Study on A Novel Sacrificial-Energy Dissipation Outrigger

Xinzheng Lu
Professor, Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Tsinghua University, Beijing, China

Wenjie Liao
Graduate Student, Beijing Engineering Research Center of Steel and Concrete Composite Structures, Tsinghua University, Beijing, China

Qing Jiang
Associate Professor, School of Civil Engineering, Hefei University of Technology, Hefei, China

Yaning Zhu
Graduate Student, School of Civil Engineering, Hefei University of Technology, Hefei, China

Qingshun Yang
Assistant Professor, School of civil engineering, Qinghai University, Xining, China

ABSTRACT: The frame-core tube-outrigger structural system is widely used in tall buildings, in which outriggers coordinate the deformation between the core tube and the moment frame, leading to a larger structural lateral stiffness. Existing studies indicate that outriggers can be designed as a "fuse" of tall buildings through dissipating seismic energy after yielding, to protect the main structure. Under the action of the maximum considered earthquake (MCE), it is found that the hardening effect of BRB outriggers will increase the percentage of the inelastic energy dissipation of the other structural components. Meanwhile, due to the local buckling-induced severe deterioration and damage of conventional outriggers, conventional outriggers are difficult to repair after an earthquake. To overcome these problems, this study proposes a novel sacrificial-energy dissipation outrigger (SEDO) to improve the seismic resilience of tall buildings. The inclined braces of this novel SEDO are composed of a sacrificial part and an energy dissipation part. Therefore, it remains elastic under the design-based earthquake (DBE) and dissipates inelastic energy under the MCE. Moreover, the detailing of this novel SEDO are proposed based on experimental studies. The optimum strength ratio between the sacrificial part and the energy dissipation part is determined as 6:4 based on nonlinear time-history analyses (THAs). Afterwards, SEDOs are used in a tall building to verify its seismic performance through nonlinear THAs. Consequently, this study indicates that the novel SEDO is able to protect the other structural components and effectively improve the seismic resilience of tall buildings.

1. INTRODUCTION

Since 2000, the number of super-tall buildings has grown rapidly around the world, leading to the development of different kinds of novel structural systems. Among these, the frame-core tube-outrigger structural system is widely used (Ding et al., 2014). Outriggers play an essential role in such a structural system, and many studies have been performed on the outriggers, such as the working mechanism (Moudarres, 1984; Wu et al., 2003) and the location optimization of outriggers (Hoenderkamp, 2008; Balling & Lee, 2015). The seismic performance of outriggers was experimentally studied and the corresponding finite element (FE) model was validated with the test results (Nie & Ding, 2013; Yang et al., 2016). In addition, the damped outrigger system has

achieved significant progress in recent years (Smith & Willford, 2010; Zhou et al., 2017).

Existing studies identified that when a tall building is subjected to the action of a service level earthquake (SLE, i.e., 63% probability of exceedance in 50 years) or the action of a design-based earthquake (DBE, i.e., 10% probability of exceedance in 50 years), the outrigger should remain elastic to reduce the structural deformation and control the damage to the structural and nonstructural components. By contrast, when a tall building is subjected to the action of maximum considered earthquake (MCE, i.e., 2% probability of exceedance in 50 years), Soong et al. (2002) proposed that energy dissipation devices should be designed to reduce the MCE response. To date, many energy dissipating components (such as buckling restrained braces (BRBs) and coupling beams) have been proposed (Yang et al., 2016; Ji et al., 2017). Lu et al. (2014 & 2016) identified that the outriggers can play the role of the main energy dissipating components based on a number of nonlinear time-history analyses (THAs) of two super-tall buildings. Moehle (2015) pointed out that outriggers can be designed as a "fuse" to dissipate energy and protect other components from damage. Thus, after an optimized design, the outriggers can remain elastic under SLE and DBE actions and enter an inelastic state under MCE actions as a fuse for seismic energy dissipation.

