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Seismic response control for a high-rise structure subjected to far-field long-period ground motions: A case study

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Abstract

High-rise structures are vulnerable to far-field long-period ground motions (hereafter long-period motions), which lead to significant responses beyond expectations based on their intensities. Placing dampers to control responses of high-rise structures is the way engineers are mostly concerned with. However, determination of damper placements for the high-rise structures seldom depends upon the responses to long-period motions instead of normal motions, as could contradict with unfavorable situations for the high-rise structures. The paper focuses on comparisons of five damper placement methods through the analysis of structural responses with respect to different types of input motions. Two kinds of dampers, including viscous dampers and buckling restrained braces (BRB), are deployed. The results suggest that the drift-related placement method under excitations from long-period motions can achieve as significantly effective as that for normal motions; meanwhile, BRBs are favorable for reducing responses as a result of taking advantage of characteristics of long-period motions. The study verifies that the utility of the placement methods on the basis of excitations from normal motions is applicable to the high-rise structure when subjected to long-period motions.

Keywords: far-field long-period ground motion, high-rise building, seismic response controls.

1. Introduction

It is well reported that long-period ground motions account for the resonant-induced responses in recent decades [1-4]. In context of this, evaluation of performance for high-rise buildings under long-period ground motions is necessary. Long-period ground motions differ from normal ground motions considering long-period characteristics relative to high-frequency components, as the formers are product of amplifications from either basins or plains, in which long-period surface waves by the conversion of body waves is an outstanding feature [5-8].

Seismic response controls for high-rise buildings benefit from supplemental dampers. Fluid viscous damper and buckling restrained braces are often adopted as reduction measurement for high-rise buildings. For instance, Ding [9] adopted a scheme combing the outrigger with viscous dampers to study the effectiveness of dampers in reducing responses of a high-rise building based on parametric analysis. Similarly, Lin explored the properties of single outrigger system embracing BRB so as to investigate optimal placements and reasonable design scheme for core-tube tall buildings [10]. Takewaki carried out analysis of oil dampers in reducing responses of two high-rise buildings to check reliability of the two structures under specific simulated long-period ground motions [3]. Several frequently used damper placement methods are adopted to place the viscous dampers for frame structures, and this aims to explore relationships between the placement methods and structural and non-structural repair costs [11]. However, there is not a comprehensive study regarding effectiveness of reduction schemes involving types of dampers and placement methods on reduction responses with respect to different types of ground motions.

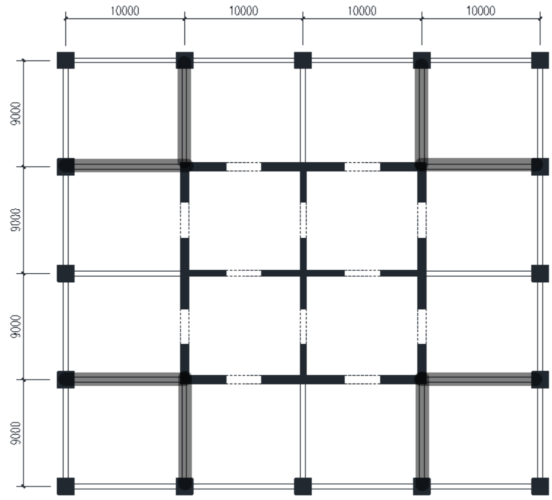
The frame-core tube structure is herein simplified as a representative of high-rise buildings to investigate the effectiveness of the five placement schemes, which are often determined by normal ground motions, on reduction response in the case for long-period motions. In addition, the BRB and VD dampers are involved to consider the sensitivity of the dampers to different types of ground motions. The determination of design parameters for two kinds of the dampers is conditioned on same capacity of energy dissipation. Thus, the preliminary investigations related to the utility of damper schemes in the case for long-period motions is presented.

2. Structural model

To investigate performance of super-high rise building under long-period ground motions, a frame-core tube archetype is introduced herein. The height of the structure with 60 stories is 240 m. The layout size of the floor is 40×36 m and that of core tube is 20×18 m. The size of square columns change from 2000 mm at bottom to 1000 mm at top. External thickness of the shear walls is averaged at 750 mm and inner thickness is 500 mm. Size for peripheral beam is 500×900 mm and coupling beam is 500×700 mm. In addition, the planar layout is referred in figure 1.

The structure is simplified from an actual super-high rise building in Chongqing, China, where the seismic precautionary intensity of this zone is 6 (0.05g) and site classification is Ⅱ, based on the Chinese seismic code. Dead and live load for the structure is 5 kN/m^2 and 2 kN/m^2, respectively.

