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Response of space frame structure resting on non-linear rubber base isolation system

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ABSTRACT: The response of a multi-storey space frame structure resting on non-linear rubber base isolation system (lead rubber bearing), subjected to bi-directional harmonic and seismic ground motions are studied. A four-storey space frame structure having six degrees of freedom (three translations along x, y, z-axes and three rotations about these axes) at each node is considered for the study. The response quantities obtained from the analysis are the acceleration, base shear, bending moment and displacements. In this study, the response of the base isolated structure is compared with the response of the corresponding fixed base structure. It is found that the base isolation system can be used effectively to suppress the dynamic response of a multi-storey space frame structure. In addition, the effects of superstructure time period, isolation period, excitation frequency, post-to-pre yield stiffness ratio and yield force on the effectiveness of the base isolation system are also investigated. It is shown that these parameters have considerable influence on the effectiveness of the base isolation system in reducing the response of the structure.

1 INTRODUCTION

The base isolation is an aseismic design strategy in which an isolation system is used to decouple the superstructure from the ground so that the damaging horizontal components of earthquake ground motion cannot be transmitted into the structure. The various types of base isolation devices adopted are laminated rubber bearing (with and without lead core), frictional bearing and roller bearing. The laminated rubber bearing is the most practical, convenient and one of the most widely used bearings (Kelly (1982, 1986), Kelly & Hodder (1982), Tsai & Kelly (1989), Young & Lee (1993), Pan & Cui (1994), Chen & Ahmadi (1994) and Varma et al (2002)). The main advantages of laminated rubber bearing are lower cost than others, simplification in layout and are relatively easy to manufacture (Pan & Cui (1994), and Naeim & Kelly (1999)). The laminated rubber bearing has already been incorporated in a large number of existing buildings and new constructions to provide the required level of seismic protections. The laminated rubber bearing consists of alternating layers of steel plates and hard rubber with and without lead core. The laminated rubber bearing with lead core is called lead rubber bearing. The lead plug acts as a hysteretic damper. It can provide a high stiffness to the bearing before yielding of the lead and thus act as a wind restraint. The lead rubber bearing generally exhibits non-linear force deformation behaviour (Kelly & Tsai (1985), skinner et al (1993), and Naeim & Kelly (1999)).

The review shows that in most of the studies relating to seismic analysis, the structure has been idealized as a shear building having only one horizontal degree of freedom at each floor. But, in shear type of idealization, the effect of stiffness of the beam on the response of the structure is neglected. Krishnamoorthy (2008) observed that, the stiffness of beam will have the effect on the response of the structure and the analysis which considers the effect of stiffness of beam may be more realistic as compared to the analysis which neglects the stiffness of beam. The formulation of mathematical model of the structure is the most critical step in any seismic analysis, because how well the computed response agrees with the actual response of a structure during an earthquake depends primarily on the quality of the structural idealization. The quality of the structural idealization can be improved by more realistic idealization of buildings that considers beam flexure and all translations along x, y, z-axes and all rotations about these axes. Krishnamoorthy & Kiran Kumar Shetty (2004, 2006) have studied the dynamic response of a multi-storey space frame structure resting on linear rubber base isolation system. In their study, they have idealized the structure as an assemblage of beams and columns, interconnected at nodal points or nodes. The beams and columns were modelled using two noded frame elements with six degrees of freedom at each node i.e., three translations along x, y, z-axes and three rotations about these axes.

In the present study, the multi-storey space frame structure resting on non-linear rubber bearing (lead rubber bearing) is analysed by considering all the six degrees of freedom (three translations along x, y, z-axes and three rotations about these axes) at each node. The total degrees of freedom of the fixed base structure in this idealization are 6 × n, where n is the number of nodes. The total size of the stiffness matrix, mass matrix and the damping matrix of the fixed base structure is 6n × 6n. The objectives of the study are (i) to study the effectiveness of non-linear base isolation system in suppressing the structural response of a four-storey space frame structure having six degrees of freedom (three translations along x, y, z-axes and three rotations about these axes) at each node. (ii) to study the effects of superstructure time period, isolation period, excitation frequency, post-to-pre yield stiffness ratio and yield force on the effectiveness of base isolation system.

2 ANALYTICAL MODELING

The structure is divided into number of elements consisting of beams and columns. The beams and columns are modelled using two noded frame elements with six degrees of freedom at each node i.e., three translations along x, y, z-axes and three rotations about these axes. For each element, the stiffness matrix, k_s, consistent mass matrix, m_s, and transformation matrix, t_s, are obtained. The mass matrix and the stiffness matrix of each element from local direction are transformed to global direction as proposed by Paz (2001). The mass matrix and the stiffness matrix of each element are assembled by direct stiffness method to get the overall mass matrix, M, and overall stiffness matrix, K, for the entire structure. Knowing the overall mass matrix, M, and overall stiffness matrix, K, the frequencies for the superstructure (fixed base structure) is obtained using simultaneous iteration method. The damping matrix for superstructure is obtained using Rayleigh's equation, C = α M + β K, where α and β are the constants. These constants can be determined easily if the damping ratio for each mode is known. The overall dynamic equation of equilibrium for the entire structure can be expressed in matrix notations as

$$M\ddot{u} + C\dot{u} + Ku = f(t) \qquad (1)$$

where M, C and K are the overall mass, damping, and stiffness matrices of size 6n × 6n, where n is the number of nodes. $\ddot{u}$, $\dot{u}$, u are the relative acceleration, velocity and displacement vectors with respect to ground and f(t) is the nodal load vector. $u = u_1, v_1, w_1, \theta_{x1}, \theta_{y1}, \theta_{z1}, u_2, v_2, w_2, \theta_{x2}, \theta_{y2}, \theta_{z2}, \ldots u_n, v_n, w_n, \theta_{xn}, \theta_{yn}, \theta_{zn}$.