Yang et al. (2016) performed experimental and numerical studies on energy-dissipating outriggers. Their research identified that, due to the global buckling of the inclined braces and the local buckling of the chords, conventional outriggers (COs) have limited deformation and energy-dissipating capacities. Furthermore, COs are difficult to repair after earthquakes and lack resilience. By contrast, if the chords of the outriggers are constructed of high-strength steel, the elastic deformation capacities of the chords are increased significantly. Meanwhile, if the braces are constructed with BRBs, the brace will be free from global buckling and its energy dissipation capacity is significantly increased. However, Zhu (2018) identified that, because of the hardening behavior of the BRB after yielding, the internal force on the BRB outriggers (BOs) subjected to the MCE will be significantly larger than their yield strength, resulting in more severe damage in the other key components of the tall building (e.g., the shear walls and the moment frames). Such behavior will prevent the outrigger from serving as a fuse and reduce the structural resilience.

As a consequence, this study proposes a novel sacrificial-energy dissipating outrigger (SEDO). This type of novel outrigger can remain in the elastic state under SLE and DBE actions, controlling the structural deformation efficiently. Furthermore, the SEDO can prevent damage to other components through an innovative sacrificial mechanism under MCE actions. Since no previous studies have been performed on this novel SEDO, this study proposed the detailing of the SEDO based on experimental studies. The optimum strength ratio between the sacrificial and the energy dissipation parts has been determined through numerical analysis and parametric discussion. Then, SEDOs are used in a tall building to verify their seismic performance through nonlinear THAs. The results indicate that after the adoption of the proposed SEDOs, the inelastic energy dissipation of the outriggers increases significantly while those of the shear walls and other structural components decreases. Therefore, the SEDO is able to protect the other structural components and effectively improve the seismic resilience of tall buildings.

2. THE PRINCIPLE CONCEPT OF THE SEDO

As studies results abovementioned indicate, an ideal outrigger should be equipped with the following properties under the MCE action, including:

(1) The inelastic energy should be dissipated in the braces that are easy to replace after an earthquake, and the chords that are difficult to repair should remain elastic.

(2) The hardening effect of the braces after yielding should be avoided to protect the other

components (e.g., the shear walls and the moment frames).

(3) The outrigger should have sufficient and stable strength and ductility when subjected to significant inelastic deformation.

Based on above demands, a novel outrigger, the sacrificial-energy dissipating outrigger (SEDO), is proposed herein. The schematic drawing of a SEDO is shown in Figure 1.

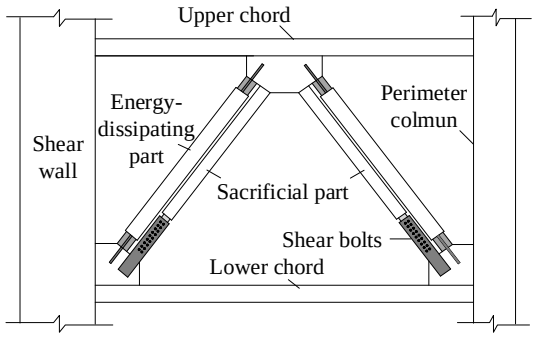
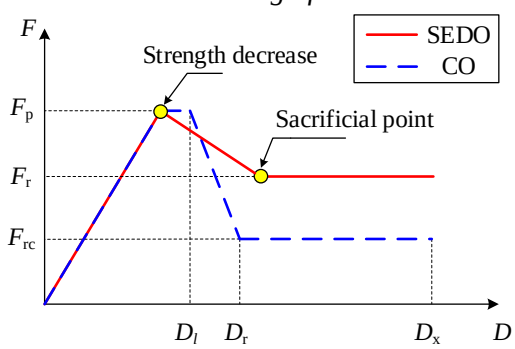


Figure 1: Schematic drawing of a SEDO



F_r: Residual strength of SEDO

F_{rc}: Residual strength of CO

D_l: Deformation of strength loss

D_r: Deformation of residual strength

D_x: Ultimate deformation

Figure 2: Force-deformation backbone models of the braces in SEDO and CO

High strength steel is used in the chord of a SEDO, to avoid inelastic deformation and the corresponding repairs after an MCE action. In addition, the braces of a SEDO are composed of a sacrificial part and an energy-dissipating part. Under the SLE and DBE actions, the sacrificial and energy-dissipating parts resist the seismic loads together. However, under the MCE action, the sacrificial part will break and be out of service. Meanwhile, the energy-dissipating part yields and constantly bears the seismic load, dissipating the seismic energy (Figure 2). Therefore, the SEDO achieves the performance objective of remaining in the elastic state under the DBE action, and dissipating energy as a fuse under the MCE action.

