Analysis of High-rise Building with Energy-dissipation Story System

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SUMMARY:
The outrigger and belt truss system had some problems which include irregularities of structural rigidity and internal forces, weak stories induced by outrigger. A new concept for the structural design of super high-rise buildings, energy-dissipation story system, had been proposed to ease these conflicts. Nonlinear time history analyses were performed on a 252m high-rise building model, whilst displacement, inter-story drift, additional damping ratio and base shears of the building were analyzed in detail. The results show that: (1) Seismic performance of the building with energy-dissipation stories is better than the building with outriggers. (2) The inter-storey drifts of the building with energy-dissipation stories are more uniform than the building with outriggers. (3) Energy-dissipation story system can effectively increase the model additional damping ratios of building, and its effective position is at the middle of the building.

Keywords: High-rise building, Energy-dissipation story, Outrigger, Seismic performance

1. INTRODUCTION

The outrigger and belt truss system is commonly used as one of the super high-rise building systems to effectively control the excessive displacement due to wind and earthquake excitations. The 42-story-high First Wisconsin Center with its steel structure in Milwaukee, the 88-story-high Jin Mao Building with its composite structure in Shanghai, the 101-story-high Taipei 101 with its composite structure in Taipei and the 101-story-high World Financial Center with its composite structure in Shanghai were excellent examples of this system (Gunel and Ilgin, 2007).

Outrigger and belt truss are generally positioned at plant levels to reduce the obstruction they create. Depending upon the number of levels of outriggers and their stiffness, the perimeter columns of a structure with outrigger perform a composite behavior with the core for deflection control. The outrigger and belt truss system could provide additional lateral stiffness up to 25 to 30 percents (Taranath, 1998) or lateral drift could decrease about 25 to 32 percent (Park et al., 2010), but there were also inevitable seismic problems which include irregularities of structural rigidity and internal forces, weak stories induced by outrigger and had difficulty to realize the destruction of yield mechanism (Xu, 2005).

A new concept, building with energy-dissipation story system, in which the combinations of dampers and braces were substituted for outrigger braces, had been recently proposed by Zhou et al. (2007). The stiffness sufficiently generated by energy-dissipation story ensured that the building for normal use under frequent earthquake and normal wind excitations, and the damping resulting from energy-dissipation story could have a reduction in dynamic lateral response under basic earthquake, severe earthquake and strong wind, thus protected the security of the main structure better (Ding et al., 2007; Deng et al., 2008; Ding et al., 2009). Then Wang et al. (2011) proposed six vibration control schemes with nonlinear viscous dampers and lead-viscoelastic dampers to control structural dynamic responses under wind and earthquake excitations based on a 288m super-rise building model, so the validity and feasibility of the proposed schemes in reducing structural vibration responses was fully approved.

The other representative concept for energy dissipation building system of high-rise building was "Damped outrigger", Willford and Smith (2008) successfully applied the outrigger damping system to a high-rise building in Philippine. The approach taken here was to install dampers between the perimeter columns and the ends of stiff outrigger elements cantilevering from the core of the building to make full use of the relative big displacement of these two components (Smith and Willford 2007). Analysis showed that this system greatly improved the building model damping ratio, thus effectively reduced in the wind load of dynamic response (Chen and Wang, 2009; Chen et al., 2010). The seismic performances of the tall buildings with five different types of damped outriggers were also analyzed by Zhou et al., (2010) and further studies are needed in order to evaluate the performance of the damped outrigger system under seismic forces.

The validity and feasibility of the building with energy-dissipation story system in reducing structural vibration responses under wind and earthquake excitations was preliminary approved. Question arises on which floor the energy-dissipation story should be placed and the quantity of the damping can be provided additionally, so that the responses can be reduced most effectively and building could show better performance. Thus, the objective of this paper is to study the seismic performance of building with energy-dissipation story related to these factors.

