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Seismic Performance of Core-outrigger Structure with Fuses

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Biography

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Abstract

Core-outrigger structure system (COS) has been widely used in high-rise buildings. Perimeter frame columns connected to the core tube by the outrigger will take part in bearing the bending moment, and thus the lateral resistant stiffness of the structure will be remarkably increased. However, the outrigger will also lead to sudden changes in lateral resistant stiffness and internal force, which could cause severe damage in adjacent floors.

In this paper, a newly-conceived energy dissipation system for the core-outrigger structure system is investigated. Buckling-restrained column (BRC) is equipped between the outrigger and perimeter frame columns. In this system, BRC acts as structural fuse to protect primary structure and its plastic large deformation dissipates earthquake input energy and allows the uplift of exterior end of the outrigger.

The effectiveness of core-outrigger structure with fuses (COSF) is evaluated through the elasto-plastic time history analysis and seismic energy response analysis by means of case study. In comparison with original core-outrigger structure (COS), COSF is shown to be able to reduce energy dissipation in the primary structure.

Keywords: Core-outrigger structure (COS); buckling-restrained column (BRC); fuse;
elasto-plastic time history analysis; seismic energy response analysis

Introduction

The core-outrigger system (COS) is regarded as one of the most effective ways for increasing structural stiffness and has been widely used in tall building structures. An outrigger is a stiff beam or truss that connects the shear walls to exterior columns. When the structure is subjected to lateral forces, the outrigger and the columns resist the rotation of the core and thus significantly reduce the lateral deflection. However, the large stiffness of the outrigger can lead to large forces capable of damaging the outrigger, the columns, the core or connections. Structural fuses can be used to reduce such damage by getting yielded before major structural members.

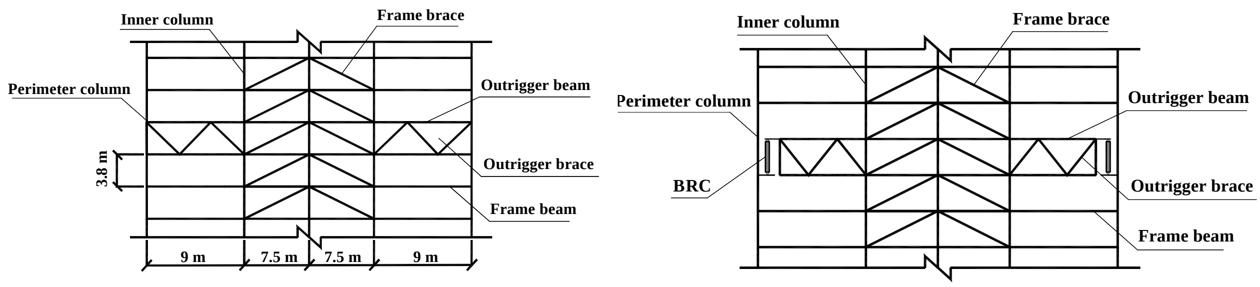
Outrigger damping was developed by Arup and incorporated in the design of the St. Francis Shangri-La Place development in Manila, Philippines (Smith & Willford 2008). The geometric leverage offered by outriggers can also be used to drive supplementary mechanical damping devices: large relative movements between outrigger tips and perimeter columns can efficiently drive relatively compact dampers bridging between them. Inspired by this design, this paper will investigate seismic performance of a similar design with buckling-restrained column (BRC) acting as structural fuse in place of viscous damper in Arup's design. More specifically, BRC is placed between the outrigger and perimeter frame columns. The effectiveness of core-outrigger structure with BRC (BRC-COS) is evaluated through the elasto-plastic time history analysis and seismic energy response analysis on a model building subjected to earthquake records.

