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Integrated optimal seismic design of mega-brace dampers under story drift constraint for super tall buildings

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ABSTRACT

Earthquake actions for tall buildings are significant, thus numerous tall buildings are controlled by earthquake actions. Viscous dampers are used to absorb and dissipate large amounts of energy under earthquake actions and improve mechanical performance and seismic characteristics. There are a variety of forms of viscous dampers. One is mega brace dampers which possess the advantage of enlarging the relative displacement at the endpoints of the dampers, thus offering the dampers a better ability of energy dissipation. The choices of positions for dampers should consider two factors, stiffness and damping. Dampers should be set in this positions which hardly influence rigidity weakening, at the same time provide a larger damping. The sensitivity coefficient of braces to the maximum story drift can reflect the impact of stiffness. Another factor can be expressed with how much energy the dampers consume. On this basis, this paper obtains the arrangements and forms of the dampers. An integrated optimal seismic design procedure based on mega-brace dampers system under story drift constraint is developed in this study. Thus, the optimal number of dampers can be reached through saving overall structural cost by reducing the earthquake action on primary structure. A 468-meter real super-tall building project is employed to illustrate the applicability and validity of the integrated optimal seismic design method.

1. INTRODUCTION

Earthquake actions for tall buildings are significant, thus numerous tall buildings are controlled by earthquake actions. There have been various damping measures since then. Bo (2014) proposed a variety of seismic resistance measures, one of which is the energy dissipation devices - viscous dampers. Viscous dampers are used to absorb and dissipate large amounts of energy under earthquake actions and improve mechanical performance and seismic characteristics. The categories of the viscous dampers are different. Constantinou and Symans (1992) noted that viscous dampers are widely used because of the relatively simple design. Soon after, Taylor and

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Tonawanda (1999) proposed the toggle-brace dampers with a displacement amplification effect. Then, Hanson and Soong (2001) introduced kinds of motion amplification devices.

In this paper, a kind of displacement amplification device mega-brace damper is introduced. Mega-brace damper possesses the advantage of enlarging the relative displacement at the endpoints of the damper, thus offering the damper a better ability of energy dissipation. Chen (2011) introduced that the application of mega-brace dampers in Mayor building in Mexico made the mayor mansion stand the test of a strong earthquake in 2003. At the same time, Chen (2012) introduced several arrangement forms of mega-brace dampers, and pointed out that these forms all had a good energy dissipation effect. So the question about where the mega-brace dampers should be placed in order to have a better ability of shock absorption causes people's thinking. This paper presents a method of position choice for mega-brace dampers. The paper noted that choices of positions for dampers should consider two factors, stiffness and damping. Dampers should be set in these positions which hardly influence rigidity weakening, at the same time provide a larger damping ratio. Zhao (2014) proposed the concept of sensitivity coefficients, and thus stiffness factor can be expressed with the sensitivity of braces to maximum story drift. Damping factor can be reflected by the capacity of energy dissipation. Finally, the positions and forms of mega-brace dampers can be gained by the consideration of stiffness and damping factors. Zhang (2014) advanced that integrated optimization can not only improve structural performance, but also reduce the project cost.

On this basis, the optimal positions and numbers of mega-brace dampers can be reached through integrated optimization of the main structure under story drift constraints. Finally, a 468-meter real super-tall building project is employed to illustrate the applicability and validity of the integrated optimal seismic design method.

2. THEORETICAL BASIS

Mega-brace dampers are a kind of displacement amplification devices. Mega-brace damper possesses the advantage of enlarging the relative displacement at the endpoints of the damper, thus offering the damper a better ability of energy dissipation. This paper presents a new method for position determination. It noted that choices of positions for dampers should consider two factors, stiffness and damping. Dampers should be set in this positions which hardly influence rigidity weakening, at the same time provide a larger damping. Stiffness factor can be expressed with the sensitivity of braces to maximum story drift. Damping factor can be reflected by the capacity of energy dissipation. Finally, the positions and forms of mega brace dampers can be gained by the consideration of stiffness and damping factors.