2. MODELING

2.1. Model Description

The model studied is a 60 stories composite building that has a rectangular plan of 34 m x 44 m with height of 252 m (Figure 1), and each story height is 4.2 m. The plan of the building is shown in Figure 2. The lateral system of the building studied is of a central reinforced concrete core, concrete-filled steel tube columns, truss beams. Typical floor system consists of wide flange beams with section of H800×500×35×45Q345 and H800×500×35×45Q345 which span from the core wall to the perimeter columns. Dimension of main components and strength of material used for modelling are given in Table 1. Building with outrigger system i.e. reinforced concrete core acting in conjunction with the outrigger and belt truss provide the resistance to the lateral loads (Figure 3), building with energy-dissipation story system i.e. reinforced concrete core acting in conjunction with the energy-dissipation story and energy-dissipation belt truss provide the resistance to the lateral loads (Figure 4). The energy dissipation devices of energy-dissipation story system are viscoelastic dampers with their stiffness k_1=900kN/mm, k_2=700kN/mm, and linear damping coefficient c_1=400kN/mm·s^{-1}, c_2=500kN/mm·s^{-1}.

The dynamic analysis of the model under seismic actions with intensity Ⅷ is conducted by using ETABS software program. A series of time history analysis of building with outrigger and with energy-dissipation story are carried out using five natural seismic waves and two artificial waves. The comparison between spectra by ground motions, artificial spectrum and spectrum used in Chinese seismic code is shown in Figure 5.