Referring to the design principle, earthquake action is of controlling load for the structure. Because of this, the paper herein is concerned with reduction response under ground motions. With an aid of software Perform-3d, the dynamic properties are performed, and the first three periods are 5.49, 5.18 and 3.47 sec, respectively. It is apparent that the structure is characterized by long-period properties, which account for resonant responses under long-period ground motions [3].



(a) plan scheme

(b) elevation scheme

Figure 1 Schematic diagram of damper position; note that gray areas are locations for dampers in plan.

3. Ground motions

Selection of ground motions for structural time-series analysis is required to match a design spectrum, as referred from Chinese seismic code. Following this line, normalized design spectrum β is determined based on the seismic environment and structural properties.

Noted that the abscissa of the code spectrum herein is prolonged to 10 sec at same slope as that for 6 sec. The long-period ground motions are chosen from the Niigata ken Chuetsu event [12], during which the long-period ground motions cause significant responses for high-rise buildings even if epicentral distances exceed 150 km. On the other hand, normal ground motions are available from PEER ground motions database.

Consequently, the six ground motions are selected herein, and the details are listed in table 1. It is found from figure.2 that average β spectra for normal and long-period motions match well the code spectrum at the periods adjacent to the fundamental period of the structure.

Performance of the structure is investigated at the level of precautionary intensity, and thus PGAs of the selected ground motions are adjusted to 49 gal, which refers to the code. In addition, time-analysis for the structure is carried out at two horizontal directions, and thus the intensity ratio of X to Y direction is 0.85.

Table 1 Information of selected ground motions

Record	Event	Epicentral distance (km)	Magnitude (M)	PGA (gal)	Duration (sec)
CHB026	Niigata ken Chuetsu	244.4	6.8	12.9	384
CHB028		195.7	6.8	28.1	287
CHBH10		229.6	6.8	16.9	285
RSN737	Loma Prieta	53.7	6.9	166.3	60.0
RSN873	Landers	163.9	7.2	62.1	48.39
RSN873	Landers	163.9	7.2	62.1	48.39

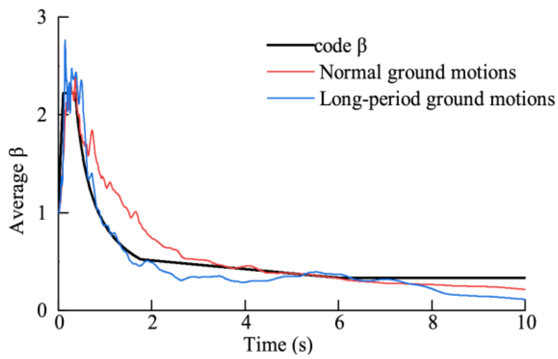


Figure 2. Average β spectra for normal and long-period ground motions.

4. Scheme of damper

4.1 Type of damper

To investigate effectiveness of reduction responses with respect to types of dampers, viscous damper and buckling restrained brace (BRB) are involved. It is known that viscous dampers provide a fluid pressure to resist structural deformations. Its function is written as $F = Cv^{\alpha}$, where the C is damping coefficient; v is the relative velocity; a is the velocity exponent ranging from 0 to 1, which depends on the type of viscous device. In contrast, the working principle of BRB is dependent upon the relative displacement between two ends of a brace. It plays a combinatorial role in reducing response, as it not only increases lateral stiffness of the structure but enables to dissipate seismic energy after yielding.

Furthermore, we should define a criterion which determines the parameters for designing VD and BRB in order to evaluate the different kinds mechanics at same capacity. Thus, the design principle for the two types of damper devices is herein conditioned on same capacity of energy dissipation. Damping force of the viscous damper is assumed to be the linear relationship with velocity, that is, $a = 1$. In this regard, it is reasonable that hysteretic behaviour of viscous dampers shares the same period with the structure [13]. Thus, energy dissipation of the viscous damper for a hysteretic cycle is formulated as follows:

$$W_{vd} = 2\pi^2 u^2 C^2 / T_1 \tag{1}$$

Where, u is the relative displacement between two ends of the viscous damper; C is the viscous coefficient; T_1 is the fundamental period of the structure. Interstorey drift ratio at elasto-plastic stage for a frame-core tube type structure is limited to θ=1/100, referring to Chinese code, and it means that the maximum displacement of the structure is u=40mm.

4.2 Damper placement

Material components for BRB is Q235. Accordingly, its yielding stress is 235 Mpa and elastic modulus is 206 Gpa. Reduction ratio for stiffness is 0.02 after yielding. Effective length for core components of BRB is 1 m and its core area equals to 10000 mm^2. Because of this, we can readily simulate the hysteretic behaviour of BRB by an aid of software PERFOR-3d when its maximum displacement reaches 40 mm, and resulting energy dissipation is 358 kJ. Further, 62340 N/(m/s) of coefficient for the viscous damper is obtained as a result of resolution of equation (1). The parameters for the viscous damper and BRB are listed in table 2.