2.1 Stiffness Factor

Stiffness factor can be expressed with the sensitivity of braces to maximum story drift, which is derived as:

$$SI_i = \frac{g_i^o - g^A}{g^A}, \quad (1)$$

where SI_i is the stiffness index for the i-th mega-brace; g^A is the maximum story drift of the primary structure; g_i^o is the maximum story drift of the structure without i-th mega-brace.

The stiffness can be reflected by the change of maximum story drift before and after the utilization of the damper. If SI_i is negative, it is advantageous for structure to remove the i-th brace. Because the maximum story drift decreases and the overall stiffness of the structure becomes larger. The smaller SI_i is, the better it is. If SI_i is positive, it is unfavorable for structure to remove the i-th brace. Because the maximum story drift increases and the overall stiffness of the structure becomes smaller. The larger SI_i is, the more unfavorable it is.

2.2 Damping Factor

In this section, damping factor can be reflected by the capacity of energy dissipation. As follows:

$$W_{cj} = \lambda F_{dj\max} \Delta u_j, \quad (2)$$

where W_{cj} is the energy consumption of i-th energy dissipation component works cyclically under the expected story displacement Δu_j; $F_{dj\max}$ is the maximum damping force of i-th energy dissipation damper in respective horizontal seismic action; Δu_j is the relative displacement of the endpoints for energy dissipation devices; λ is the function of exponential damping according to specification.

From the above formula, it can be seen that in the case of setting the same parameters, the ability of energy dissipation of each damper can be reflected by the relative displacement of two endpoints of the dampers. The greater relative displacement is, the more energy dampers dissipate. The smaller relative displacement is, the less energy dampers dissipate.

2.3 Position Determination

In this paper, three kinds methods are proposed to decide the positions.

Option one: stiffness ordering scheme. That is, considering only the stiffness factor, mega-brace dampers should be arranged in the areas where the value of is smaller.

Option two: damping ordering scheme. Considering only the damping factor, mega-brace dampers should be arranged in the areas where relative displacement of the endpoints is larger.

Option three: stiffness-damping ordering scheme. Consider the stiffness and damping two factors and a scoring system is utilized to determine the positions. The dampers should be arranged in the areas where the composite score is high.

Finally, the three methods are compared to select the most reasonable option.

3. INTEGRATED OPTIMAL DESIGN

Comparison to primary structure there exists optimal space of the components. Since the energy dissipation technology can improve the structural damping, making responses of the main structure under earthquake action decrease. Therefore, the structure can be optimized after enhancing the performance of the structure, which is called integrate optimal design by Zhang (2014). Integrated optimal design not only can ensure the performance of the structure improves, but also can reduce the overall structure cost by optimizing the components. In this paper, the best number and form of the mega-brace dampers can be reached by the integrated optimal design under story drift constraint.

Optimization process is as follows:

(1) Position determination: first get the order of positions where mega-brace dampers can be arranged; then put a certain amount of dampers at these positions, making the maximum story drift meet specification limits. Thereby, different amounts of dampers can be obtained;
(2) Damping ratio calculation: calculate the additional damping ratio provided to the main structure by different numbers of dampers according to specification;
(3) Structural optimization: optimize main structure under different options; then calculate the cost of main structure and mega-brace dampers for each option.
(4) Cost analysis: reach the best economical option and the best number and form of the mega-brace dampers through cost analysis.

