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RESPONSE OF SEGMENTAL BUILDINGS TO RANDOM SEISMIC MOTIONS

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ABSTRACT

This paper investigates the seismic response of segmental buildings subjected to random excitations. The constrained optimization method is used to determine the optimal parameters for seismic isolation systems with the objective of minimizing the mean square acceleration response of a building subjected to random excitations. The seismic response of a typical segmental building to random excitations is investigated, and the results are compared with the response of corresponding fixed-base and base isolated buildings. The comparisons show that, similar to the base isolation technique, segmentation also effectively reduces the seismic building responses. However, when compared with the conventionally base-isolated building, the displacement response across the isolated system at the base level of the segmental building is significantly reduced.

KEYWORDS: Segmental Building, Base-Isolation, Random Excitation, Seismic Response, Earthquake Engineering

INTRODUCTION

The effect of earthquakes on a structure depends on both the characteristics of earthquake ground motion and the dynamic properties of the structure. Unfortunately, the fundamental frequency of conventional buildings, especially that of low- to medium-rise ones, is usually within the range of frequencies where earthquake energy is the strongest. The buildings thus act as an amplifier for the ground excitation during earthquake, and the acceleration experienced at the upper floor levels increases towards the roof level. The high acceleration can be harmful to both the building and its contents.

It is well known that seismic hazard of a building can be mitigated by increasing the ductility of the building. However, for traditional buildings, a large ductility can be achieved only through yielding of structural members during a strong earthquake. Following the yielding, the buildings will sustain severe damage in both structural and non-structural components.

Base isolation has been proven to be one of the most effective techniques that can protect both the building and its contents against harmful horizontal motions of earthquakes (Kelly 1986). In base isolation, a building is decoupled from the harmful horizontal components of earthquake ground motion by a mechanism that, while carrying the vertical load of the building, will significantly reduce the transmission of horizontal load into the building, see Figure 1(a). Recently, this technique is rapidly gaining worldwide acceptance (Kelly 1988).

However, for all base-isolated (BI) buildings, although the relative displacement within the superstructure is usually small, the displacement across the base isolation system can be relatively large. The base displacement is therefore of main concern in the building code provisions for seismic base isolation (UBC 1991). Because of the large displacement demand on the isolation system, the necessary flexibility of base isolation is usually provided at the foundation level for a low - to medium-rise building. In addition, the effectiveness of base isolation reduces as the superstructure becomes more flexible and therefore limits the application of base isolation technique to only buildings in the low- to medium-rise range (Pan 1992, Skinner et al. 1993, and Pan and Cui 1994).

In order to alleviate the above problem, the authors (Pan et al. 1993 and 1995) proposed a new isolation concept in which the superstructure of a base-isolated building is divided into several segments.

Each segment may comprise a few stories and is interconnected by additional vibration isolation systems located in the upper stories, Figure 1(b).

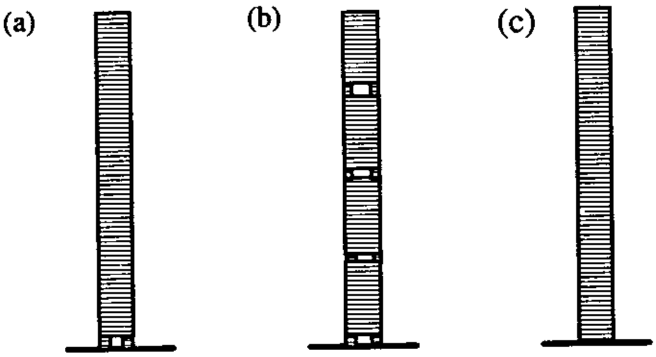

Fig. 1 Schematic buildings models (a) base-isolated (b) segmental and (c) fixed-base buildings

The segmental (SG) building concept can be viewed as an extension of the conventional base isolation technique with a distributed flexibility in the superstructure. Absorption and dissipation of earthquake input energy are afforded by all vibration isolation systems in the segmental building, rather than by the only isolation system at the base level. Therefore, the order of displacement demand on each vibration isolation system will be smaller than the displacement demand at the corresponding building level in a solely base-isolated structure. Alternatively, as compared with the fixed-base building shown in Figure 1(c), one can view the segmental building as a collection and concentration of flexibility at strategic locations in the superstructure.