Table 2 Parameters of damper

BRB		Viscous damper	
Stiffness(N/m)	2.06E+9	Coefficients N/(m/s)	62340
Yield force(N)	2.35E+6		
Stiffness ratio	0.02	Velocity exponent	1.0

As shown in figure 1 for structural plain, the four dampers are placed between the core walls and the peripheral columns. Thus, the damper placement methods herein are concerned with the vertical location. The five damper placement methods are involved in present paper. They are divided into two categories, containing the methods referring to vertical location and simple iterative methods based on structural responses. It is noted that the number of the storeys, which are placed four dampers, is fixed to three. A brief description for the five methods is presented as follows.

(1) Top method, for which the dampers are arranged at each top three storeys. The reason for this is that responses of top storeys for super-high rise structures often appear to be obvious when subjected to long-period ground motions, as is likely to trigger intense anxiety and action difficulty for top residents.

(2) Bottom method, for which the dampers are arranged at bottom three storeys. It results from the fact that bottom components of a structure bear relatively great shear force under excitations.

(3) Uniformly-height method, for which the dampers are distributed at an equal interval along the height. Accordingly, the dampers herein are arranged at 20, 40, 60 storeys, respectively. In practice, damped-outrigger system, which is incorporated into the strengthened storey, is often adopted in the super-high rise structure to reduce responses [9]. Thus, this method is possibly used based on the designing principle of strengthened storey, which is frequently designed at the equal interval along the height.

(4) Drift-based method. It is suggested that placing damper at storeys with large drifts is preferable to enable the dampers to dissipate energy in comparison of other storeys with small drifts. Following this line, we carry out the three iterative processes to arrange the dampers according to last resulting drifts. Specifically, the structure without dampers (original structure) is subjected to a ground motion at first, and then first set of the dampers are placed at the storey with the maximum drift; sequentially, the structure with the dampers is subjected to the ground motion again so as to locate corresponding index of the maximum drift. This process is performed at three times.

(5) Energy-based method. This technique is similar to Drift-based method. The difference is that hysteretic energy is treated as an indicator to conduct damper placement instead of the drifts. This is because appearance of hysteretic energy indicates that the components of the structure stay at yielding state to dissipate energy from seismic excitations. In other words, structural components can be protected at an expense of dissipation energy by the dampers.

It is noted that the methods described above are abbreviated with “Top”, “Bot”, “Uni”, “Dft”, “Eng”, respectively, in following figures.

5. Comparison of structural response

The variables involved in comparisons of structural responses contain types of damper, damper placements and ground motions. The comparisons are presented with respect to types of damper, namely, viscous and BRB, in order to express the clear perspectives.

5.1 Viscous damper

The results of the iterative technique based on drift and energy are listed in table 3. It is found that location indexes obtained from the drift-based technique are mainly concentrated at upper storeys. It is reasonable that the maximum drifts tend to increase with the height increasing. However, the slight difference is that the results for the long-period ground motions are relatively low in comparison with those for the normal motions. On the other hand, location indexes from energy-based technique are distributed either upper or bottom storeys, as the variations are dependent upon the ground motions.

Table 3 Iterative placement for viscous damper by drift and energy based method

Record	RSN737		RSN873		RSN880		CHB026		CHB028		CHBH10	
Scheme	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng
1	43	58	44	8	43	60	34	14	41	60	35	58
2	42	59	43	9	44	59	35	13	42	59	36	60
3	44	60	42	58	45	9	33	15	39	58	41	59

Note that #1-3 represents the results from the sequence of iterative process. The resulting locations are shown in the form of storeys.

5.1.1 Energy dissipation

Variations of energy dissipation in terms of damper placements are shown in figure 3. For normal ground motions seen in (a)-(c), it is clear that the drift-based method enables the structure to dissipate relatively small hysteretic energy, and correspondingly damper energy is greater than others. This means that the placement permits the dampers to take advantage of relative drifts to dissipate energy. In other words, the energy which was dissipated in the form of hysteretic loop for the original structure is consumed by the dampers. Meanwhile, uniform, top and energy methods show relatively inferior to drift-based method. In contrast, it is expected that the bottom method exerts slight influence on reduction responses, since the drifts at bottom of the structure are small.

Similarly, the drift-based method is preferable to dissipate energy under long-period ground motions. However, a slight difference is that energy-based method is not as effective as that under normal ground motions. For example, the ratio of hysteretic energy relative to the original structure is 248 % in the case of CHB028.