3. OPTIMUM STRENGTH RATIO OF THE SACRIFICIAL PART TO THE ENERGY-DISSIPATING PART

Under the MCE action, the sacrificial part of a SEDO will break. Meanwhile, the energy-dissipating part constantly withstands loads. Therefore, the energy-dissipating performance of a SEDO is mainly determined by the strength of the energy-dissipating part. To make full use of the energy-dissipating capacity of a SEDO, the strength ratio of the sacrificial part to the energy-dissipating part should be optimized, which is defined as the optimum ratio. Referring to the relationship of the strengths showed in Figure 2, the total strength of the sacrificial part and the energy-dissipating part is defined as F_p (i.e., peak strength), and the strength of the energy-dissipating part is defined as F_r (i.e., residual strength). Hence, the strength of the sacrificial part is defined as $F_s = F_p - F_r$. The strength ratio is F_s/F_r. In this work, the optimum F_s/F_r ratio is determined through the nonlinear THAs of a typical tall building designed by Zhu (2018). The details of this tall building are given in Section 3.1.

3.1. Introduction of the typical tall building

This typical tall frame-core tube-outrigger building is designed following the Technical Specification for Concrete Structures of Tall Building JGJ3-2010 (2010) and the Code for Seismic Design of Buildings GB50011-2010 (2010). The structure is composed of steel reinforced concrete (SRC) perimeter columns, a reinforced concrete core tube, and outriggers between the core tube and the perimeter columns. The tall building has an 8.5-degree seismic design intensity. The peak ground accelerations (PGAs) of the DBE and the MCE are equal to 300 cm/s^2 and 510 cm/s^2, respectively (GB50011-2010 (2010)). The elevation of this building is shown in Figure 3, and the total height is 206.3 m. In addition, outriggers are arranged on the 29th and

55th stories, whose heights are equal to the story height. The planar section of the building is square and biaxially symmetrical. And the layout of the outrigger story is shown in Figure 4.

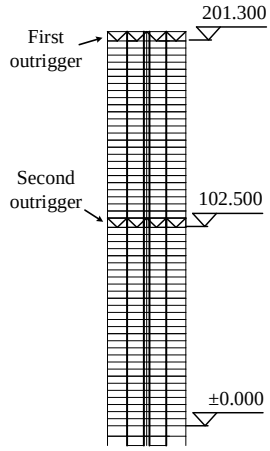


Figure 3: Elevation of the tall building (unit: m)

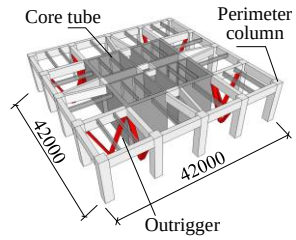
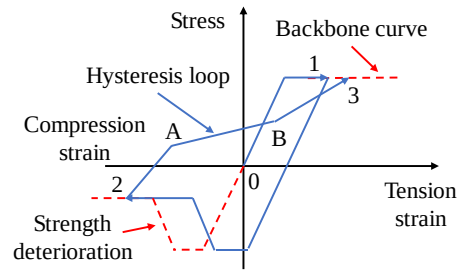


Figure 4: Layout of outriggers (unit: mm)