The nodal load vector due to earthquake is obtained using the equation

$$f(t) = -M I \ddot{u}_g(t) \qquad (2)$$

where M is the overall mass matrix, I is the influence vector, $\ddot{u}_g(t)$ is the ground acceleration. The resulting equation of dynamic equilibrium is solved using Newmark's method to obtain the displacements and acceleration at the nodes as explained in Chopra (1995). Owing to its unconditional stability, the constant average acceleration scheme (with β = 1/4 and γ = 1/2) is adopted.

2.1 *Modelling of isolation bearing*

The lead rubber bearing generally exhibits non-linear force deformation behaviour. In the present study, the force deformation behaviour of the lead rubber bearing is modelled as non-linear, with two transnational degrees of freedom (x and z direction) at each node. The non-linear force deformation behaviour of the rubber bearing is modelled through the bi-linear hysteresis loop (Figure 1). The bearing passes through two phases 1) elastic phase and 2) plastic phase. Initially, as the load is applied, the bearing behaves elastically along the curve E_0. The displacement u_t, at which plastic behaviour in tension may be initiated and the displacement u_c, at which plastic behaviour in compression may be initiated are calculated, respectively, from

$$u_t = Rt / k_i \qquad (3)$$

$$u_c = Rc / k_i \qquad (4)$$

where Rt and Rc are the respective values of the forces, which produce yielding in tension and compression and k_i, the elastic stiffness of the bearing. The bearing will remain on the curve E_0 as long as the displacement, u satisfies

$$u_c < u < u_t \qquad (5)$$

If the displacement u increases to u_t, the bearing begins to behave plastically in tension along the curve T on Figure 1; it remain on the curve T as long as the velocity $\dot{u} > 0$. When $\dot{u} < 0$, the bearing reverse to elastic behaviour on a curve such as E_1 with new yielding points given by;

$$u_t = u_{max} \qquad (6)$$

$$u_c = u_{max} - (Rt - Rc)/ k_i \quad (7)$$

where u_{max} is the maximum displacement along the curve T, which occurs when $\dot{u} = 0$; Conversely, if u decreases to u_c, the bearing begins a plastic behaviour in compression along curve C and it remains on this curve as long as $\dot{u} < 0$. The bearing returns to an elastic behaviour when the velocity again changes direction and $\dot{u} > 0$. In this case, the new yielding limits are given by

$$u_c = u_{min} \quad (8)$$

$$u_t = u_{min} + (Rt - Rc)/ k_i \quad (9)$$

where u_{min} is the minimum displacement along the curve C, which occurs when $\dot{u} = 0$. The same condition given by Equation 5 is valid for the bearing to remain operating along any elastic segment such as E_0, E_1, E_2,… as shown in Figure 1. The damping for each bearing (in x and z direction) is calculated using the equation

$$C_b = 2\xi_b \sqrt{k_b M_t} \quad (10)$$

where ξ_b is the damping ratio of the bearing, k_b is the stiffness of the bearing ($k_b = k_i$, in the elastic region and $k_b = k_p = \eta\, k_i$, in the plastic region; η = post-to-pre yield stiffness ratio) and M_t is the mass on each bearing. The post-yield stiffness of the isolation system, k_p, is generally designed in such a way to provide the specific value of the isolation period, T_b, expressed as

$$T_b = 2\pi / \omega_b, \quad (11)$$

where $\omega_b = \sqrt{k_p / M_t}$,
is the base isolation frequency. The stiffness and the damping of the bearings are added to the overall stiffness matrix and overall damping matrix of superstructure at corresponding global degrees of freedom.

2.2 *Determination of member forces*

The displacement obtained at each node is assigned for each member. The forces in each member are then obtained by multiplying element stiffness matrix with the nodal displacement vector.

3 RESULTS AND DISCUSSIONS

3.1 *Studies on the performance of base isolated structure subjected to harmonic ground motion*

The response of a multi-storey space frame structure resting on non-linear base isolation system, subjected to bi-directional (x and z directions) harmonic ground excitation equal to 0.2 g sin (ωt) (where ω is the harmonic excitation frequency; and t is the time variable) is studied. A four-storey space frame structure mounted on non-linear rubber bearing considered for the analysis is shown in Figure 2. The various material and geometric properties considered for the study are also shown in the same figure. Damping ratio of superstructure is taken as 5% of critical for all modes, damping ratio of bearing is taken as10% of critical. The horizontal displacements, top floor absolute acceleration, base shear and the bending moment in the members due to this loading are computed.