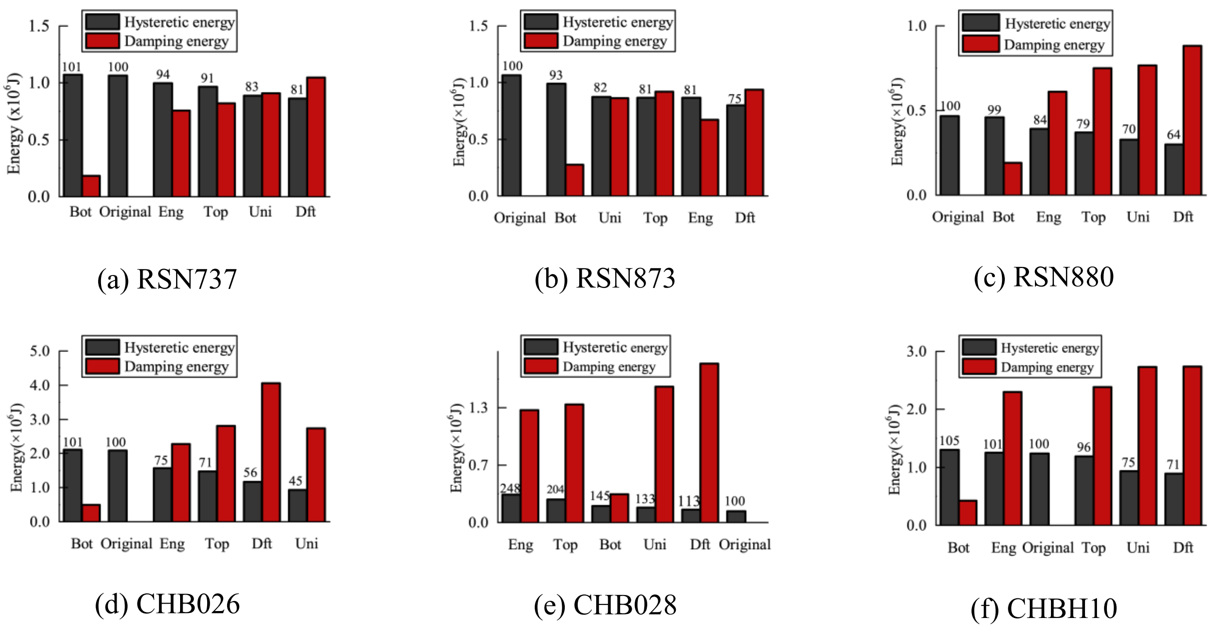
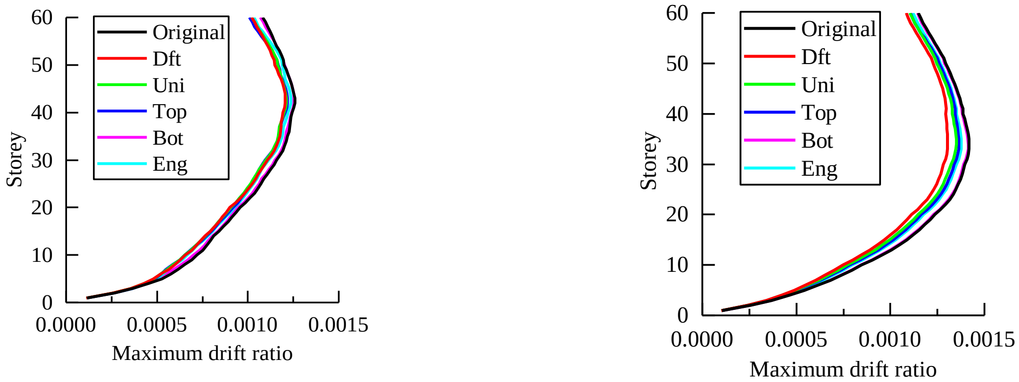


Figure 3. Comparisons of energy dissipation with respect to damper placements. Note that values of hysteretic energy in column represent ratios relative to the original structure.