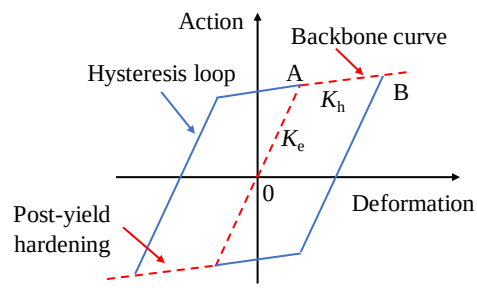
3.2. FE model

The nonlinear FE model of this tall building is established using the Perform-3D software, which is widely used for the nonlinear analysis of buildings under seismic action (Poon et al., 2011). The lumped hinge model is adopted to model the frame beams, and the lumped hinge model at the element ends and the shear hinge model in the middle are adopted to model the coupling beams. The plastic zone model with fiber section segments is used for the SRC perimeter columns. The multiple-vertical-line-element model is applied to the shear walls (CSI, 2006). Note that the confinement effect of the concrete is considered with the Mander et al. (1988)'s model. In addition, the parameters of the action-deformation hysteretic curves of the aforementioned models are determined based on the actual structural design and the default values in Perform-3D.

Furthermore, the fiber model is adopted to model the braces of the conventional outriggers, with the stress-strain relation considering buckling-induced deterioration shown in Figure 5a. Since no buckling occurs in the BRBs, the truss elements with post-yield hardening behavior shown in Figure 5b (CSI, 2006) are adopted to model the BRBs. The yield strengths of the braces of the conventional outriggers and the BRB outriggers are determined based on the sectional strength. The relation between the yield strength and the buckling behavior of the conventional outriggers, as well as the post-yield hardening behavior of the BRB outriggers, is determined following the experimental results of Yang et al. (2016). Moreover, classical Rayleigh damping with a damping ratio of 5% is adopted in the analyses (GB 50010-2010).



(a) Typical buckling component



(b) Typical BRB component

Figure 5 Backbone curve and hysteresis loop of the brace in the conventional outrigger and the BRB outrigger

3.3. Determination of the optimum F_s/F_r ratio

The peak strength of an outrigger (F_p) is equal to the DBE level seismic force, to keep the outrigger elastic and control the structural deformation under the SLE and the DBE actions. To find the optimum F_s/F_r ratio, nine SEDOs with nine F_s/F_r ratios, namely, F_s/F_r = 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8, and 1:9 were designed. Seven ground motions were selected from the PEER Ground Motion Database (2013), following the specification of ground motion selection in the Code for Seismic Design of Buildings GB50011-2010 (2010). The ground motions were scaled to the MCE level (i.e., PGA = 510 cm/s^2). Nonlinear THAs of the buildings with different SEDOs were

performed using the seven selected ground motions.

The inelastic energy dissipated by the SEDOs subjected to ground motion *i* is defined as $E_{SEDO,\ i}$. Subjected to different ground motions, the values of $E_{SEDO,\ i}/E_{p,\ i}$ with different F_s/F_r ratios are compared, as shown in Figure 6. It can be seen that different ground motions have different optimum F_s/F_r ratios. However, most of the optimum F_s/F_r ratios approach 6:4. Consequently, 6:4 is defined as the optimum F_s/F_r ratio herein, and the experimental study in Section 4 is based on this value.

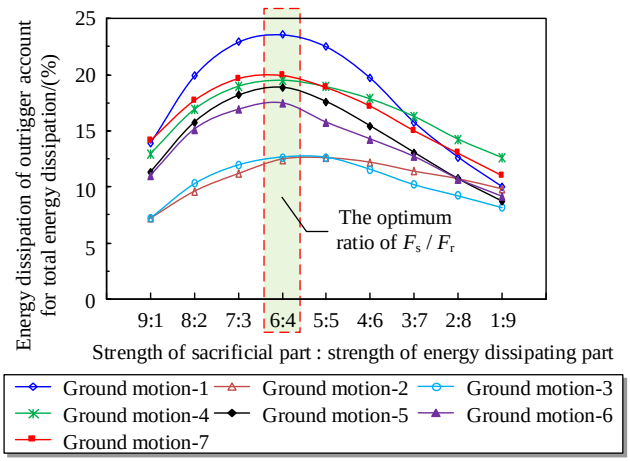


Figure 6: Ratios of the energy dissipation of outriggers to the total inelastic energy dissipation with different F_s/F_r