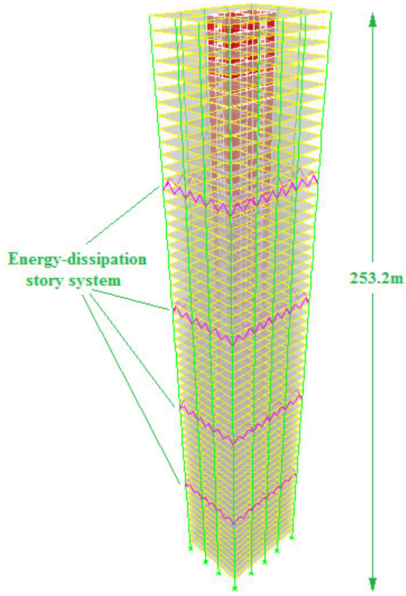


Figure 1. 3D building elevation

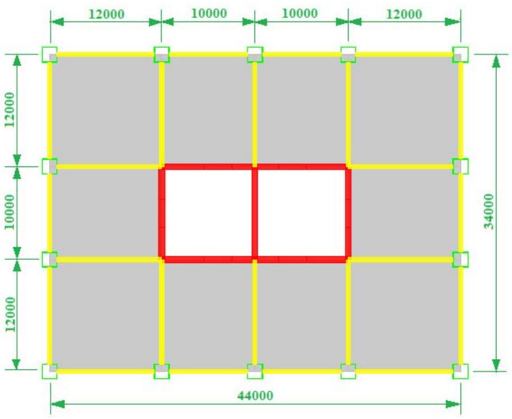


Figure 2. View of floor layout

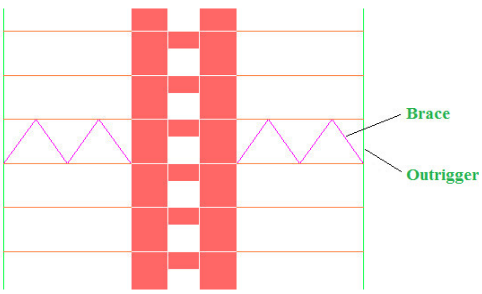


Figure 3. View of outrigger

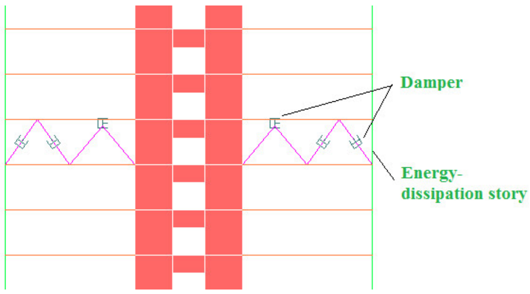


Figure 4. View of energy-dissipation story

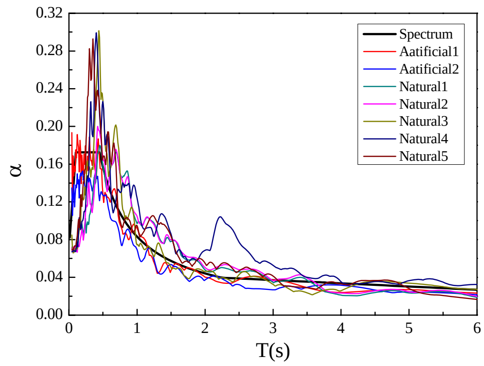


Figure 5. Comparison between spectra

Table 1. Dimension of main components and strength of material (unit: mm)

<table>
<tr><th>Story</th><th>Frame beams</th><th>Concrete-filled steel tube columns</th><th>Shear wall</th><th>Slab</th></tr>
<tr><td>1-20</td><td rowspan="4">Middle beams
H800×400×30×35Q345
Spandrel beams
H800×400×20×25Q345</td><td>2000×2000C80</td><td>1000C60</td><td rowspan="4">120C40</td></tr>
<tr><td>21-35</td><td>1600×1600C70</td><td>800C50</td></tr>
<tr><td>36-50</td><td>1200×1200C60</td><td>600C40</td></tr>
<tr><td>51-60</td><td>900×900C50</td><td>400C40</td></tr>
</table>

2.2. Model Arrangements with Single Energy-dissipation Story

Various models are run in order to find out the optimum location of the energy-dissipation story.

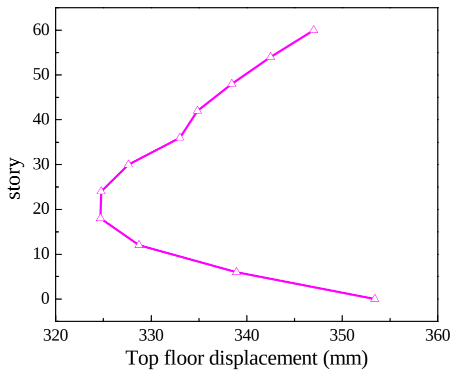
Single energy-dissipation story is placed at ten different positions which are at 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% and 100% of the height of the building; i.e. Energy-dissipation story that located at the top of the building has position 100% of the height of the building.

2.3. Model Arrangements with Multi-energy-dissipation Stories

Basic model arrangements are as follows:
1) Model without energy-dissipation story (MT0).
2) Model with one energy-dissipation story (MT1).
Place the energy-dissipation story at 25th story.
3) Model with double energy-dissipation stories (MT2).
Place the energy-dissipation stories at 15th and 35th story.
4) Model with three energy-dissipation stories (MT3).
Place the energy-dissipation stories at 10th, 25th and 40th story.
5) Model with three energy-dissipation stories (MT4).
Placing the energy-dissipation stories at 10th, 25th and 40th story are run in order to get the reduction in displacement to the same degree.

3. RESULTS

The use of energy-dissipation story has improved the performance under lateral loads of the building. Ten options on displacement and additional damping ratio are compared in Figure 6 and 7, including the model without energy-dissipation story.