Model Description

A residential tower with 39 stories and a total height of 148 meters is adopted as the model building in this study. An outrigger truss is located at the 19th mechanical floor. The information of the structural members is listed in Table 1. In favor of comparison, a pair of 2D models is adopted, as shown in Figure 1. The only difference of the BRC-COS model from the COS model is that two addition BRCs are equipped between the outrigger and perimeter columns. The yield capacity and axial stiffness of each BRC is 2000kN and 447928kN/m, respectively. The post-yield stiffness ratio of the BRC yield is defined as 0.02. The damping ratio of the structure is 0.02 and the total mass of structure is 7.17e6 kg. The modal information of BRC-COS and COS is listed in Table 2.

Table 1. The dimensions of the structural members

Frame member	Dimensions (mm)	Material
Perimeter column	□ 1500×1500×200	Q345
Inner column	□ 800×700×35×25	Q345
Frame beam	H 600×500×8×12	Q345
Outrigger beam	H 1000×800×18×22	Q345
Outrigger brace	H 600×400×12×12	Q235
Frame brace	H 400×300×8×12	Q235



(a) COS (b) BRC-COS

Figure 1. Simplified 2D models

Table 2. The modal information of BRC-COS and COS

	Period (s)		Modal participation mass ratio	
Mode	BRC-COS	COS	BRC-COS	COS
1st (T_1)	3.456	3.258	76.3%	78.7%
2nd (T_2)	1.108	1.118	12.9%	10.3%
3rd (T_3)	0.547	0.551	4.2%	4.5%
4th (T_4)	0.370	0.376	2.2%	2.1%
5th (T_5)	0.262	.0.230	1.4%	1.5%

Ground Motions and Elastic Response History Analysis on BRC-COS

A group of 12 ground motions listed in Table 3 was selected for response history analysis (RHA). For each site class defined in China Code for Seismic Design of Buildings GB50011-2010, 3 ground motions were chosen. The important characteristics of earthquake ground motion include its intensity (e.g., peak ground acceleration, PGA), duration of strong shaking (e.g., significant duration), and frequency content (e.g., site character period (T_g)).The range of characteristic period of each site class was listed in Table 3. In order to characterize frequency content accurately, some more representative period parameters have been proposed in literature. Among others, the mostly recognised one is mean period (T_m), which averages periods in the Fourier spectrum as follows,

$$T_m = \frac{\sum_i C_i^2 \cdot \left(\frac{1}{f_i}\right)}{\sum_i C_i^2} , \qquad (1)$$

where C_i = Fourier amplitudes of the entire accelerogram; and f_i = discrete Fourier transform frequencies between 0.25 and 20 Hz. The T_m of each ground motions is also list in Table 3.

Table 3. Information of ground motions

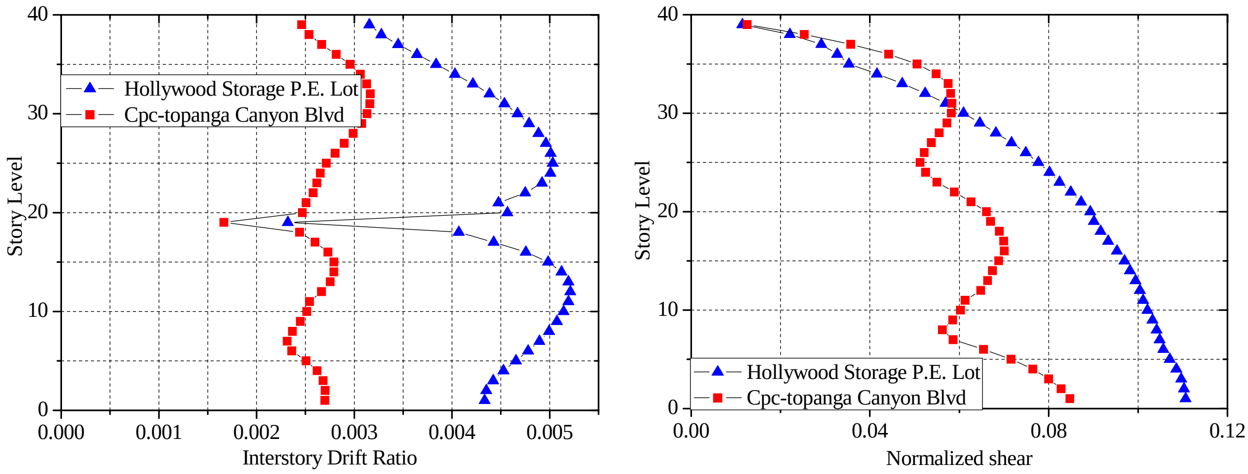
No.	Ground motion	Site class	T_g (s)	T_m (s)
1	Fsd-santa Felicia Dam	1	0.25~0.35	0.29
2	Cpm-cape Mendocino	1	0.25~0.35	0.37
3	Sup-superstition Mountain	1	0.25~0.35	0.32
4	El Centro	2	0.35~0.45	0.59
5	Tar-tarzana-cedar Hill Nursery	2	0.35~0.45	0.30
6	Thangshan_Beijing	2	0.35~0.45	0.72
7	Cpc-topanga Canyon Blvd	3	0.45~0.65	0.70
8	Emc-fairvie Wave	3	0.45~0.65	0.43
9	Hollywood Storage P.E. Lot	3	0.45~0.65	0.68
10	Shanghai03	4	0.65~0.90	1.09
11	Shanghai01	4	0.65~0.90	1.36
12	Tri-treasure Island_90	4	0.65~0.90	1.15