Pan et al. (1995) carried out a study on the behavior of segmental buildings subjected to deterministic earthquake input. The deterministic study found that, while keeping the acceleration response in the superstructure at a low level, segmentation of the superstructure could reduce the base displacement. It is important to note that the optimum parameters of the vibration isolation systems may vary significantly for different earthquakes, since the seismic response of buildings depends not only on the dynamic properties of the superstructure but also on the characteristics of earthquake ground motion. In order to have a more complete understanding of the seismic behavior of segmental buildings; random seismic analysis is therefore carried out in this study using a similar numerical example. Results obtained from the present random vibration study show a trend similar to those observed for the deterministic study (Pan et al. 1995).

In this paper, the constrained optimization method is used to determine the design parameters of the vibration isolation systems so as to minimize the root mean square acceleration response of the segmental building subjected to a random excitation. In the analysis, the behavior of the vibration isolation system is assumed to be linearly elastic. The dynamic characteristics and random seismic response of the segmental building are investigated. A numerical example is used to illustrate the salient points of the segmental (SG) building. The numerical results are compared with those obtained from the corresponding fixed-base (FB) and conventional base-isolated (BI) buildings.

EQUATIONS OF MOTION

The multiple-degrees of freedom (MDOF) model used in the seismic analysis of segmental building represents a collection of shear buildings in segments where the floors are rigid diaphragms and the axial deformation of columns can be neglected. Therefore, the only possible displacement of each floor is the lateral one. In the analysis of a segmental building the vibration isolation systems can be regarded as virtual stories with a given lateral stiffness and without a story height.

Let $x_i(t)$ be the lateral displacement of the i-th floor relative to the ground, the equations of motion can be written in the following matrix form

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)=-M\{1\}\ddot{u}_g(t) \tag{1}$$

where x is a vector of the relative displacements; M, C, and K are the mass, damping and stiffness matrices respectively; and $\{1\}$ is a vector of unity that couples each lateral degree of freedom to the ground acceleration $\ddot{u}_g(t)$. Equation (1) can be decoupled into a set of single variable differential equations by using modal analysis method. Let $q_i(t)$ be the displacement of the i-th mode, the equation of motion for the i-th mode is

$$\ddot{q}_i(t)+2\xi_i\omega_i\dot{q}_i(t)+\omega_i^2 q_i(t)=-p_i\ddot{u}_g(t) \tag{2}$$

where ξ_i, ω_i and p_i are damping ratio, frequency and participation factor of the i-th mode, respectively.

For a lightly damped system, the response processes corresponding to two different modes are almost statistically independent (Clough and Penzien (1975)). In this condition, σ_r^2, the total variance of the response process corresponding to the r-th degree of freedom (DOF) can be obtained as

$$\sigma_r^2=\sum_{i=1}^{m}\sigma_{ri}^2 \tag{3}$$

where σ_{ri}^2 is the response variance of the r-th DOF in the i-th mode and m is the number of modes included in the analysis.

The variances of displacement, σ_{xri}^2, velocity, $\sigma_{\dot{x}ri}^2$, and acceleration, $\sigma_{\ddot{x}ri}^2$, for the r-th DOF of i-th mode can be obtained respectively from following equations:

$$\sigma_{xri}^2=\phi_{ri}^2 p_i^2\int_{-\infty}^{+\infty}|H_i(\omega)|^2 S_{\ddot{u}_g}(\omega)d\omega \tag{4}$$

$$\sigma_{\dot{x}ri}^2=\phi_{ri}^2 p_i^2\int_{-\infty}^{+\infty}\omega^2|H_i(\omega)|^2 S_{\ddot{u}_g}(\omega)d\omega \tag{5}$$

$$\sigma_{\ddot{x}ri}^2=\phi_{ri}^2 p_i^2\int_{-\infty}^{+\infty}\omega^4|H_i(\omega)|^2 S_{\ddot{u}_g}(\omega)d\omega \tag{6}$$

where ϕ_{ri} is the i-th modal value corresponding to the r-th DOF, and $S_{\ddot{u}_g}(\omega)$ is the power spectral density of the stationary process which models the seismic ground acceleration. Note that $|H_i(\omega)|$ is the transfer function of the i-th mode and is given as follows:

$$|H_i(\omega)|=\frac{1}{\omega_i^2\sqrt{\left(1-\frac{\omega^2}{\omega_i^2}\right)^2+\left(2\xi_i\frac{\omega}{\omega_i}\right)^2}} \tag{7}$$