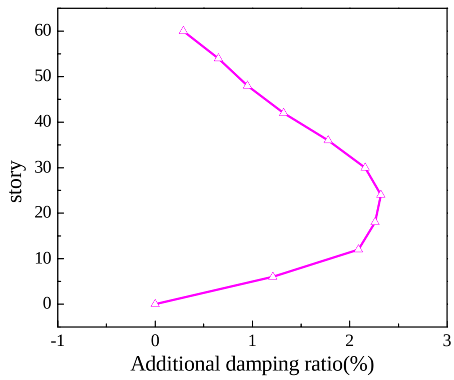
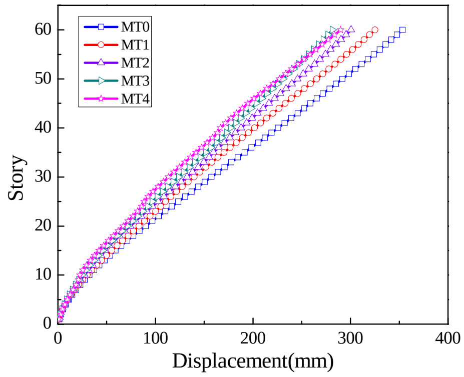


Figure 6. Top floor displacement of various models **Figure 7.** Additional damping ratio of various models

The results show that the optimum location of energy-dissipation story is at the middle of building, placing at the lower part of the building also effectively reduces the value of the responses, and placing at the upper part of the building is the least compared to placing the energy-dissipation story at other positions. Figures 6 also indicates that placing the energy-dissipation story at 40% of the height of the building can reduce top floor displacement most, and a similar trend of additional damping ratio, which is about 2.32%, achieves its maximum level at 40% of the height of the building (Figure7).

Comparison of the graphs of the displacement responses against the five basic model arrangements in Figure 8 show that appreciable decline in the deflection when placing the energy-dissipation stories at effective position. There is 7.99% reduction in top floor displacement by the use of one energy-dissipation story. Whereas 14.94% and 20.33% drop is achieved by the use of two and three energy-dissipation stories with respect to MT0 (Table 2). Compared to the model with energy-dissipation story, there is 17.96% reduction by the use of three outriggers. Notice that the more multi- energy-dissipation stories arrange, the larger the top floor displacement decline.

A comparable fashion of reducing of inter-story drifts as can be seen in Figure 9 for the use of energy-dissipation story and outrigger with respect to MT0. Altough there is a sudden fluctuation and change in the gradient of slope with the addition of energy-dissipation story, the inter-story drifts of builiding with energy-dissipation story are smaller than the builiding with outrigger.



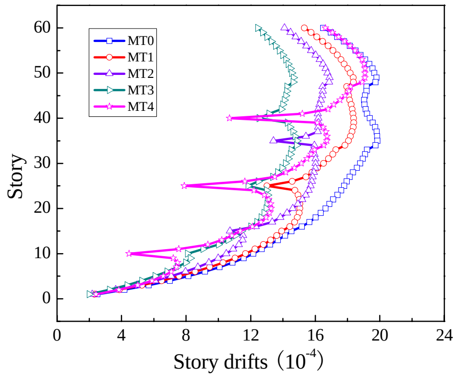


Figure 8. Displacement of basic model arrangements **Figure 9.** Story drifts of basic model arrangements

Table 2. Top floor displacement and percentage reduction of basic model arrangements

Options	MT0	MT1	MT2	MT3	MT4
△Top(mm)	353.41	325.17	300.61	281.56	289.93
Reduction in △(%)	-	7.99	14.94	20.33	17.96

Table 3. Comparison of basic model arrangements

Options	MT0	MT1	MT2	MT3	MT4
Natural period(s)	6.1646	5.9274	5.7929	5.6710	4.9973
Additional damping ratio (%)	-	2.33	4.12	5.60	-
Base shears(kN)	27080	24956	24262	22782	32555

Based on the ranges of values that appear in Table 3, the natural vibration period of the building decrease due to the stiffness which is provided by multi-energy-dissipation stories, while the additional damping ratio gradually increase and consequently minimize the base shear of the building. It is clearly indicated that energy-dissipation story can provide sufficient stiffness, meanwhile additional damping ratio can reach 5.60% in the model building with three energy-dissipation stories. Compared with building with three outriggers (MT4), it has been shown that building with three energy-dissipation stories (MT3) can significantly increase the model damping ratios of building and effectively decrease the dynamic responses and the base forces of building. Super high-rise building with energy-dissipation story is expected to show better seismic performance than the same building with outrigger.