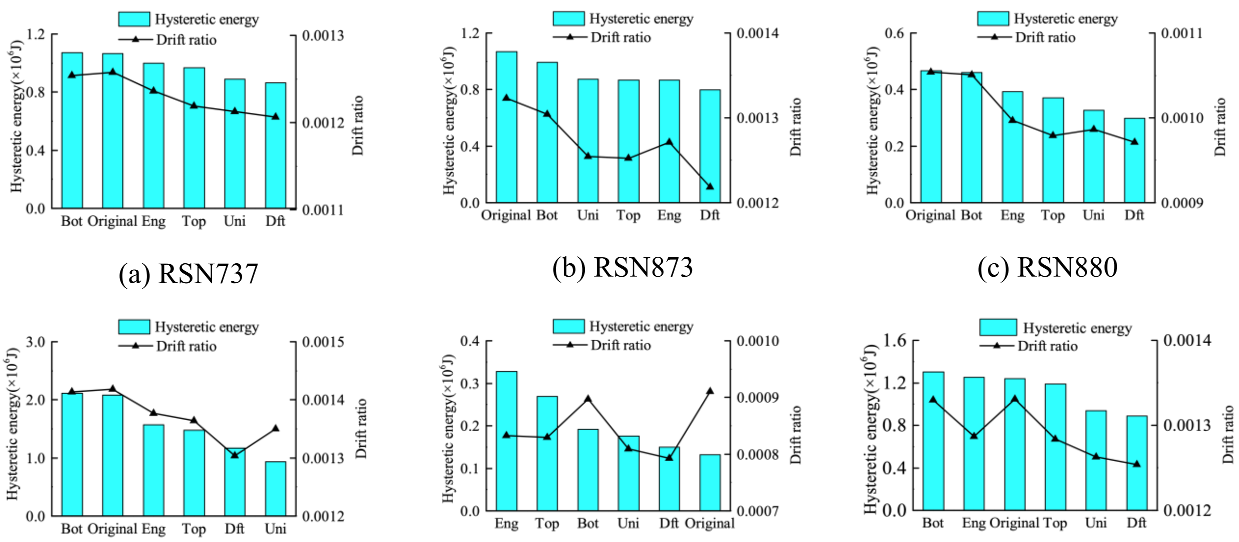
5.1.2 Drift ratio

It is known that drift ratios are often used to evaluate the overall performance of a structure subjected to dynamic excitations. Thus, effectiveness of damper placements should be evaluated in terms of drift ratios. However, due to limitation of space, we herein present drift ratios for the damper placements in two cases, including the normal motion for RSN737 and long-period motion for CHB026. In general, it is clear from figure 4 that the maximum drift ratios for long-period ground motions are significantly greater than those for the normal motions. Meanwhile, the dampers are effective to reduce responses, despite the variations in terms of the methods. The sequences related to effectiveness among the methods are consistent with those evaluated from energy dissipation.



(a) RSN737 (b) CHB026

Figure 4 Maximum drift ratios for the placement methods with respect to ground motions



(a) RSN737 (b) RSN873 (c) RSN880

(d) CHB026 (e) CHB028 (f) CHBH10

Figure 5. Comparisons between structural hysteretic energy and drift ratios with respect to ground motions. Note that hysteretic energy dissipation is on the left side and drift ratio is on the right side

Furthermore, the relationships between hysteretic energy and drift ratios with respect to the ground motions are shown in figure 5. The drift ratios present the similar trend to the hysteretic energy regardless of the types of the ground motions. However, the drift ratios are obtained from the maximum value over duration in contrast to hysteretic energy obtained from accumulation over duration. Thus, the energy for long-period motions is generally greater than that for normal ground motions. Meanwhile, the drift-based and uniform-based method are preferable to reduce responses subjected to normal and long-period ground motions.

5.2 Buckling restrained brace

BRB as being an alternative to VD is used in following section. Similarly, the five schemes mentioned above are used to investigate the effectiveness of the placements for BRB. The results for iterative methods are listed in table 4. The locations for drift-based method are distributed at the middle-upper of the structure in contrast to that for energy-based method for which the locations are distributed at either upper or bottom. This trend is not closely related to the types of the ground motions, since maximum drift ratios appear at the middle-upper of the structure while the strain energy dependent upon shear forces is mostly dissipated at the bottom.

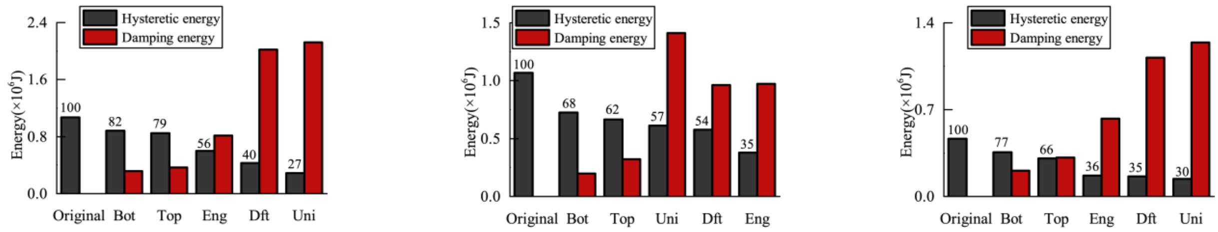
Table 4.Iterative placement for BRB

Record	RSN737		RSN873		RSN880		CHB026		CHB028		CHBH10	
Scheme	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng	Dft	Eng
1	43	58	44	8	43	60	34	14	41	60	35	58
2	37	8	47	11	38	58	42	58	33	58	42	60
3	33	60	41	58	51	9	38	23	28	59	31	13