3.2 *Effect of excitation frequency and isolation period on the response of base isolated structure*

The variation of maximum response with excitation frequency for a structure with fixed base time period (T_s) equal to 0.75 sec is shown in Figure 3, for various values of isolation time period (T_b). The yield force ($R_t = R_c$) and the post-to-pre yield stiffness ratio (η) is taken as 0.08 W and 0.2 respectively; W = total weight of the building. The response of the base isolated and fixed base structure is sharply peaked and the peak is centered around the fundamental natural frequencies of the corresponding base structure. This peak is due to resonating effect. The peak value of the acceleration, base shear and bending moment decreases due to isolation. However, the peak value of the top floor and base displacements increases due to isolation (this happens because of the low stiffness of the isolation bearing). It can also be seen from Figure 3 that the peak value of the acceleration, base shear and bending moment decreases with increase in the isolation period but the peak value of the top and base displacements increases with increase in the isolation period. Thus, an increase in the isolation period decreases the peak value of acceleration, base shear and bending moment but increases the peak value of displacements.

At frequency of excitation equal to fundamental natural frequency of base isolated structure, the response of base isolated structure is greater than the response of the fixed base structure i.e the base isolation is not effective when excitation frequency is equal to the fundamental natural frequency of base isolated structure. However the typical earthquake accelerations have dominant periods of about 0.1 to

1sec (skinner et al (1993)) i.e. excitation frequency of the typical earthquake accelerations is more than 6.28 rad/sec. At frequency of excitation equal to fundamental natural frequency of fixed base structure, the response of fixed base structure become maximum, while for the same excitation frequency the response of base isolated structure is very small compared to the response of fixed base structure. Beyond a certain excitation frequency, $\omega = 9$ rad/sec, the response curves of base isolated structure with different isolation period is almost same. In the excitation frequency range, $\omega > 11$ rad/sec, the top floor acceleration, base shear and bending moment curves of base isolated structure is slightly less than that of fixed base structure, where as the top floor displacement curves of base isolated structure and the fixed base structure is almost same, this indicates that isolation is less effective when excitation frequency is greater than 11 rad/sec. Thus the effectiveness of base isolation is dependent on the frequency characteristics of ground motion.

3.3 *Effect of superstructure time period on the response of base isolated structure*

The effect of superstructure time period on the response of base isolated four-storey space frame structure is studied. The yield displacement of the isolator is taken as 2.5 cm. This value of yield displacement provides (for $R_t = R_c = 0.08$ W and $\eta = 0.2$) a time period of the bearing in lateral direction as 2.5 sec based on post-yield stiffness of the isolator. Figure 4 shows the variation of maximum top floor acceleration, base shear, bending moment and displacements with excitation frequency for various values of superstructure time period. It can be seen from Figure 4 that the peak value of the acceleration, base shear, bending moment, top and base displacements (which occur at the fundamental natural frequency of base isolated structure) increases with increase in the time period of superstructure. Thus, an increase in the superstructure time period increases the peak value of the acceleration, base shear, bending moment and displacements.

3.4 *Effect of post-to-pre yield stiffness ratio on the response of base isolated structure*

Figure 5 shows the effect of post-to-pre yield stiffness ratio on the response of base isolated four-storey space frame structure with fixed base time period equal to 0.75 sec. The yield force and the yield displacements of the isolator are taken as 0.08 W and 2.5 cm respectively. It can be observed from Figure 5 that the peak value of the acceleration, base shear and bending moment (which occur at the fundamental natural frequency of the corresponding base isolated structure) increases with increase in the post-to-pre yield stiffness ratio but the peak value of the top and base displacements decreases with the increase in the post-to-pre yield stiffness ratio. This is because as the post-to-pre yield stiffness ratio increases the post-yield stiffness of the bearing increases and there by the time period of the bearing decreases. Thus, an increase in the post-to- pre yield stiffness ratio increases the peak value of the acceleration, base shear and bending moment but decreases the peak value of the displacements. It can also be observed from the figure that the top floor acceleration of base isolated structure with different post- to- pre yield stiffness ratio is almost same beyond a certain excitation frequency, $\omega = 5$ rad/sec. Similar trend is observed in the case of top and base displacements.

3.5 *Effect of yield force on the response of base isolated structure*

The variation of maximum response with excitation frequency for a structure with fixed base time period equal to 0.75 sec and isolation period equal to 2.5 sec for various values of yield force is shown in Figure 6. The post-to-pre yield stiffness ratio (η) is taken as 0.2. It can be observed from Figure 6 that up to an excitation frequency of 1.5 rad/sec the top floor acceleration of base isolated structure with different yield force is almost same. Similar trend is observed in the case of base shear and the bending moment. In the region of excitation frequency between, 1.5 rad/sec to 3.0 rad/sec, (near the natural frequency of isolation bearing) as the yield force increases the acceleration, base shear and the bending moment decreases. But beyond a certain excitation frequency, $\omega = 3$ rad/sec, the increase in yield force increases the acceleration, base shear and bending moment. However, the top and base displacement decreases with the increase in yield force at all excitation frequency. This shows that augmenting the yield force will magnify the acceleration, base shear and the bending moment in case of a high-frequency input ground motion.

3.6 *Response of a four-storey space frame structure under real earthquake motion*

The response of a multi-storey space frame structure resting on non-linear base isolation system, subjected to El Centro earthquake excitation is studied. The top floor displacement, base displacement, top floor absolute acceleration, base shear and bending moment at bottom column due to this loading are computed at a time interval of 0.0004 seconds for a total period of 16.0 seconds. The time history response is shown in Figure 7, for fixed base ($T_s = 0.5$

sec) as well as base isolated (T_b = 2.5 sec) structure. Damping ratio is assumed to be 5% and 10% for superstructure and bearing respectively. It can be seen from Figure 7 that there is a considerable reduction in the top floor absolute acceleration, base shear and bending moment due to isolation. However, the horizontal displacement increases due to isolation. But the displacement at top and base of the isolated structure are almost same at all the time intervals. This indicates that the structure moves rigidly during earthquake.