4. CONCLUSION

The use of energy-dissipation story system for super high-rise building was studied based on nonlinear time history analysis, and the conclusions are as follow:

(1) Seismic performance of the building with energy-dissipation stories is better than the building with outriggers.

(2) The inter-storey drifts of the building with energy-dissipation stories are more uniform than the building with outriggers.

(3) Energy-dissipation story system can effectively increase the model additional damping ratios of building, and its effective position is at the middle of the building.

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REFERENCES

Gunel, M. H. and Ilgin, H.E. (2007). A proposal for the classification of structural systems of tall buildings. *Building and Environment*. **42**, 2667-2675.

Taranath, B.S. (1998). Structural Analysis & Design of Tall Buildings, McGraw-Hill Book Co., New York, USA.

Park, K., Kim, D., Yang, D. Joung, D. Ha, I. and Kim, S. (2010). A Comparison Study of Conventional Construction Methods and Outrigger Damper System for the Compensation of Differential Column Shortening in High-rise Buildings. *International Journal of Steel Structures*. **10:4**, 317-324.

Xu, P.F. (2005). Complex High-rise Building Design, China Architecture & Building Press, Beijing.(in Chinese)

Zhou, Y., Deng, X.S. and Wu, C.X. (2007). The Concept and Realization of the New Systems of Tall Building with Dissipated Devices. *Earthquake Resistant Engineering and Retrofitting*. **29:6**, 1-9. (in Chinese)

Ding, K., Zhou, Y. and Deng, X.S. (2007). Seismic Analysis on Frame-core Wall Structure with Energy-dissipation Story. *Earthquake Resistant Engineering and Retrofitting*. **29:3**, 35-40. (in Chinese)

Deng, X.S., Ding, K. and Zhou, Y. (2008). Analysis of Seismic Effect and Influence on Frame-tube Structure with Seismic Energy-dissipation Story. *Earthquake Resistant Engineering and Retrofitting*. **30:1**, 1-8. (in Chinese)

Ding, K., Deng, X.S. and Zhou, Y. (2009). Seismic Response Analysis of Super High-rise Structure with Strengthened Story and Viscous Seismic Energy Dissipation Story. *Earthquake Resistant Engineering and Retrofitting*. **31:1**, 35-43. (in Chinese)

Wang, D.Y., Zhou, Y. and Wang, S.H. (2011). Vibration reduction for a super-high structure with energy dissipation story. *JOURNAL OF VIBRATION AND SHOCK*. **30:2**, 85-92. (in Chinese)

Willford, M.R. and Smith, R.J. (2008). PERFORMANCE BASED SEISMIC AND WIND ENGINEERING FOR 60STORY TWIN TOWERS IN MANILA. *The 14th World Conference on Earthquake Engineering*. **Vol I:** 05060092.

Smith, R. J. and Willford, M. R. (2007). The damped outrigger concept for tall buildings. *The Structural Design of Tall and Special Buildings*. **16**, 501-517.

Chen, Z.Q. and Wang, Z.H. (2009). A NOVEL PASSIVE ENERGY DISSIPATION SYSTEM FOR FRAME-CORE TUBE STRUCTURE. *The Seventh Asia-Pacific Conference on Wind Engineering*. **Vol I:** 8-12.

Chen, Y., McFarland, D. M., Wang, Z., et al. (2010). Analysis of Tall Buildings with Damped Outriggers. *JOURNAL OF STRUCTURAL ENGINEERING*. **11,** 1435-1443.

Zhou, Y., Lü, X.L. and Zhang, C.Q. (2011). Seismic performance of a super-tall building with energy dissipation outriggers. *JOURNAL OF VIBRATION AND SHOCK*. **30:11**, 186-189. (in Chinese)