GROUND EXCITATIONS

In this study, the modified Kanai-Tajimi model (Clough and Penzien (1975), and Tajimi (1960)) is used as the earthquake ground input. The power spectral density function of this stationary filtered white noise process is

$$S_{\ddot{u}_g}(\omega)=|H_{g2}(\omega)|^2|H_{g1}(\omega)|^2 S_0 \tag{8}$$

where

$$|H_{g1}(\omega)|^2=\frac{1+4\xi_{g1}^2\left(\frac{\omega}{\omega_{g1}}\right)^2}{\left[1-\left(\frac{\omega}{\omega_{g1}}\right)^2\right]^2+4\xi_{g1}^2\left(\frac{\omega}{\omega_{g1}}\right)^2}$$

and

$$|H_{g2}(\omega)|^2 = \frac{\left(\dfrac{\omega}{\omega_{g2}}\right)^4}{\left[1-\left(\dfrac{\omega}{\omega_{g2}}\right)^2\right]^2 + 4\xi_{g2}^2\left(\dfrac{\omega}{\omega_{g2}}\right)^2}$$

in which $\xi_{g1}, \xi_{g2}, \omega_{g1}$ and ω_{g2} are some characteristic damping ratios and frequencies which depend on the soil properties; and S_0 is a scale factor depending on both the ground motion energy and site conditions. In this paper, these parameters are determined based on the recommendations of the Joint Committee for Structural Safety (1974). For firm soil, the characteristic frequencies ω_{g1} and ω_{g2} respectively are equal to 53.41 rad/s and 3.14 rad/s, while ξ_{g1} and ξ_{g2}, are all equal to 0.6.

OPTIMIZATION OF ISOLATION SYSTEMS

It is well known that variation of the stiffness and damping coefficient in isolation systems has a significant influence on the seismic response of an isolated structure. Therefore, the selection of design parameters of a base isolation system is an important issue faced by the designer. In this paper, a constrained optimization algorithm implemented in MATLAB (1992) is used to find the optimum parameters of the isolation systems. The objective of the optimization is to minimize the root mean square (RMS) of the maximum absolute acceleration of floor responses of the segmental building subjected to a random excitation. The objective function can therefore be formulated as follows:

$$\min\left[\sum_{r=1}^{n}\sigma_{ar}^2\right]^{1/2} \tag{9}$$

where σ_{ar}^2 is the variance of absolute acceleration of the r-th floor. The constraints considered in the optimization procedure are the RMS relative displacements across the isolation system between segments. They take the following form:

$$\max\ \Delta_i \le \Delta_i^* \tag{10}$$

where Δ_i is the RMS relative displacement across the i-th isolation system. In the above inequalities, the quantity with an asterisk indicates the corresponding displacement constraint.

NUMERICAL EXAMPLE AND DISCUSSIONS

To help demonstrate the dynamic characteristics of a segmental (SG) building, the building shown in Figure 2 is used as a numerical example. The example building is a 16-story beam column frame structure, divided into four segments that are interconnected by vibration isolation systems. The total height of the building is 48.6 m. The lateral stiffness of the segments varies along the building height. Being a constant for all stories in a segment, it starts with 2.4×10^9 N/m for the first segment, reduces to 1.29×10^9 N/m for the second segment and 6.76×10^8 N/m for the third segment, and finally becomes 3.15×10^8 N/m for the fourth segment. The lumped mass of a typical story is 3.49×10^5 kg, while the mass of the roof and the base isolation raft are 1.39×10^5 kg and 2.52×10^5 kg, respectively. These parameters are selected based on the structural information of a recently completed base-isolated building (Pan et al. (1994)). The modal damping ratio is assumed to be 5 % of critical in the analysis. For comparison purpose, the corresponding fixed-base and base-isolated models are also investigated.

The optimum stiffness of the four isolation systems connecting the adjacent segments are determined by minimizing the RMS of maximum absolute acceleration floor responses of the building to a random excitation with S_0 assumed to be unity. The constraints of the RMS relative displacements across the vibration isolation systems, Δ_i^*, are set to be 0.042 m for the isolation system at foundation level and

0.021 m for the other three isolation systems. The optimal lateral stiffness of the isolation systems for both the BI and the SG models are summarized in Table 1. The optimal stiffness of the fourth isolator turns out to be equal to that of the fourth segment, suggesting the advantage of having a larger mass in the upper part of the SG building acting as a mass-damper.