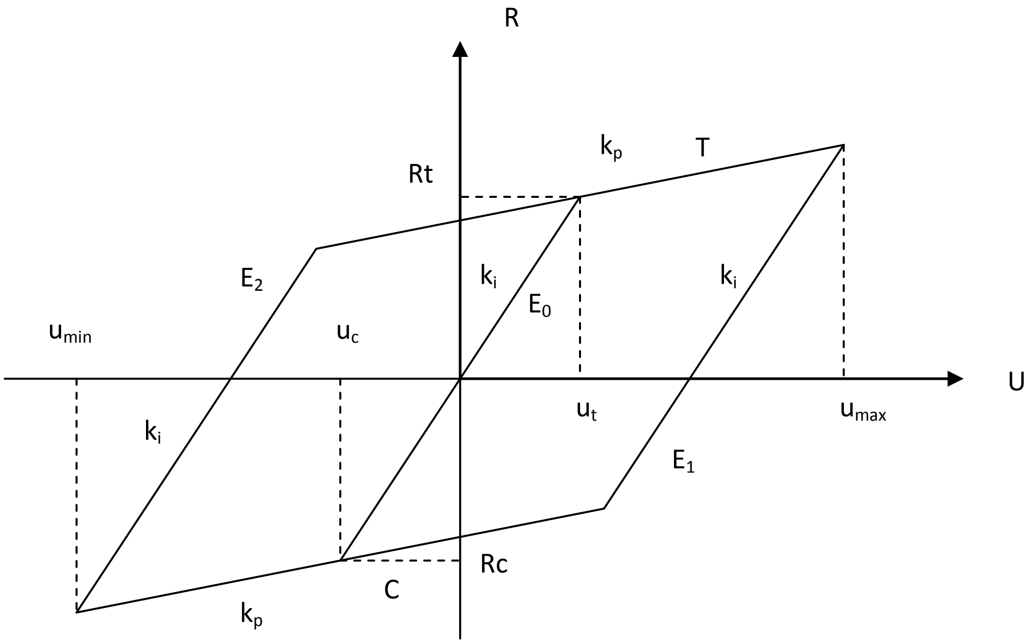
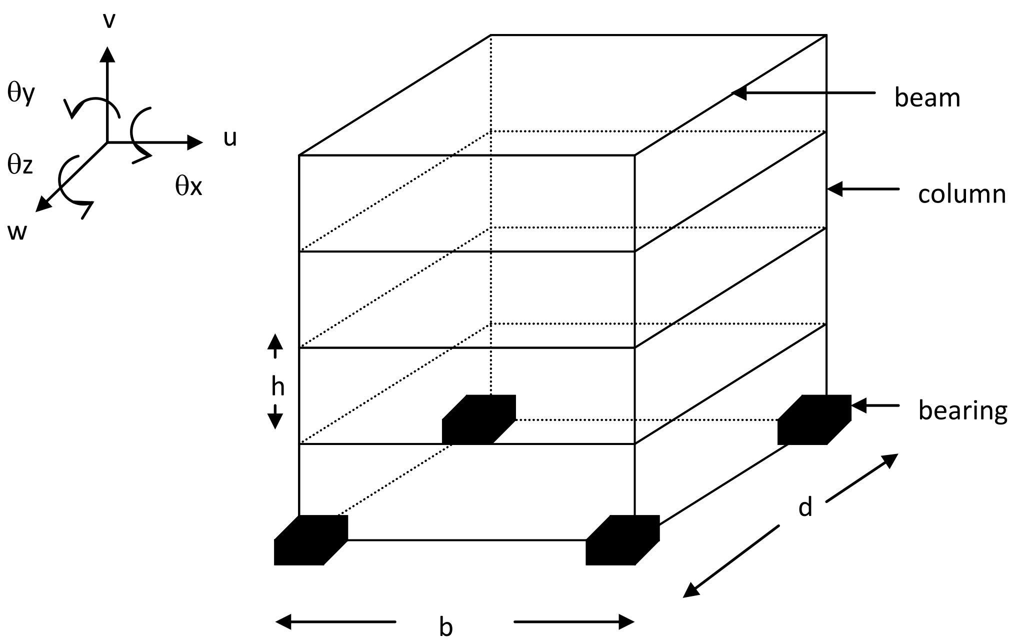


Figure 1 Bi-linear hysteretic model



Modulus of elasticity E = 2.24 × 10^7 kN/m^2

Ts (sec)	Mass on each beam kN-sec^2/m^2	b (m)	d (m)	h (m)	Size of beam (m)	Size of column (m)
0.5	3.525	4	4	3.3	0.3 × 0.6	0.6 × 0.6
0.75	4.2166	6	6	3.3	0.3 × 0.6	0.6 × 0.6
1.0	4.656	8	8	3.3	0.3 × 0.6	0.6 × 0.6