4. EXPERIMENTAL STUDY AND THE FE MODELING OF THE BRACES OF SEDO

4.1. Experimental study of the braces of SEDO

An experimental study was performed to develop the feasible detailing of the brace of SEDO. Figure 7 shows the 3D scheme of the brace of SEDO. To efficiently avoid the eccentric loads after the failure of the sacrificial part, the brace is designed such that the energy-dissipating part is surrounded by the sacrificial part. Consequently, during the loading procedure, the specimen deformation is almost symmetric. The sacrificial part is bolted to the joint plate. Two bolts with a design total shear strength of 606 kN are adopted for the connection. Figure 8a and Figure 8b show the front view and the 1-1 cross section, respectively. Low-cost and easy to fabricate steel plates with a yield strength of 345 MPa are selected to manufacture the sacrificial part. The strength of the steel plates is much larger than that of the bolts. In addition, a BRB with outstanding energy dissipation ability is used in the energy-dissipating part, equipped with type LY225 low-yield steel core. According to the proposed 6:4 optimum F_s/F_r ratio, the maximal strength of the BRB is designed as 400 kN. The installation and the test device are shown in Figure 9.

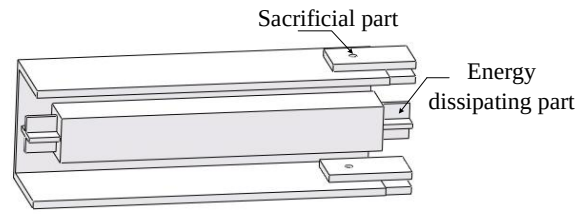
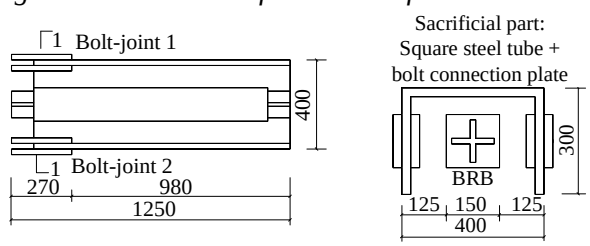


Figure 7: 3D scheme of the brace of SEDO



(a) Front view *(b) 1-1 cross section*

Figure 8: Dimension of the brace of SEDO (Unit: mm)

Figure 9: Test setup

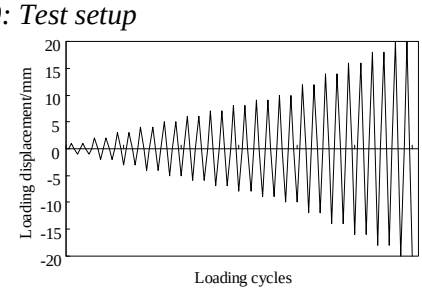
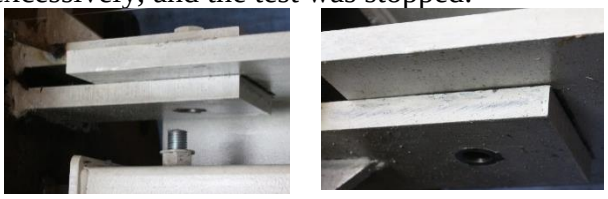


Figure 10: Loading protocol

The test adopted a pseudo-static loading protocol with displacement control. The axial displacement of the energy-dissipating part is selected as the control parameter. And the loading

protocol is shown in Figure 10. When the loading reached the first cycle of the 3 mm loading displacement, the upper bolt in the sacrificial part was broken by the shear force (Figure 11a). When the loading reached the second cycle of the 3 mm loading displacement, the lower bolt in the sacrificial part was broken (Figure 11b). At that time, the sacrificial part no longer contributes to the load bearing. Furthermore, when the loading displacement reached 22 mm, the core region of the energy-dissipating part (i.e., BRB) deformed excessively, and the test was stopped.