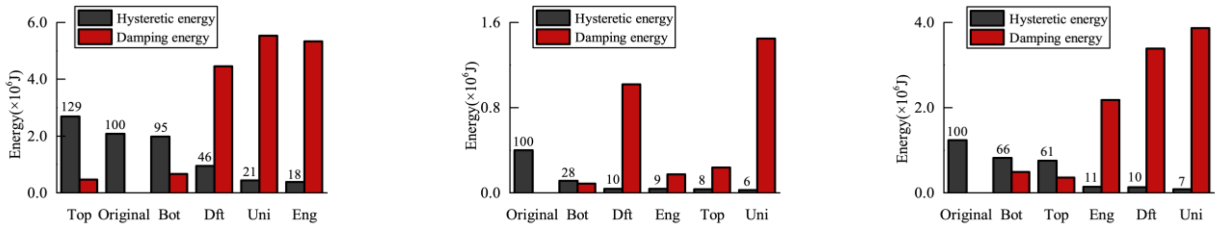
Note that #1-3 represents the results from the sequence of iterative process. The resulting locations are shown in the form of storeys.

5.2.1 Energy dissipation

In general, energy dissipation under long-period motions is greater than that for normal motions, and this is highly dependent upon the duration of the motions. However, the preferable schemes do not significantly vary from the type of ground motions. Both the draft-based and uniform methods dissipate more energy than other alternatives do. These are similar to those for VBs mentioned above. On the other hand, the BRBs for the case of the long-period motions are effective to protect the structure from the damages caused by elasto-plastic deformations, as the drift-based and uniform methods for CHB028 and CHBH10 present relatively low hysteretic energy ratios relative to the original structure.