As seismic response of structures varies largely with different ground motions, elastic analysis is performed in advance to explore the response features of the selected ground motions. The maximum interstory drift ratio, base shear and earthquake input energy of elastic BRC-COS model under each ground motion with the same PGA of 220gal are listed in Table 4. In general, the responses tend to be higher corresponding to higher T_m, which is closer to the fundamental period, T_1. However, there is large disperse in this trend. Even for those with close T_m, the responses vary dramatically, e.g. the responses under Hollywood Storage P.E. Lot (T_m = 0.68s) and Cpc-topanga Canyon Blvd (T_m = 0.70s) as shown in Fig. 3. It can be seen that higher mode contribution in the latter case is especially significant, although the participation mass ratio of the first mode of BRC-COS is 76.3%, much higher than those of higher modes.

The Fourier, velocity, absolute acceleration and equivalent velocity amplitude spectra of the above two ground motions are compared in Figure 4, indicating that the equivalent velocity amplitude spectrum could be the most promising indicator among others, for the higher mode contributions.

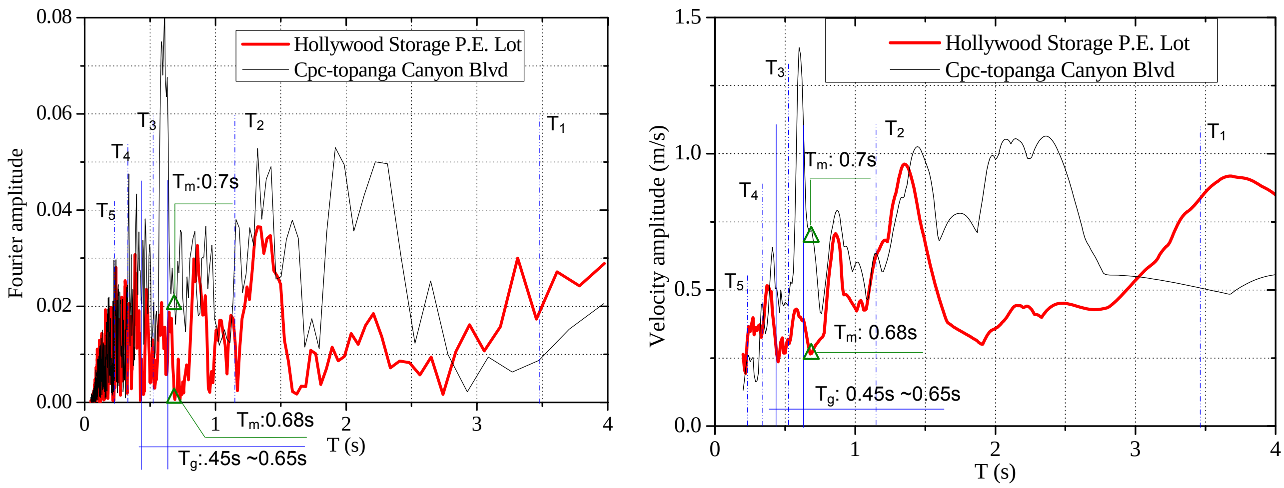
Table 4. The maximum interstory drift ratio, base shear, input energy of elastic BRC-COS model