Figure 2 Four-storey space frame structure resting on non-linear rubber bearing

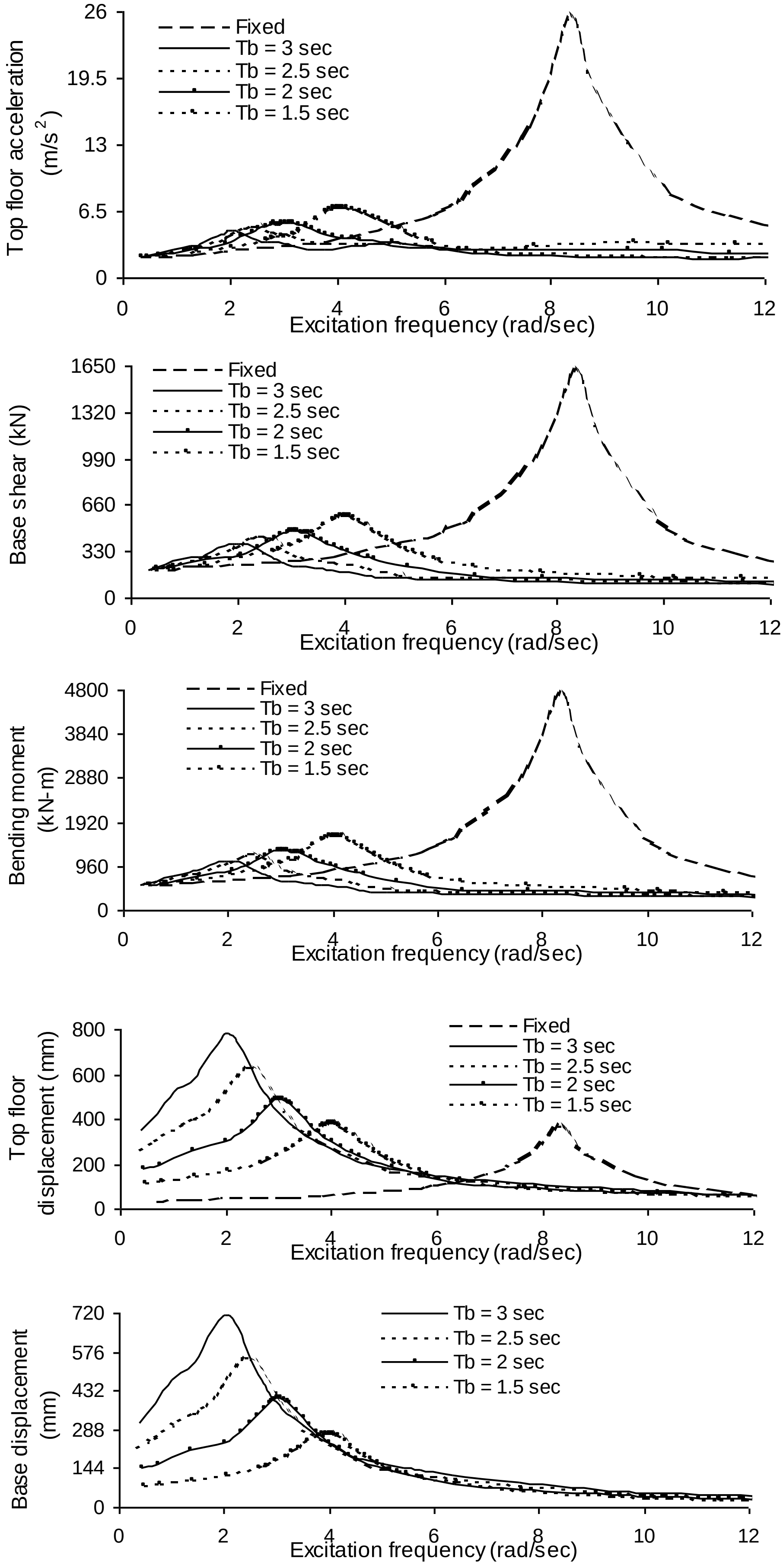


Figure 3. Variation of maximum response of a four-storey space frame structure with excitation frequency for various values of isolation period