The flowchart is as follows:

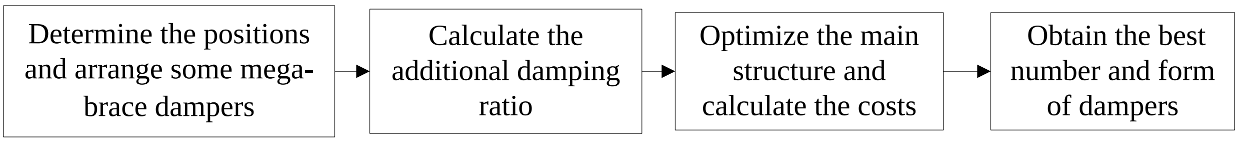
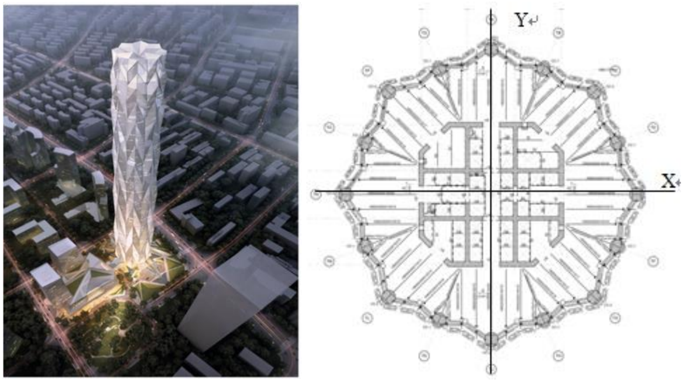


Fig.1: Integrated optimal process

4. CASE STUDY

In this case, a high-rise building in Chengdu is investigated. The project is a hybrid structure of the reinforced concrete core-profile steel concrete columns-outrigger truss-mega brace system structure with a height of 468m. Floor plans of overall structure model and standard floor are shown in Fig. 2. The seismic fortification intensity is 7 degrees and seismic measures should meet the requirements of 8 degrees. Due to the large number of braces in tower, they are divided into 12 zones shown in Fig. 7.



(a) Overall Structure Model (b) Typical Floor of the Structure
Fig. 2: High-Rise Building

4.1 Stiffness Calculation

Since braces are divided into 12 zones and each zone is symmetric based on symmetric axis X and Y. The stiffness of all braces can be reached by calculating and analysing four braces. The stiffness ordering is shown in Fig. 3 and the SI_i represents the stiffness of braces.

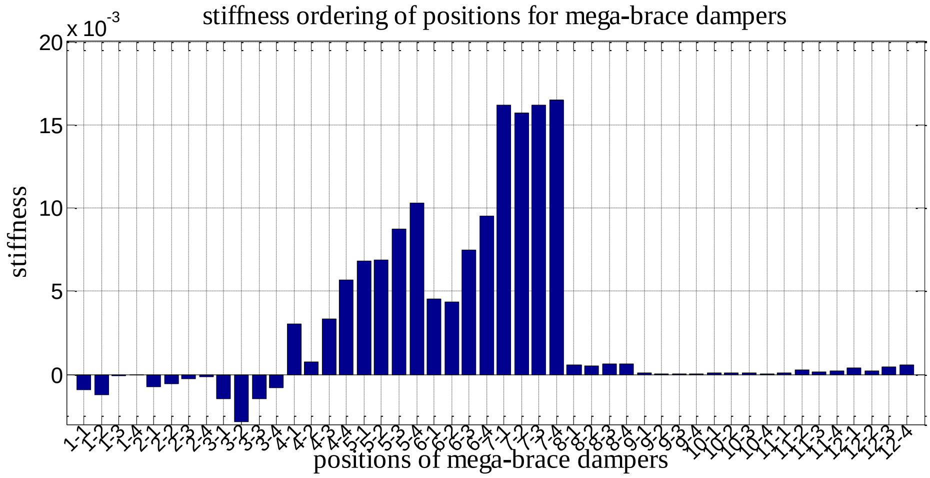


Fig. 3: Stiffness Ordering of Positions for Mega-Brace Dampers

Where the previous number represents zones and the latter represents the positions of dampers. Take 1-1 for an example, the previous 1 is the meaning that the damper is in the first zone; the latter 1 represents the first damper in four. From the figure above, it can be seen that the value of stiffness is negative in zone 1, 2, 3, indicating that it is advantageous for structure to remove these braces. Because the maximum story drift decreases and the overall stiffness of the structure becomes larger. The smaller is, the better it is. If the value of stiffness is positive, it is unfavorable for structure to remove these braces. Because the maximum story drift increases and the overall stiffness of the structure becomes smaller. The larger is, the more unfavorable it is.