(a) Failure mode of the 1st bolt *(b) Failure mode of the 2nd bolt*

Figure 11: Failure mode of the bolted connections

Figure 12 shows the experimental hysteretic curve of the brace of SEDO, in which the positive values present compression. The maximum compressive strength is 789 kN, with a corresponding displacement of 2.45 mm. The maximum tensile strength is -865 kN, with a corresponding displacement of -2.45 mm. After the peak strength, due to the failure of the bolts, the resistance dropped to 402 kN (in compression) and -384 kN (in tension). Consequently, the average resistance of the energy-dissipating part is F_r = 393 kN, while the average resistance of the sacrificial part is F_s = 434 kN. The F_s/F_r ratio is approximately 5.3:4.7, which is close to the optimum F_s/F_r ratio of 6:4.

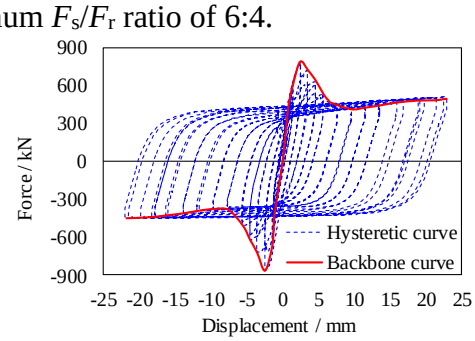


Figure 12: Force-displacement hysteretic curve of the brace of SEDO

4.2. FE modeling of the brace of SEDO

The FE modeling of the brace of SEDO is conducted by using the Perform-3D software. In this study, the fiber model is used for the brace of SEDO, and the material property adopts the predefined buckling material in Perform-3D (Figure 5a) with the addition of strength deterioration in tension (CSI, 2006), leading to strength degradation in both tension and compression (Figure 13). In addition, the parameters of the hysteresis curve are calibrated with the experimental outcomes in Figure 12. Subjected to the same loading procedures, the simulated and experimental hysteretic curves are compared in Figure 14, which shows that the FE model in Perform-3D can accurately represent the behavior of the brace in the SEDO.

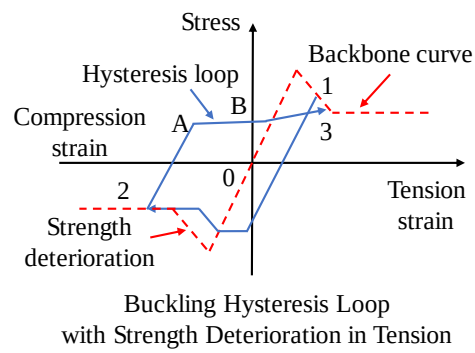


Figure 13: Backbone curve and hysteresis loop of the brace of SEDO

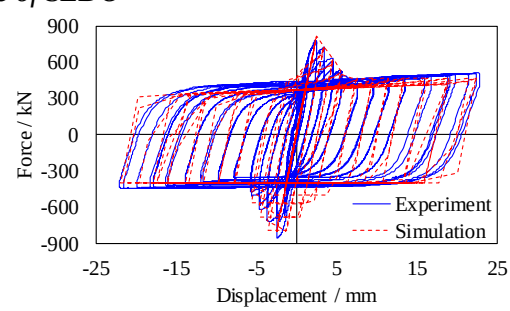


Figure 14: Comparison between the numerical and experimental results of the brace of SEDO

5. PERFORMANCE OF THE SEDO IN THE TYPICAL FRAME-CORE TUBE-OUTRIGGER TALL BUILDING

The computational model of this tall building has been introduced in Section 3.1. The outriggers in this building have three schemes: a conventional

outrigger, a BRB outrigger and a SEDO. The corresponding models are named as the CO model, the BO model and the SEDO model, respectively. The SEDO is modeled following the FE model described in Section 4.2. The braces in the conventional outrigger, the BRB outrigger and the SEDO have the same strength.