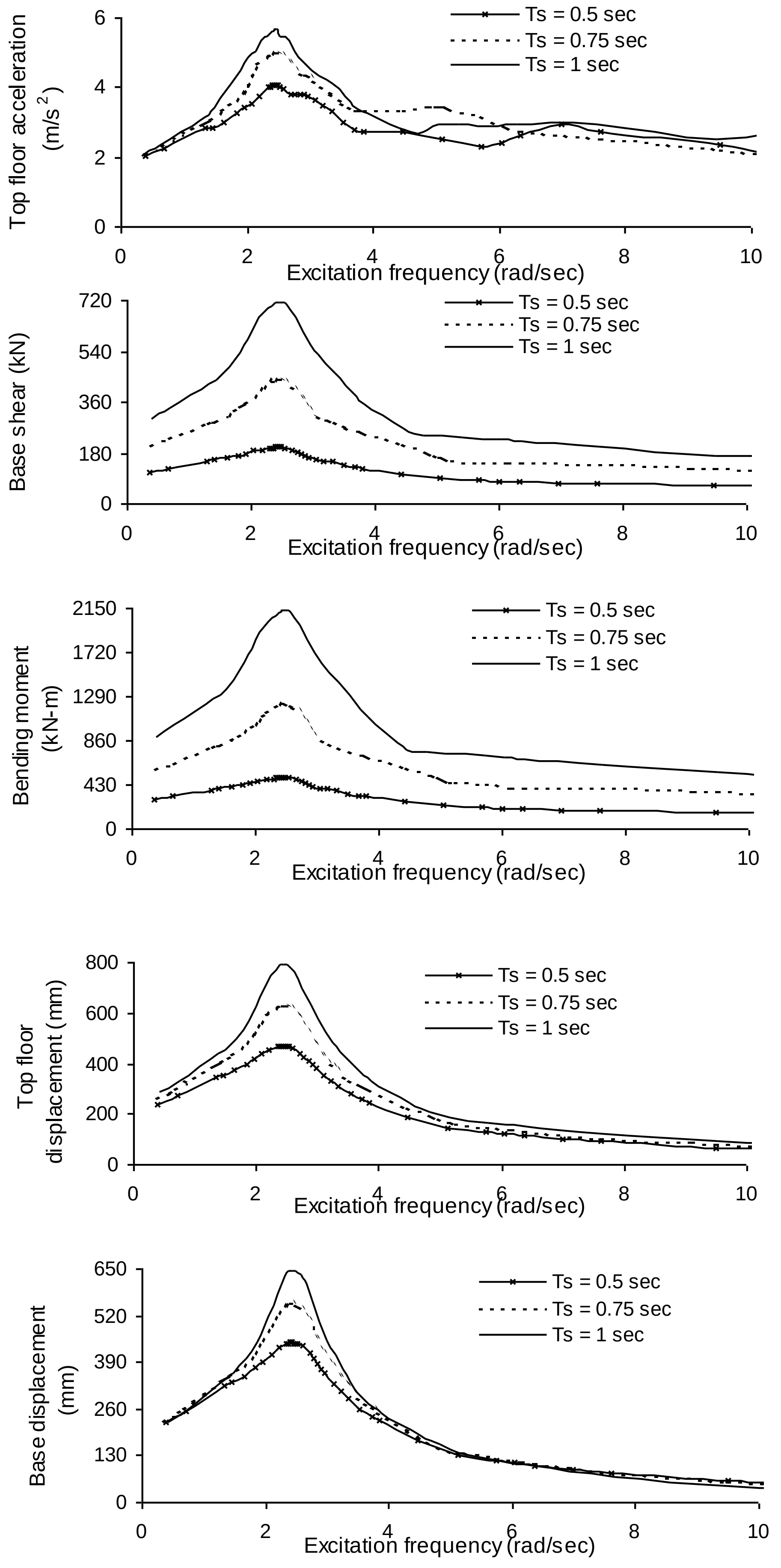


Figure 4. Variation of maximum response of a base isolated four-storey space frame structure with excitation frequency for various values of superstructure time period