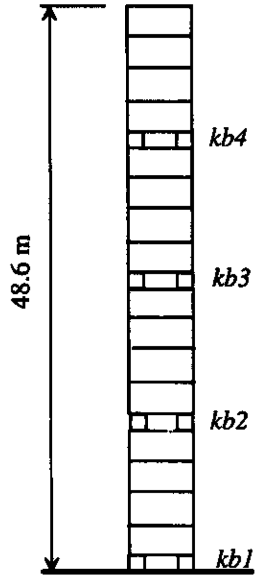

Fig. 2 Example of segmental building

Table 1: Lateral Stiffness of Isolation

	k_{b1} (10^8N/m)	k_{b2} (10^8N/m)	k_{b3} (10^8N/m)	k_{b4} (10^8N/m)
BI Model	0.59	–	–	–
SG Model	1.51	2.76	0.57	3.15

Table 2: Natural Frequencies (Hz)

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
FB Model	1.02	2.24	4.18	5.25	6.54
BI Model	0.5	1.54	2.72	4.37	5.64
SG Model	0.46	1.25	2.04	3.01	4.23

Table 3: Modal Participation

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
FB Model	3.54	1.54	0.95	0.89	0.36
BI Model	4.44	0.58	0.17	0.08	0.03
SG Model	3.96	2	0.33	0.05	0.01

The vibration frequencies and participation factors of the first five modes of the FB, BI, and SG models are summarized in Tables 2 and 3, while the first four mode shapes are shown in Figures 3(a) to 3(d). It is shown in Table 2 that the frequencies of the modes involving structural deformations, i.e., the second and higher modes of the BI model and the fifth and higher modes of the SB model, are shifted to a value much higher than the fundamental frequency of the FB model. With regard to the participation factors shown in Table 3, the values for the second and higher modes of the BI model and those for the fifth and higher modes of the SB model are insignificant compared to those for the first mode. The modes that involve structural deformation of the BI and SB buildings can therefore be considered as orthogonal to the earthquake input. Thus, while the earthquake motion may have energy at these frequencies, it can not be transmitted into the building. The effectiveness of seismic isolation in reducing damage to the structural members results directly from its ability to deflect ground motion energy through the property of orthogonality.