No. of ground motion	Maximum interstory drift ratio	Base shear (kN)	Input energy (kN.m)
1	1/1182	1593	85
2	1/1086	1727	91
3	1/826	2646	149
4	1/338	5287	750
5	1/1584	1896	70
6	1/326	5802	1042
7	1/316	5962	862
8	1/487	3675	290
9	1/191	7786	2910
10	1/165	10497	6871
11	1/156	10071	3184
12	1/246	4760	1635

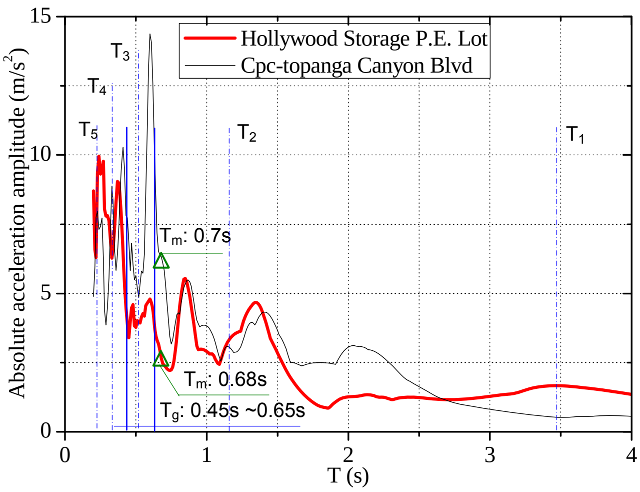


(a) Comparison of interstory drift angle (b) Comparison of normalized shear

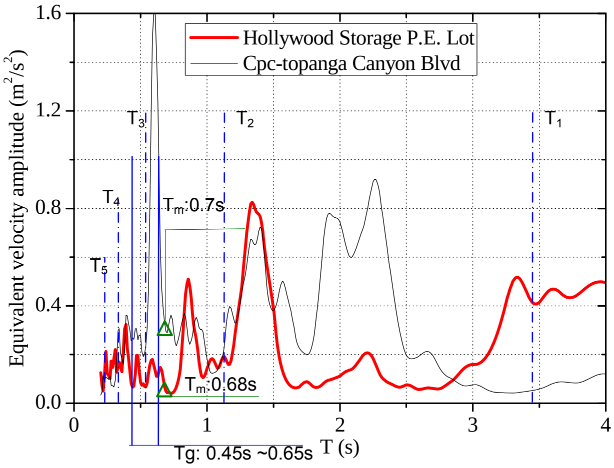
Figure 3. Comparison of interstory drift angle and normalized shear for elastic BRC-COS subjected to Hollywood Storage P.E. Lot and Cpc-topanga Canyon Blvd with PGA of 220gal



(a) Fourier amplitude spectrum (b) Velocity amplitude spectrum



(c) Absolute acceleration amplitude spectrum



(d) Equivalent velocity amplitude spectrum

Figure 4. Comparison of Fourier, velocity, absolute acceleration and equivalent velocity amplitude spectra of Hollywood Storage P.E. Lot and Cpc-topanga Canyon Blvd with PGA of 220gal