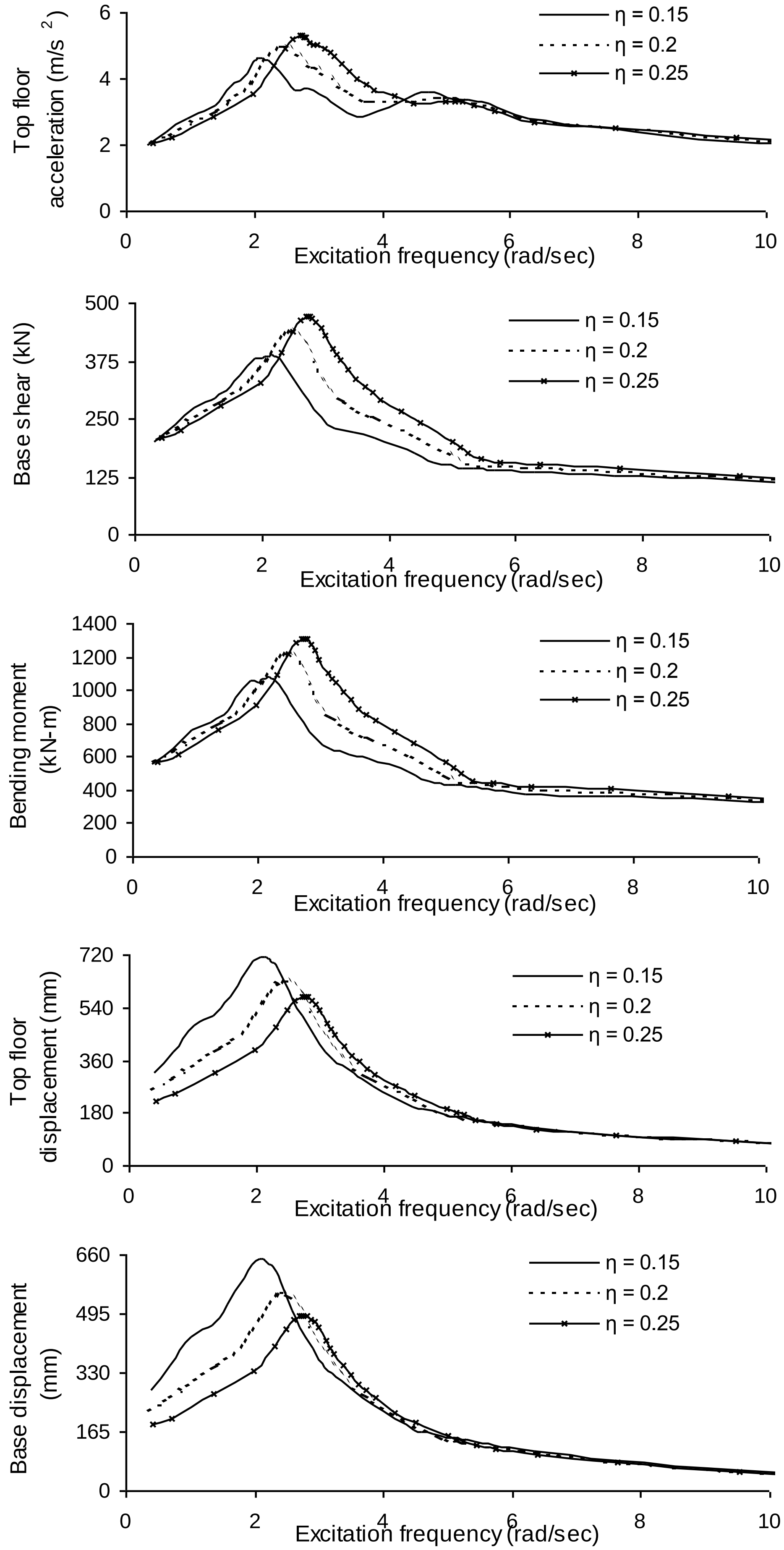


Figure 5. Variation of maximum response of a base isolated four-storey space frame structure with excitation frequency for various values of post-to-pre yield stiffness ratio

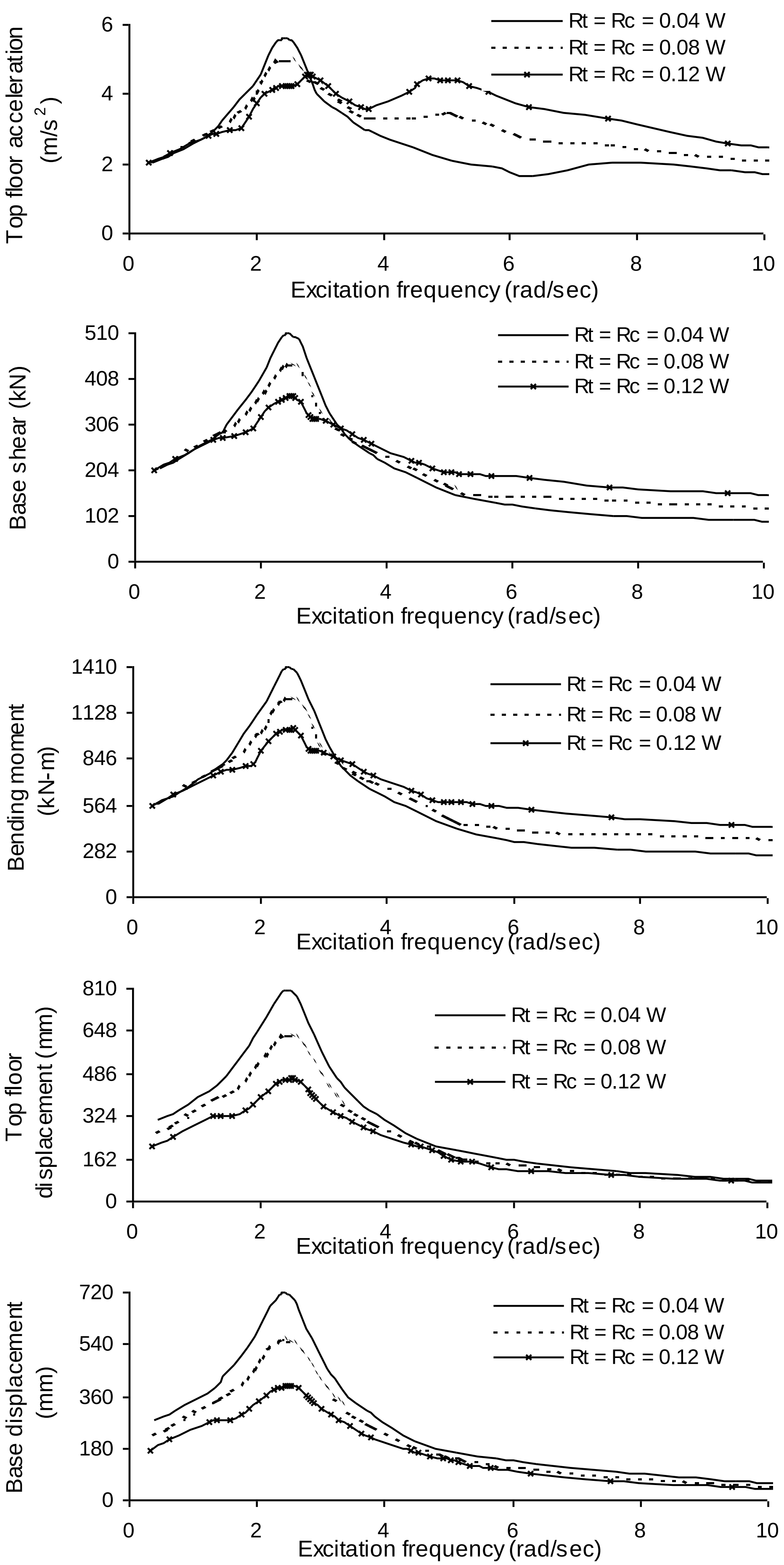


Figure 6. Variation of maximum response of a base isolated four-storey space frame structure with excitation frequency for various values of yield force