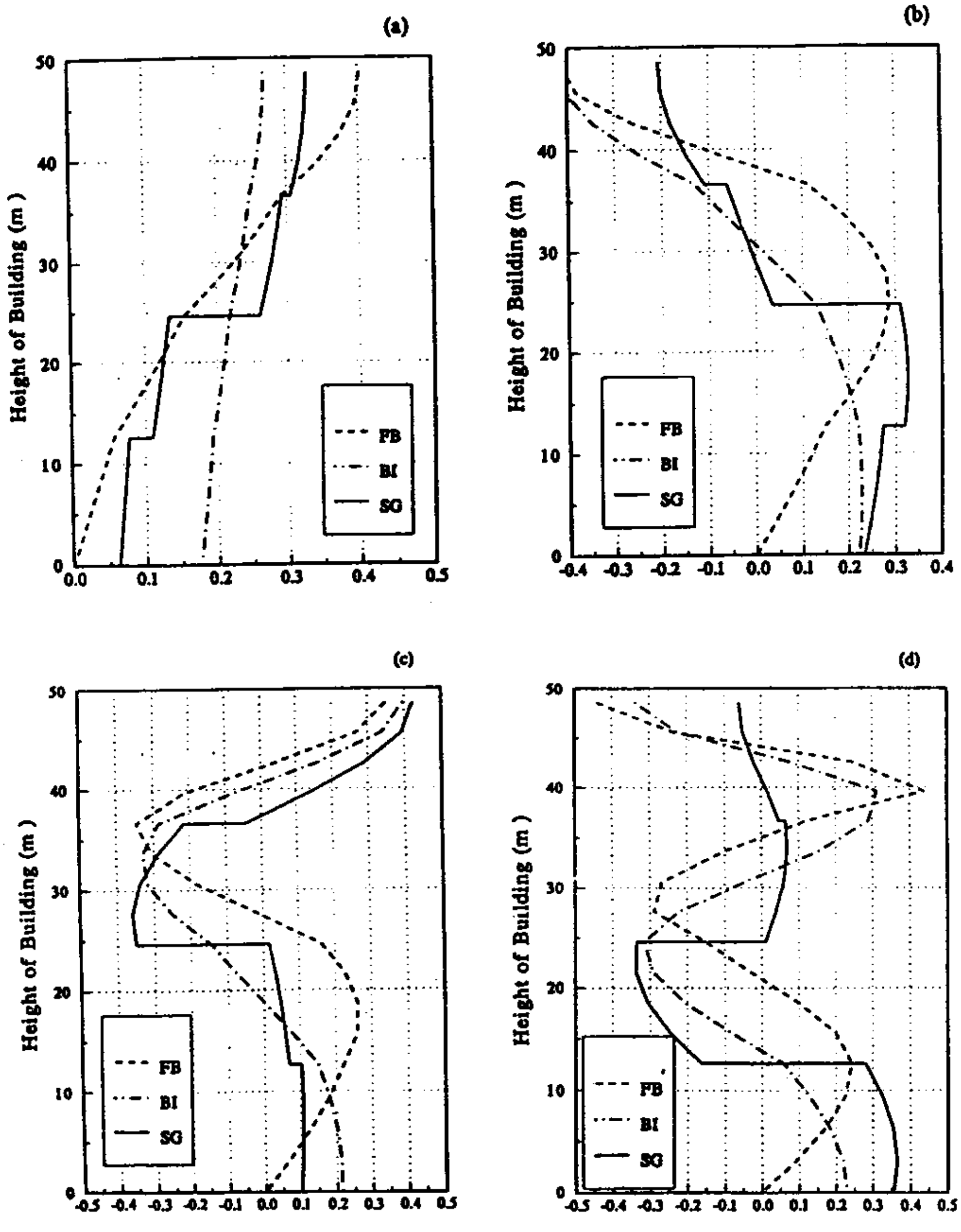

Fig. 3 Mode shapes (a) fundamental mode, (b) second mode, (c) third mode, (d) fourth mode

It is found from the fundamental mode shown in Figure 3(a), which is the most important mode for the seismic response of the BI and the SG buildings, that although the relative displacement between the roof and the base of the SG building is much larger than that of the BI building, a large amount of the deformation within the SG building is concentrated at the additional vibration isolation systems in the superstructure. Therefore, the deformation within each segment remains very small.

The RMS acceleration and displacement responses of each floor in the SG building are shown in Figures 4 and 5, respectively. For comparison, the corresponding results of the BI building and FB building are also shown in Figures 4 and 5. Figure 4 shows that the accelerations of both the SG and BI buildings are lower than that of the FB building. This indicates that the magnitude of the inertial forces, which produce the inter-story drifts and therefore potential damages in the structure, are reduced in the SG and BI buildings. This can be observed in Figures 6 and 7 for the RMS shear force and overturning moment profiles of the three buildings discussed. From these figures, it is found that the shear force and the overturning moment of the SG and BI buildings are similar but smaller than that of the FB building. However, as shown in Figure 5, the base displacement of the SG building is significantly reduced compared with that of the BI building. The displacement at the base level reduces about 46 % from 0.056 m for the BI building to 0.03 m for the SG building. This is a definite advantage of the SG building over the conventional BI building.