The Effectiveness of Structural Fuse

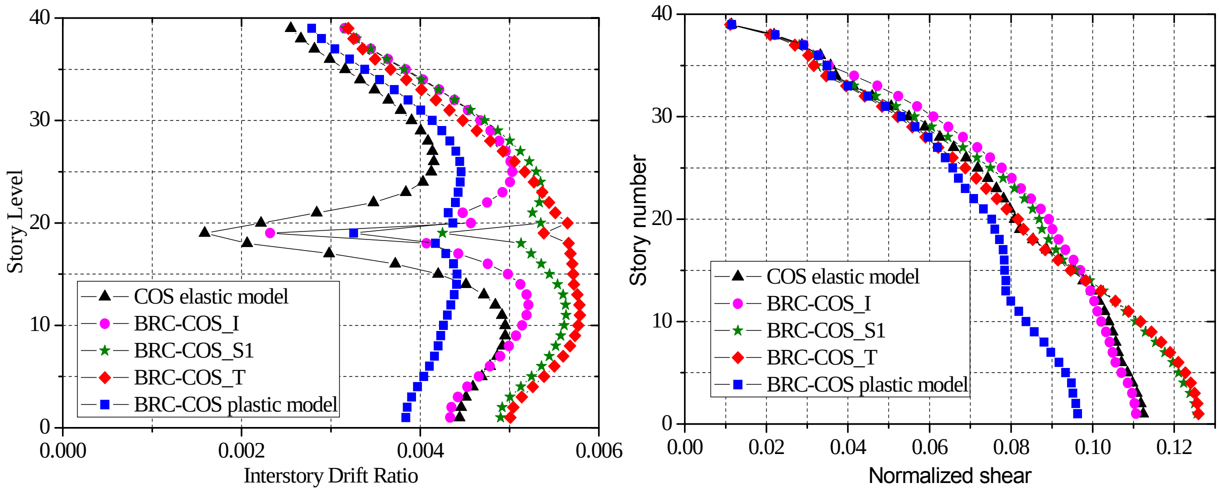
In order to focus on the contribution of structural fuse, only is the material nonlinearity of BRC considered in RHA in this section. In addition to elastic COS model and elasto-plastic BRC-COS model, 4 additional elastic BRC-COS models are analyzed for reference. The only variation among the four models is the assigned BRC axial stiffness, as listed in Table 5, in which their fundamental periods are also compared, showing minor differences.

Interstory drift ratio, normalized shear with respect to self weight and equivalent velocity of seismic input energy of the structure under Hollywood Storage P.E. Lot and Cpc-topanga Canyon Blvd are compared in Figures 5~7. It needs to be mentioned that the nonlinear response of the BRC in the BRC-COS plastic model provides the ductility used to assign secant stiffness of BRC in BRC-COS_S1 or BRC-COS_S2 as listed in Table 5, for the case of Hollywood Storage P.E. Lot or Cpc-topanga Canyon Blvd, respectively. The following comparisons are noteworthy:

1) COS vs. BRC-COS_I: the structural fuse reduces significantly the sharp change of height-wise lateral stiffness distribution due to the outrigger.
2) BRC-COS_I, BRC-COS_S1/BRC-COS_S2 vs. BRC-COS_T: the stiffness change of BRC could lead to increase of interstory drift and story shear.
3) BRC-COS_I vs BRC-COS plastic model: the energy dissipation of BRC reduces significantly the response under Hollywood Storage P.E. Lot while the reduction under Cpc-topanga Canyon Blvd is negligible, as the energy dissipated is limited and the contribution of higher modes is less affected by BRC; with the energy dissipation of BRC, the seismic energy input can be a little bit higher.