4.2 Damping Calculation

It can be found that the damping still is symmetric based on symmetric axis X and Y from calculating. Then the damping of all braces can be reached by analyzing four braces. Arrange some dampers, and the relative displacements of two endpoints can be reached. Then the ability of energy dissipation of each damper can be reflected by the relative displacements. The damping ordering is shown in Fig. 4.

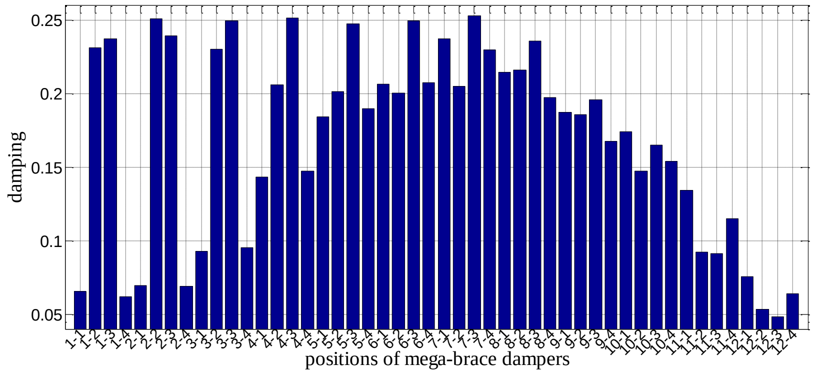


Fig. 4: Damping Ordering of Positions for Mega-Brace Dampers

From the figure above, it can be seen that the dampers dissipate more energy in the second and third position of each zone. The greater relative displacement is, the more energy dampers dissipate. The smaller relative displacement is, the less energy dampers dissipate.

4.3 Position Determination

Consider the stiffness and damping two factors and a scoring system is utilized to determine the positions. The ordering of positions considering two factors is shown in Fig. 5. The dampers should be arranged in the areas where the composite score is high.

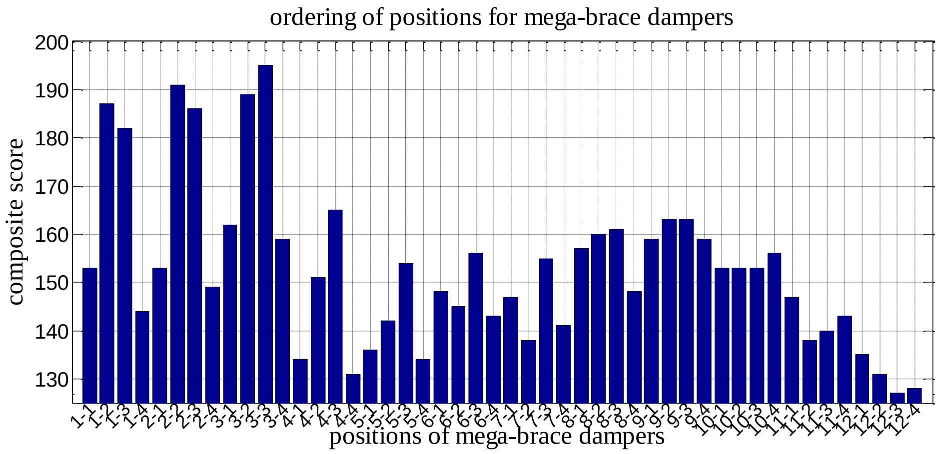


Fig. 5: Composite Ordering of Positions for Mega-Brace Dampers

Assuming that the number of dampers is 20, arrange mega-brace dampers according to the above proposed three options. The story drifts of each option are as follows in Fig. 6:

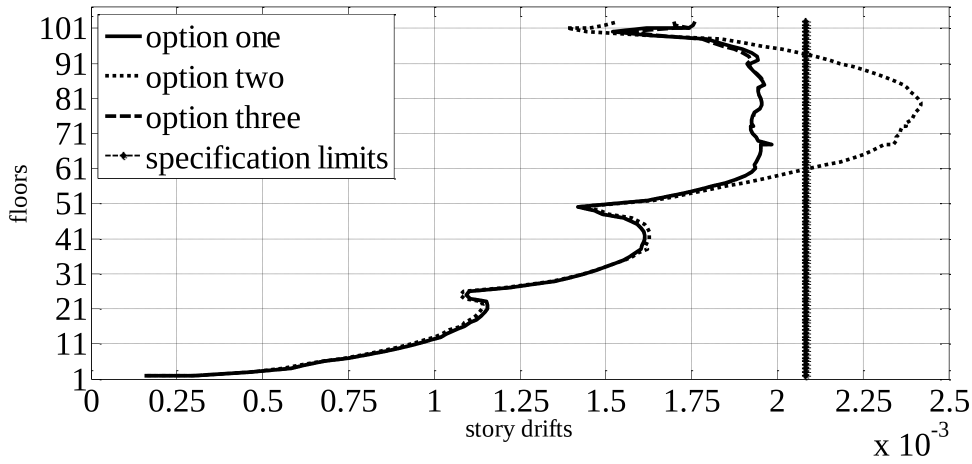


Fig. 6: Story Drifts of Each Option

From the figure above it can be seen that option one and option three meet the requirements while the maximum story drift of option two far exceeds the specification limit. Besides, the maximum story drift of option three is less than the option one's. Thereby, it's reasonable to consider two factors to determine the positions of mega-brace dampers.

4.3 Integrated Optimization

First, choose the positions of mega-brace dampers according option three; then arrange a number of dampers, and the number of the dampers is a multiple of four because the structure is symmetrical. After that, calculate additional damping ratios provided by dampers. The following table is the numbers of dampers under different damping ratios from calculating.

Table 1: Different Damping Ratios and the Corresponding Numbers of Dampers

The number of mage-brace dampers	4	8	12	16	20	24	28
Additional damping ratio	0.30%	0.54%	0.69%	0.76%	0.83%	0.92%	1.02%

And the positions of dampers for each option are shown in the flowing figure.

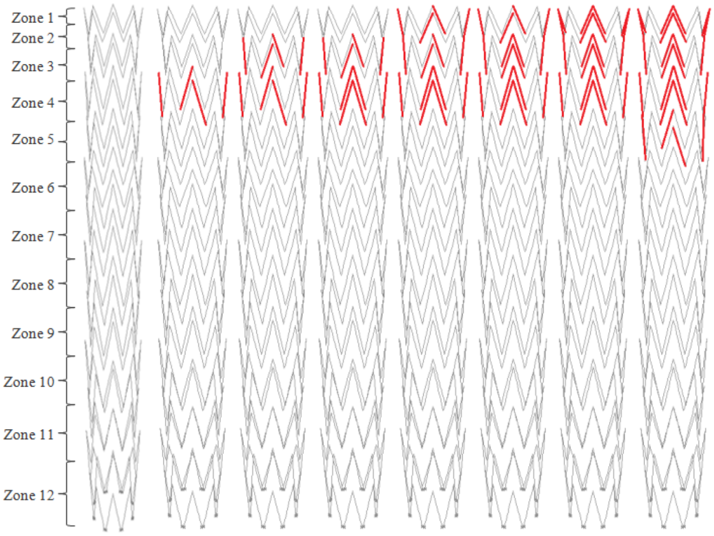


Fig. 7: Positions of Dampers for Each Option

Table 2: Economical Comparison of Each Optimal Option

Damping ratio	Cost of mega-brace damper	Cost of the structure optimization	The total cost savings
4.3%	20	211	191
4.54%	40	274	234
4.69%	60	299	239
4.76%	80	327	247
4.83%	100	344	244
4.92%	120	370	250
5.02%	140	366	226

The unit of the data in table is ten thousand yuan.