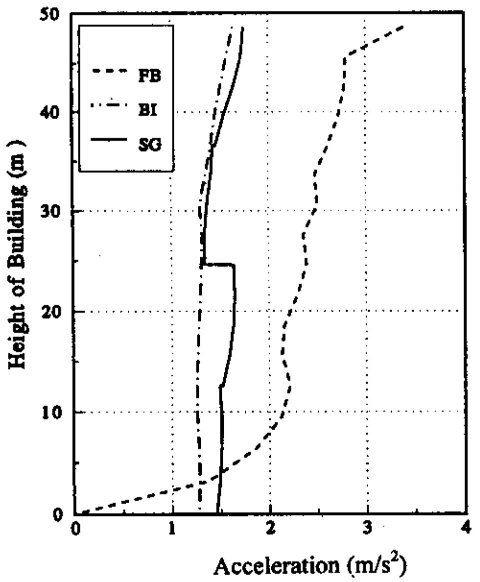

Fig. 4 RMS acceleration profile

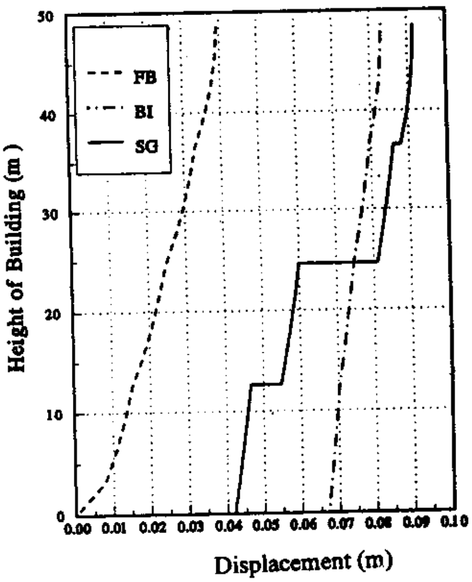

Fig. 5 RMS displacement profile

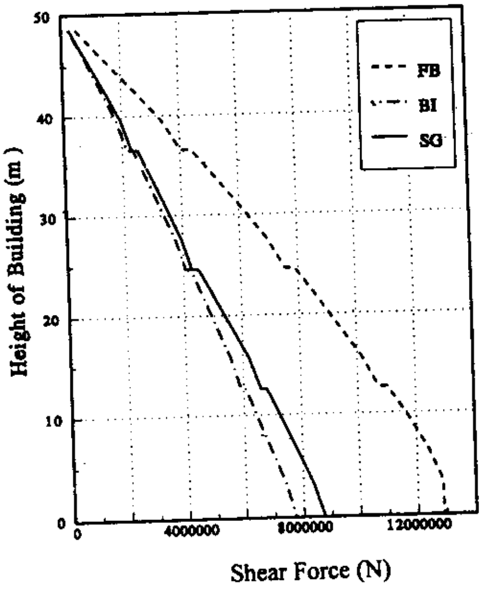

Fig. 6 RMS shear force profile

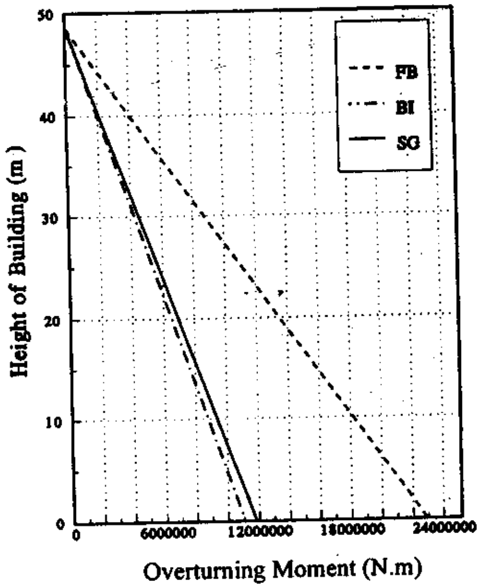

Fig. 7 RMS overturning moment profile

It is also important to note that the second and the third mode participation factors for the SG model are much higher than those for the BI model. Therefore, in the SG building, the interaction between the first mode and the higher modes is more pronounced. This may contribute to the further reduction of the overall displacement for the SG model. The interaction effect can be seen by comparing the fundamental mode, Figure 3(a), with the profile of the displacement response shown in Figure 5.

CONCLUSIONS

This paper presents a preliminary study on the seismic response of an optimized segmental building to random excitations. The following observations can be drawn from the seismic analysis results for the three building models, i.e., the fixed-base (FB), base-isolated (BI) and segmental (SG) buildings:

- Similar to the conventionally base-isolated building, the segmental building also possesses the ability to decouple the building from the harmful horizontal earthquake ground motions.
- Compared with a conventional base-isolated building, while keeping the acceleration response low, segmentation of the superstructure significantly reduces the base displacement. The result of the numerical example shows a 46 % reduction in the base displacement for the SG building when compared with that of the BI building.
- With the above observations for random seismic responses of linearly elastic isolators, segmental buildings appear to hold the promise of extending the technique of base isolation to taller buildings. These observations are consistent with those obtained in the earlier study on deterministic responses (Pan et al. (1995)). More research work is however required to investigate the effects of nonlinear isolators during strong shaking on the level of seismic response.

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