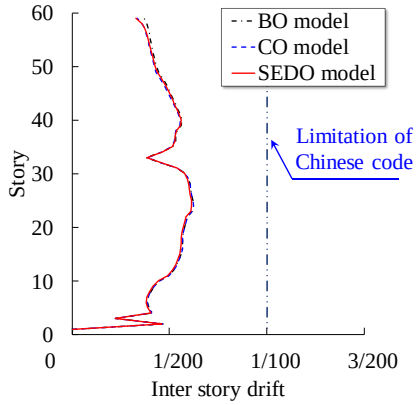


Figure 15: Inter-story drifts of the CO, BO, SEDO models

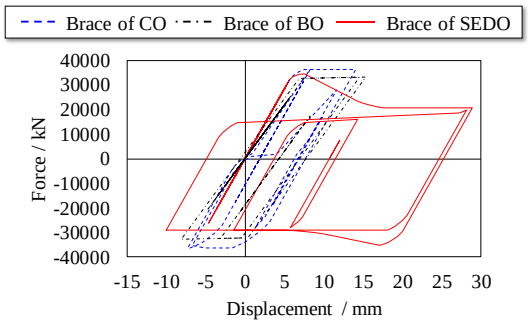


Figure 16: Hysteretic curves of typical braces in the BO, CO, SEDO models

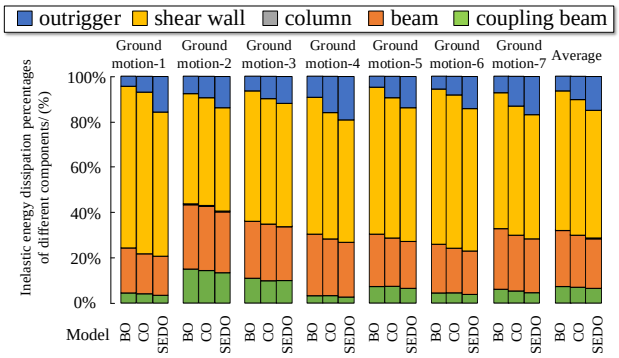


Figure 17: Inelastic energy dissipation percentages of different components

The nonlinear THAs are implemented using the Perform-3D software and the seven ground motions selected in Section 3.3 are inputted into the three FE models. The average envelopes of the maximum inter-story drift of these three models are almost the same (Figure 15). Hence, the SEDO has the same displacement control capacity as the conventional outriggers and the BRB outriggers under the MCE actions. Furthermore, Figure 16 shows the hysteretic curve of the typical outriggers, demonstrating the SEDO dissipates much more energy than the conventional outrigger and the BRB outrigger. Figure 17 shows the energy dissipation percentages of the different components. The outriggers of the SEDO model dissipate more energy than those of the BO and CO models. Meanwhile, the shear walls, beams and columns in the SEDO model dissipates less energy, which means these components are protected due to the fuse function of the outriggers.

To sum up, for this typical frame-core tube-outrigger tall building, the SEDO can efficiently dissipate seismic energy as it designed to do under MCE actions. Meanwhile, the other components can be protected, correspondingly.

6. CONCLUSIONS

In this study, a novel SEDO is proposed. The detailing and the optimum strength ratio of SEDO are studied experimentally and numerically. The performance of SEDO is validated through the nonlinear THA of a tall building. The main conclusions of this work are list as follows:

(1) The brace of the SEDO composes of a sacrificial and an energy-dissipating part. The SEDO will keep elastic under DBE and dissipate energy under MCE. The sacrificial part utilizes the shear failure of the bolts to control the post-yield strength of the brace. The energy dissipating part utilizes the BRB to provide a stable energy dissipation capacity. In addition, the optimum strength ratio of the sacrificial part to the energy-dissipating part is approximately 6 : 4.

(2) The seismic performances of a tall building using conventional outriggers, BRB outriggers and SEDOs are compared through nonlinear THAs. The results show that under MCEs, the energy-dissipating capacity of SEDOs is obviously better than those of COs and BOs. In addition, the inelastic energy dissipated by shear

walls, beams and columns are significantly reduced in the SEDO models, leading to the reduced damage in these components and better resilience.

