to high initial isolator stiffness are also observed under the pulse type motions associated in the near-fault earthquake records.

References

[1] Kelly J M. Aseismic base isolation: review and bibliography. *Soil Dynamics and Earthquake Engineering* 1986; 13:202–216.

[2] Stanton J, Roeder C. Advantages and limitations of base isolation. *Earthquake Spectra* Vol. 7; No. 2; 1991; 301-324.

[3] Jangid RS, Datta TK. Seismic behavior of base isolated building: a state-of-the-art-review. *Structures and Buildings* 1995; 110(2):186–203.

[4] Kelly J M. Earthquake-resistant design with rubber, 2nd ed. London: *Springer -Verlag;* 1997.

[5] Cheng F Y, Jiang H, and Lou K. *SMART STRUCTURES*: *Innovative Systems for Seismic Response control, Taylor and Francis,* New York, 2008.

[6] Jangid R S and Kelly J M Base isolation for near-fault motions. *Earthquake Engineering and Structural Dynamics*, USA, Vol. 30, pp. 691-707, 2001.

[7] Makris N and Chang S P. Effect of damping mechanisms on the response of seismically isolated structures. *Report No. PEER-98/06*, UC Berkeley, Calif. (1998).