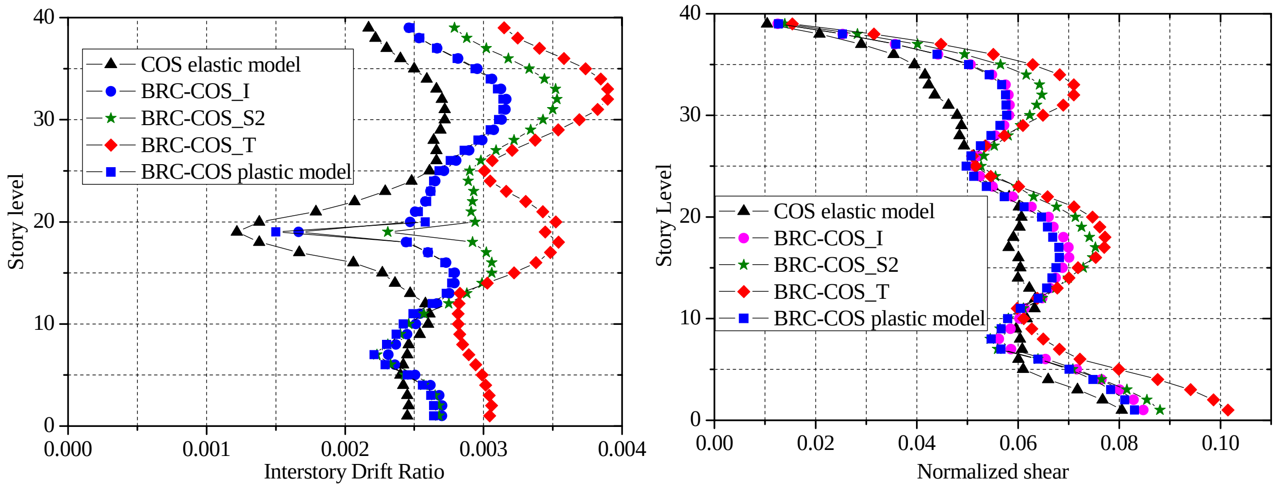
Table 5. Elastic Reference BRC-COS Models

Model Description		Fundamental period (s)
BRC-COS_I:	with BRC in initial stiffness	3.456s
BRC-COS_S1:	with BRC in secant stiffness corresponding to its ductility μ=10.5	3.621s
BRC-COS_S2:	with BRC in secant stiffness corresponding to its ductility μ= 4.6	3.548s
BRC-COS_T:	with BRC in tangent post-yield stiffness	3.726s



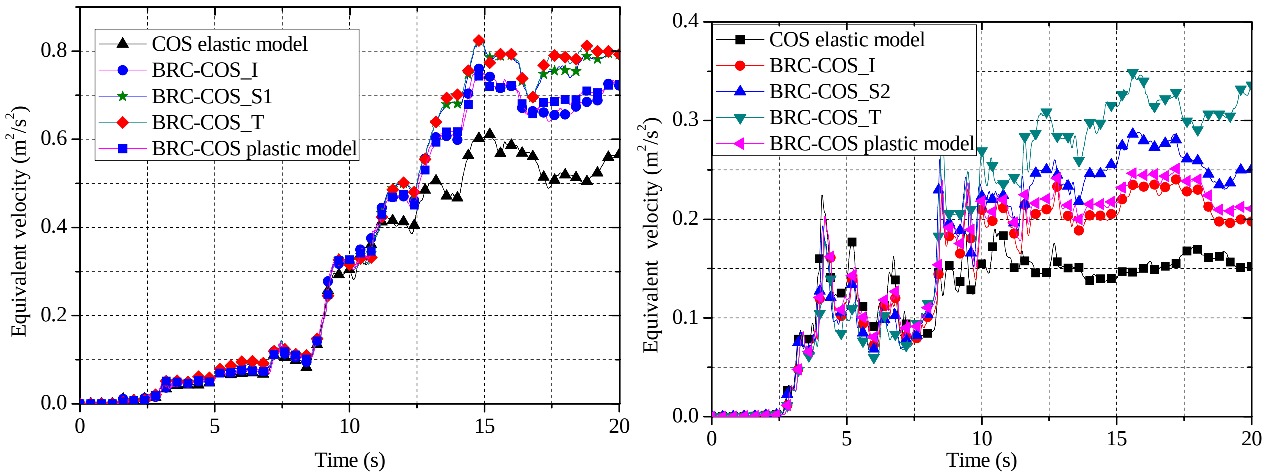
(a) Interstory drift ratio (b) Normalized shear