It should be noted that it is the first time that the conception of SEDO is proposed. Further work is still needed to improve the detailing and design method of SEDO.

7. ACKNOWLEDGEMENT

The authors are grateful for the financial support from the National Natural Science Foundation of China (No. 51778341).

8. REFERENCES

CSI (2006). *Perform components and elements for Perform-3D and Perform-Collapse (version 4)*, Computer and Structures, Berkeley.

Poon, D.C.K., Hsiao, L.E., Zhu, Y., et al. (2011). "Non-linear time history analysis for the performance based design of Shanghai Tower." *Structures Congress*, Las Vegas, Reston, Virginia, ASCE, 541–551.

Ding, J.M., Wu, H.L., Zhao, X. (2014). "Current situation and discussion of structural design for super high-rise buildings above 250 m in China." *Journal of Building Structures*, 35(03), 1–7 (in Chinese).

Moudarres, F.R. (1984). "Outrigger-braced coupled shear walls." *Journal of Structural Engineering*, 110(12), 2876–2890.

GB50011-2010 (2010). *Code for seismic design of buildings*, China Architecture & Building Press, Beijing (in Chinese).

Hoenderkamp, J.C.D. (2008). "Second outrigger at optimum location on high-rise shear wall." *The Structural Design of Tall and Special Buildings*, 17(3), 619–634.

Wu, J.R., Li, Q.S. (2003). "Structural performance of multi-outrigger-braced tall buildings." *The Structural Design of Tall and Special Buildings*, 12(2), 155–176.

JGJ3-2010 (2010). *Technical specification for concrete structures of tall building*, China Architecture & Building Press, Beijing (in Chinese).

Mander, J.B., Priestley, M.J.N., Park, R. (1988). "Theoretical stress-strain model for concrete." *Journal of Structural Engineering*, 114(8), 1804–1825.

Moehle, J. (2015). *Seismic design of reinforced concrete buildings*, McGraw-Hill Education, America, 755–758.

Nie, J.G., Ding, R. (2013). "Experimental research on seismic performance of k-style steel outrigger truss to concrete core tube wall joints." *Structures Congress*, Pittsburgh, Pennsylvania, ASCE, 2802–2813.

PEER Center (2013). *PEER ground motion database*, http://ngawest2.berkeley.edu/.

Yang, Q.S., Lu, X.Z., Yu, C., et al. (2016). "Experimental study and finite element analysis of energy dissipating outriggers." *Advances in Structural Engineering*, 20(8), 1196–1209.

Balling, R.J., Lee, J.S. (2015). "Simplified model for analysis and optimization of skyscrapers with outrigger and belt trusses." *Journal of Structural Engineering*, 141(9), 04014231.

Smith, R.J., Willford, M.R. (2010). "The damped outrigger concept for tall buildings." *The Structural Design of Tall & Special Buildings*, 16(4), 501–517.

Soong, T.T., Spencer, B.F. (2002). "Supplemental energy dissipation: state-of-the-art and state-of-the-practice." *Engineering Structures*, 24(3), 243–259.

Lu, X., Lu, X.Z., Sezen, H., et al. (2014). "Development of a simplified model and seismic energy dissipation in a super-tall building." *Engineering Structures*, 67, 109–122.

Lu, X.Z, Xie, L.L., Yu, Y. et al. (2016). "Development and application of a simplified model for the design of a super-tall mega-braced frame-core tube building." *Engineering Structures*, 110, 116–126.

Ji, X.D., Wang, Y.D, Ma, Q.F., et al. (2017). "Cyclic behavior of replaceable steel coupling beams." *Journal of Structural Engineering*, 143(2), 04016169.

Zhou, Y., Zhang, C.Q., Lu, X.L. (2017). "Seismic performance of a damping outrigger system for tall buildings." *Structural Control and Health Monitoring*, 24(1), e1864.

Zhu, Y.N. (2018). "Performance analysis and optimization of frame-core tube structures with energy dissipation outriggers." *Master's thesis, Hefei University of Technology*, Hefei, Anhui (in Chinese).