This table is about the economical comparison of each option. It can be seen that the option with the 4.92% damping ratio is the optimal.

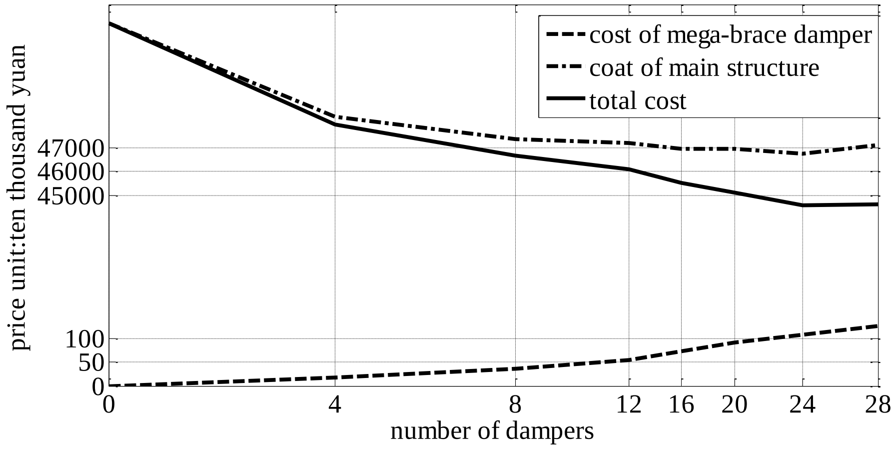


Fig. 8: Comprehensive Cost Comparison

Last, make statistical analysis for cost of mega-brace damper and cost of main structure above the proposed seven programs. The price of the mega-brace damper is 40 thousand yuan. Program with 4.92% damping ratio is optimal. From an economic point of view, damping ratio of this project under earthquake action should be 4.92% and the number of dampers should be 24. Comprehensive cost comparison is shown in Figure 8 which indicating that with the increase of damping ratio, energy dissipation efficiency is getting reduced. So there exists an optimal number of dampers. In addition, since the rigidity braces are replaced, the stiffness of the structure is weakened. There exists a reasonable number of dampers making the structure meet stiffness limits, while providing more additional damping ratio.

5. CONCLUSION

In this paper, a new method is proposed to determine the positions for mega-brace dampers. The method should consider two factors, stiffness and damping. Dampers should be set in this positions which hardly influence rigidity weakening, at the same time provide a larger damping. The sensitivity coefficient of braces to the max story drift can reflect the impact of stiffness. Another factor can be expressed with how much energy the dampers consume. On this basis, this paper obtains the arrangements and forms of the dampers. An integrated optimal seismic design procedure based on mega brace dampers system under story drift constraint is developed in this study. Thus, the optimal number of dampers can be reached through saving overall structural cost by reducing the earthquake action on primary structure. We can draw the following conclusions from this paper:

(1) Mega-brace damper is a kind of displacement amplification device which possesses the advantage of enlarging the relative displacement at the endpoints of the damper, thus offering the damper a better ability of energy dissipation. In appearance, it looks like a diagonal bracing.
(2) Determination of positions for dampers should consider two factors, stiffness and damping. Dampers should be set in this positions which hardly influence rigidity weakening, at the same time provide a larger damping.
(3) This paper presents a method which taking a comprehensive consideration of stiffness and damping and obtains that it’s reasonable to consider two factors by comparison with the other two methods.
(4) The optimal positions and numbers of mega-brace dampers can be reached through integrated optimization of the main structure under story drift constraints.
(5) From an economic point of view, damping ratio of this project under earthquake action should be 4.92% and the number of dampers should be 24.

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