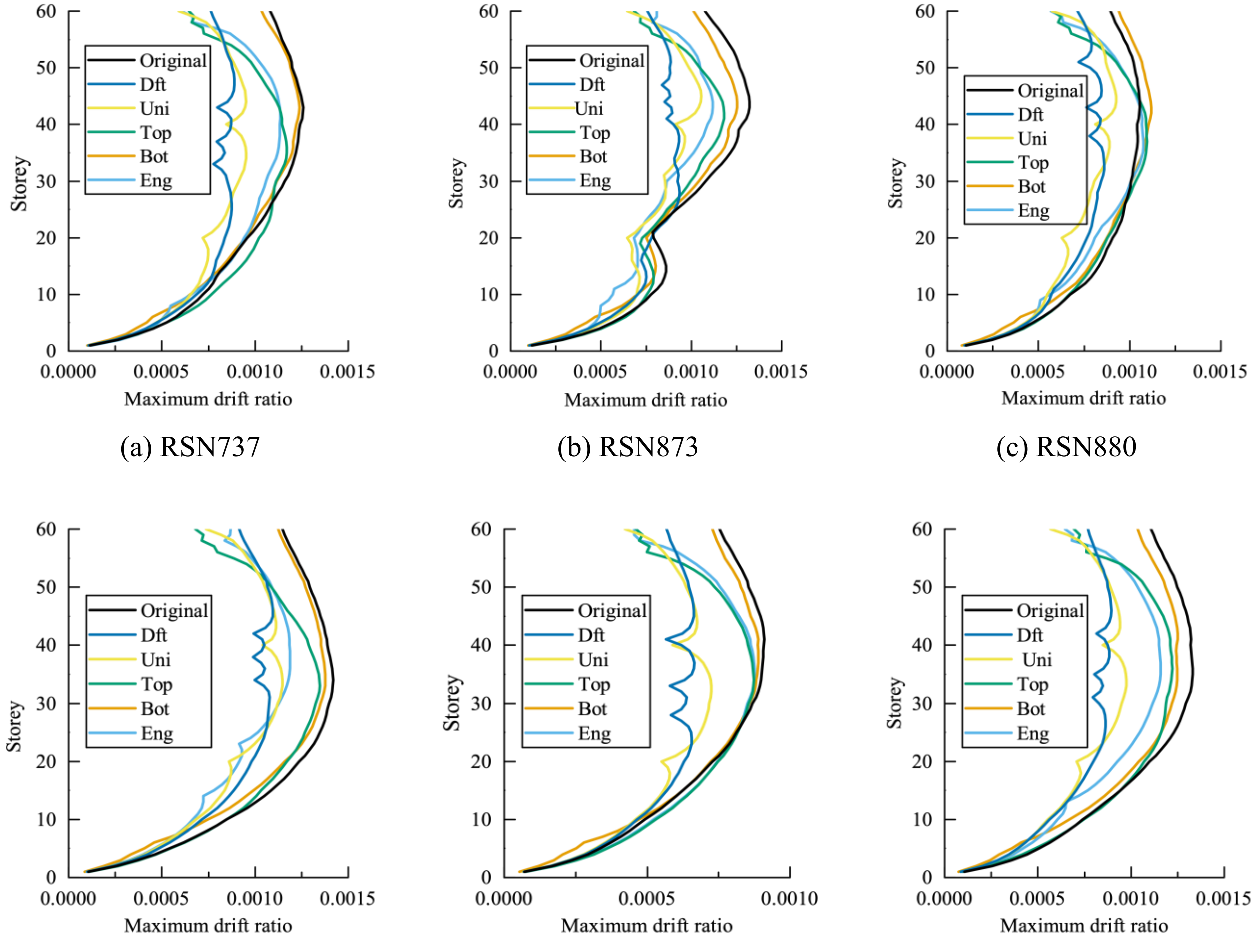
(a) RSN737 (b) RSN873 (c) RSN880



(d) CHB026 (e) CHB028 (f) CHBH10

Figure 6. Comparisons of energy dissipation with respect to damper placements. Note that values of hysteretic energy in column represent ratios relative to the original structure.

5.2.2 Drift ratio



(a) RSN737 (b) RSN873 (c) RSN880

(b) CHB026 (d) CHB028 (f) CHBH10

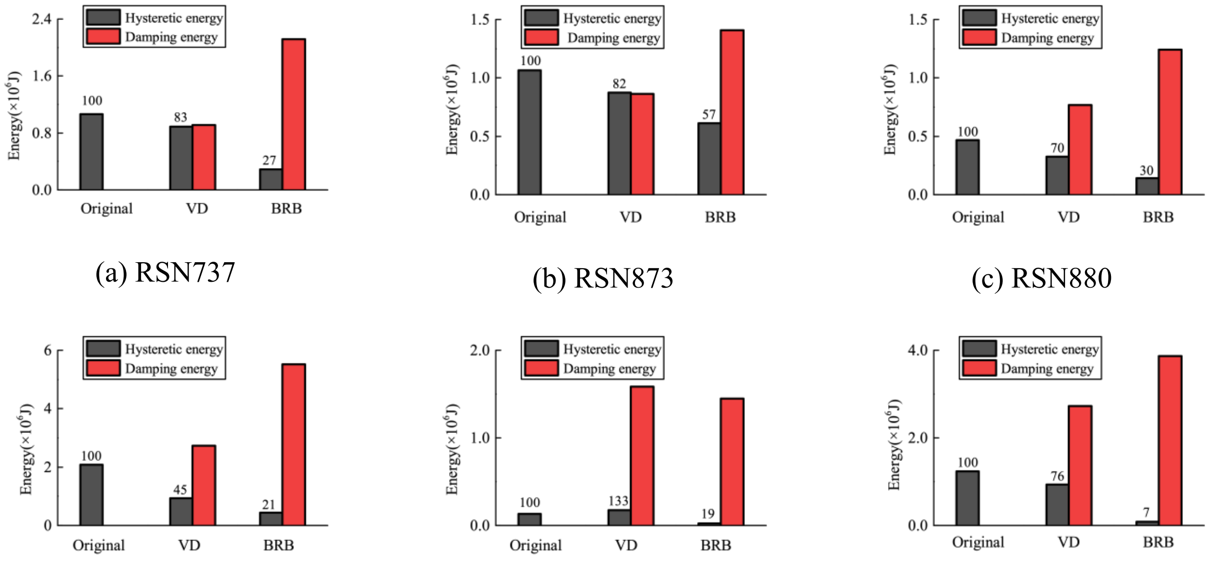
Figure7. Variations of the drift ratios with respect to the ground motions

Correspondingly, maximum drift ratios regarding the placement methods are presented in figure 7 with respect to the ground motions. Significant response reductions by means of BRB are found in uniform and drift-based methods. However, there are some slight deviations in comparison with the results for hysteretic energy mentioned above, as the effectiveness evaluated by hysteretic energy is not as same performance as that by drift ratios. Meanwhile, the maximum drift ratios for the structure with either uniform or drift-based method are reduced to the values less than 1/800, which is the upper bound for the drift ratio by compulsory requirement from Chinese seismic code, while the results for other methods are greater than 1/1000.