Figure 5. Comparison of responses under Hollywood Storage P.E. Lot with PGA of 220gal



(a) Interstory drift ratio (b) Normalized shear

Figure 6. Comparison of responses under Cpc-topanga Canyon Blvd with PGA of 220gal



(a) Hollywood Storage P.E. Lot (b) Cpc-topanga Canyon Blvd

Figure 7. Comparison of equivalent velocity time histories with PGA of 220gal

Protection Effect of Structural Fuse

The key idea of structural fuse is to protect primary structure against significant damage. In this section, material nonlinearity of each member is considered to examine the above issue. The time histories of equivalent velocity of seismic input energy are plotted in Figure 8, corresponding to COS plastic model and BRC-COS counterpart subjected to the ground motion of Hollywood Storage P.E. Lot with PGA of 400gal. It can be seen that the total seismic input energy of BRC-COS is less than that of COS, while the inelastic energy dissipated by the primary structure in BRC-COS is much less than the case in COS. Similar phenomena can be observed with other ground motions, as listed in Table 6. This proves the contribution of structural fuse to protecting primary structure from severe damage.

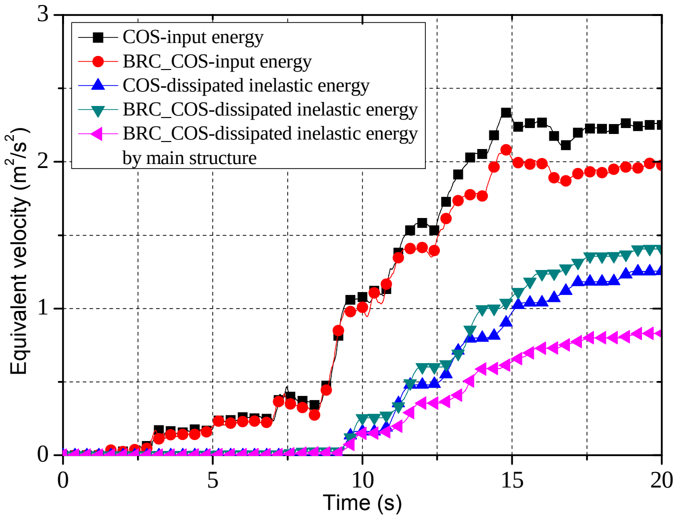


Figure 8. Comparison of equivalent velocity with COS plastic model and BRC-COS plastic model under Hollywood Storage P.E. Lot with PGA of 400gal

Table 6. Dissipated inelastic energy by COS or BRC-COS under ground motions with PGA of 400gal

No. of Ground motion	Dissipated inelastic energy in COS (kN . m)	Inelastic energy dissipated by BRC (kN . m)	Reduction percentage of dissipated inelastic energy[2]	Reduction percentage of base shear[3]
1	------	------	------	------
2	------	------	------	------
3	------	26	------	1%
4	390	331	89%	6%
5	------	------	------	------
6	612	520	88%	5%
7	314	911	75%	3%
8	------	88	------	------
9	4499	2068	34%	16%
10	6944	2170	42%	15%
11	5184	1396	11%	4%
12	1357	1048	57%	16%

Note: 1. ------ means that the structure remains in elastic range.
2. Reduction percentage of dissipated inelastic energy = 1 - Inelastic energy dissipated by main structure of BRC-COS / Dissipated inelastic energy of COS.
3. Reduction percentage of base shear = (Base shear of COS − Base shear of BRC-COS) / Base shear of COS.

Conclusions

1. Although the mean period T_m is reported in literature to be most promising parameter to characterize the frequency content of an input ground motion, it is not able to recognize the contribution of higher mode, which is indicated by the equivalent velocity amplitude spectrum.
2. Apart from the effect of stiffness change, the BRC is evidenced to be capable of reducing significantly seismic response of the COS.
3. The BRC is shown to successfully act as a structural fuse, in the sense that it can reduce both total seismic input energy and inelastic energy dissipated by primary structure and hence protect primary structure from severe damage.

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