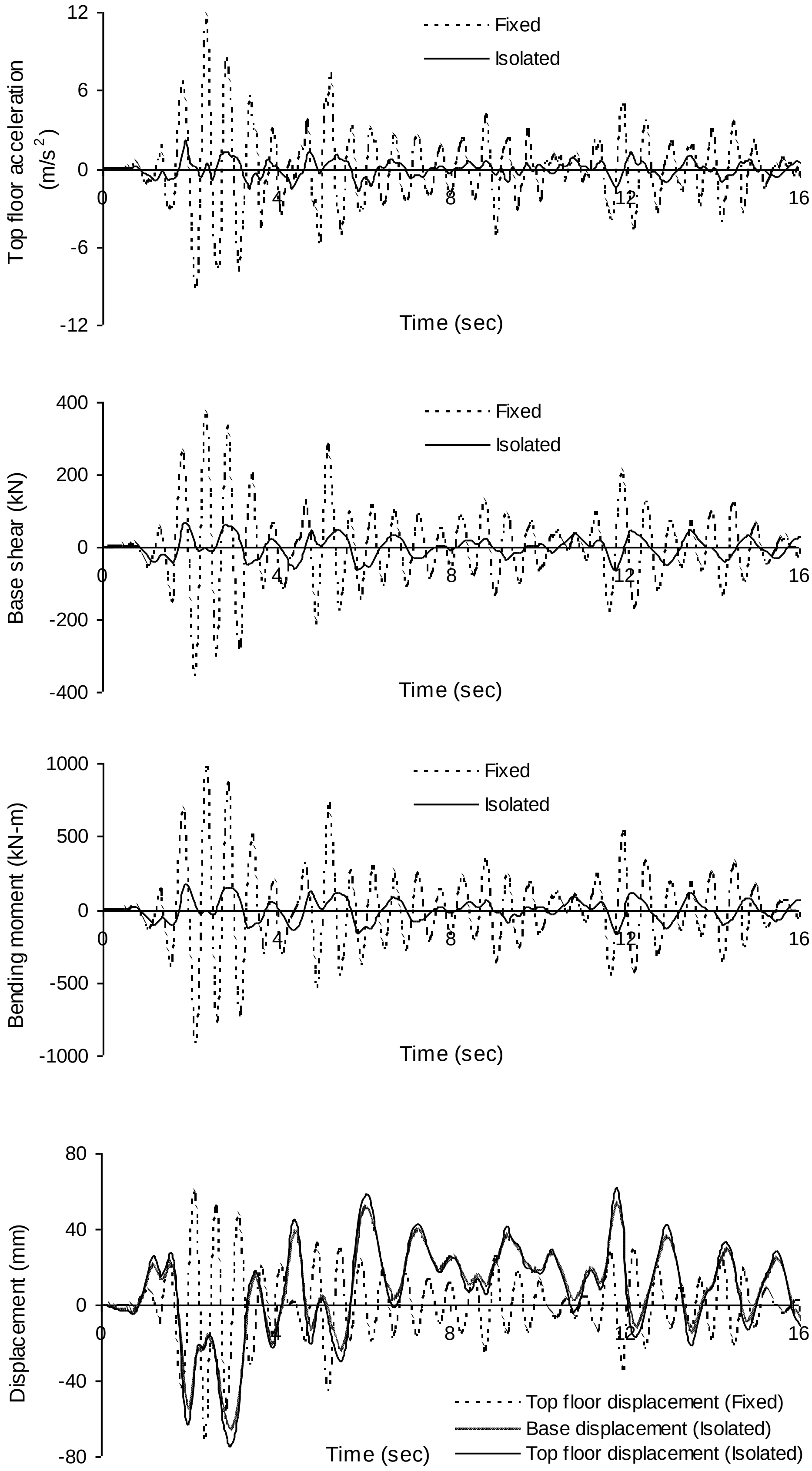


Figure 7. Response of a base isolated four-storey space frame structure subjected to El - Centro earthquake ground motion.

4 CONCLUSIONS

The response of a multi-storey space frame structure having six degrees of freedom at each node resting on non-linear base isolation system (lead rubber bearing) subjected to bi-directional harmonic ground motion and El Centro earthquake ground motions are obtained. The effect of superstructure time period, isolation period, excitation frequency, post-to-pre yield stiffness ratio and yield force on the effectiveness of the base isolation system are also investigated. The effectiveness of base isolation is studied by comparing the responses of base isolated structure with the response of the corresponding fixed base structure. The results of the study lead to the following conclusions:

1. Due to base isolation, the peak value of the acceleration, base shear and bending moment decreases but the peak value of the horizontal displacement increases. However, the frame experiences the rigid body movement. Hence the base isolation can be used effectively to control the seismic response of space frame structures. It is also found that the effectiveness of base isolation is dependent on the frequency characteristics of ground motion.
2. An increase in the superstructure time period increases the peak value of the acceleration, base shear, bending moment and displacements.
3. An increase in the isolation period decreases the peak value of the acceleration, base shear and bending moment but increases the peak value of the displacements.
4. An increase in the post-to-pre yield stiffness ratio increases the peak value of the acceleration, base shear and bending moment but decreases the peak value of the displacements
5. Augmenting the yield force will magnify the acceleration, base shear and the bending moment in case of a high-frequency input ground motion.
6. The top and base displacement decreases with increase in yield force.

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