5.3 Suggestion for favorable placement scheme

According to the results mentioned above, both the uniform and drift-based schemes are most effective to reduce responses among other methods. However, the results of the latter method vary from the ground motions. Thus, the uniform method is employed in followings to investigate the performance of energy dissipation in two types of the dampers. It is found from figure 8 that the BRBs generally tend to dissipate greater energy than the VDs do, and the corresponding hysteretic energy is less than that for original and VD. This suggests that the structure is protected by the BRBs to remain elastic performance.
Furthermore, top displacements of the structure for the two types of the dampers are presented in figure 9, where the records of RSN737 and CHB026 are representatives of the normal and long-period motion, respectively. It is found in the case of the long-period motion that the BRBs reduce top displacements at

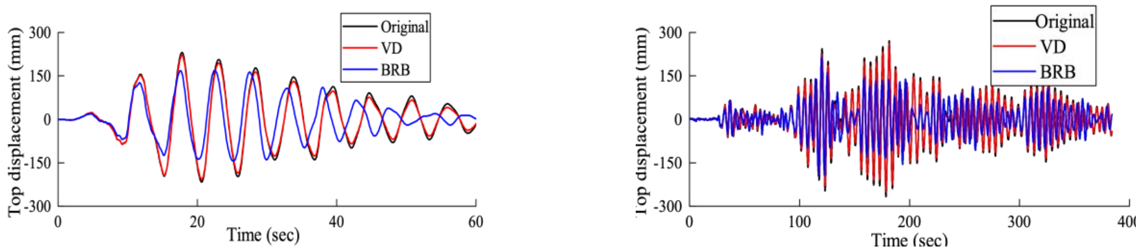
significant extent. In contrast, the VDs present slightly effective to reduce top displacements under the two ground motions. Similarly, it is suggested from figure 10 that the BRBs are more effective than the VDs to reduce the responses in the sense of the maximum drift ratios. The reason for this is that the installment of BRBs increases the lateral stiffness of the structure, and thus the long-period components of the long-period motions exert slight influence on the structure with BRBs.



(a) RSN737 (b) RSN873 (c) RSN880

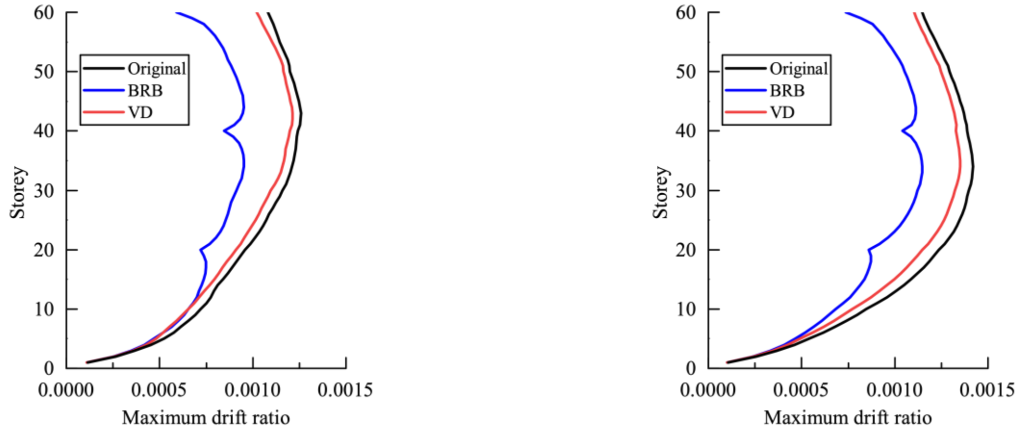
(b) CHB026 (e) CHB028 (f) CHBH10

Figure 8. Variations of the drift ratios with respect to the ground motions



(a) RSN737 (b) CHB026

Figure 9. Time history for top displacement



(a) RSN737 (b) CHB026

Figure.10 Variations of maximum drift ratios in terms of damper placement

6. Conclusions

The paper presents a case study to investigate the effectiveness of the damper placements in reducing responses with respect to normal and long-period ground motions. The drift-based and uniform methods are preferable to reduce the responses in the sense of drifts and hysteretic energy. Furthermore, comparing effectiveness of the BRBs with that of VDs suggests that the preferable damper placement for the BRBs is effective to reduce the responses to make the structure stay elastic performance under different types of the ground motions. Because of these, it is suggested that the utility of the placement schemes for the high-rise structure on the basis of excitations from the normal motions is applicable to that in the case of the long-period motions.

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8. Copyrights

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