The Research of United Energy Dissipated Design of Buckling Restrainted Braces and Viscous Dampers for Frame Structure in High Seismic Region

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Abstract: In this paper, a series of computational analysis is carried out on the united energy dissipation design of the concrete frame structure with the buckling restrained brace and viscous dampers. The calculation results show that the value of the normal lateral stiffness ratio and the additional damping ratio provided by the viscous damper. The relation chart between the two damper matching rules is obtained, which avoids the inconvenience caused by multiple iterations based on the response spectrum design method. The accuracy and practicability of the relation chart for united energy dissipation design are verified by the engineering example. It is proved that the united energy dissipation structure can effectively improve the seismic performance of the whole structure, and has good theoretical research value and practical application value, which can provide some reference for the structure design in high seismic region.

1. Introduction
At present, most of the research and engineering application of structural damping use a single type of dampers. The buckling restrained brace (called BRB for short) and the viscous fluid damper are the energy dissipation devices more used in the current seismic energy dissipation structures. The buckling restrained brace and viscous fluid damper seismic research and engineering applications, at home and abroad have been studied and applied [1 2], but for the research of two types of dampers united energy dissipation is still relatively small. Chen Xiaoqiang [3] applied the buckling restraint support and the viscous dampers to the seismic reinforcement of existing buildings. The former provided some stiffness for the structure, controlled the interlayer displacement of the structure to the allowable level of the current seismic code, while the latter is used to reduce the seismic effect, so that the original reinforcement to meet current specification requirements. Guo Daoyuan [4] applied metal dampers and viscous dampers to steel frames, and analyzed and compared the seismic response indexes under different working conditions. The results show that the two types of dampers united have better damping effect. The above research has done a good exploration in the united energy dissipation, but the research is in the initial stage, especially the concrete frame structure of the united energy dissipation research is very small, and the traditional response spectrum design method based on a number of iterations caused by the inconvenience, which is difficult to be widely used. This paper focuses on the design of concrete frame structure with the buckling restrained brace and viscous damper, and makes a series of calculation and analysis. The matching rule of two types of damper united energy dissipation is obtained, which can provide some reference for the structure design in...
high seismic region and have a certain theoretical research and practical application value.

2. The Principle of The United Energy Dissipation Structure

The buckling restrained brace (Figure.1) is a displacement-dependent damper that supports both the brace and the damper's functional characteristics, controls its elasticity under small earthquakes, and is equivalent to normal brace, providing some additional stiffness to the structure to control the structure lateral deformation. In the middle and large earthquake, the buckling restrained brace before the main structure produce yield, which uses steel pull and pressure yield energy consumption. The viscous damper (Figure.2) is a non-rigid, velocity-dependent damper that provides a damping force on the structure without increasing the stiffness of the structure to reduce the response of the structure under earthquakes.

In the high seismic region the building structure of energy dissipation applications if only the use of the buckling restrained brace to support this single displacement type damper for shock absorption, can cause greater structural stiffness, increased seismic action, large output of dampers and many other issues; If only the use of viscous dampers such a single speed dampers for shock absorption, often need to add a larger damping ratio, will increase the number of dampers and increase the cost of economic and cause other issues. Therefore, the united energy dissipation of buckling restrained brace(Figure.1) and viscous dampers(Figure.2) in the high seismic region can effectively overcome the drawbacks of using a single displacement type damper or a single speed type damper, so that the number of displacement dampers used and speed dampers used is reduced and the damper parameters are relatively reduced. The principle of united energy dissipation is to install two different types of dampers on the structure. The buckling restrained brace is mainly used to provide stiffness for the structure, effectively control the structural deformation. The viscous damper is mainly used to reduce seismic action, so that the two types of dampers can fully play their respective advantages, in the earthquake under the synergistic work to achieve a phased energy consumption, and improve the structural seismic performance.

2.1. The Normal lateral Stiffness ratio of The Buckling Restrained Brace

In 2008, Zhang Xianjiang et al [5] proposed the concept of the normal lateral stiffness ratio, which refers to the ratio of the elastic stiffness of the buckling restrained brace $K_b$ to the elastic stiffness of the frame $K_f$, that is:

$$ K = \frac{K_b}{K_f} $$

In the above formula, when the buckling restrained brace is a herringbone arrangement (Figure 3), $K_b = 2K_{be} \cos^2 \theta$; when the buckling restrained brace is single oblique arrangement (Figure 4), $K_b = K_{be} \cos^2 \theta$; $K_{be}$ the axial stiffness of the buckling restrained brace.
In structural design, the normal lateral stiffness ratio $K$ can be used as an important parameter to determine the buckling restrained brace to support the cross-sectional area of the core element. In this paper, a large number of computational analysis (Figure 5) are used to study the matching of the buckling restrained brace and concrete frame. It is found that when the normal lateral stiffness ratio $K \geq 1.5$, the maximum lateral deformation of the structure is basically stable. The value of the normal lateral stiffness ratio $K$ is form 0.05 to 1.5.

2.2. The Equivalent damping ratio of The United Energy Dissipation Structure

According to the seismic specifications, energy dissipation components attached to the structure of the effective damping ratio calculation formula:

$$\xi = \sum_j W_j \cdot (4\pi W_i)$$  \hspace{1cm} (2.2)

In the first fortification stage (small earthquake), the structure and the buckling restrained brace are kept elastic, only the viscous dampers produce energy consumption. At this time, the equivalent damping ratio of the structure is:

$$\xi_{eq} = \xi_0 + \xi_l = \xi_0 + \sum_j W_j \cdot (4\pi W_i)$$  \hspace{1cm} (2.3)

In the second or third fortification stage (earthquake or large earthquake), the structure into the elastic-plastic deformation stage, viscous dampers and the buckling restrained brace are supported by energy consumption. For viscous dampers, the energy dissipated by the structure into the elastic-plastic stage for one cycle is: $W_c = 2\pi \xi_r k_{eff} u_m T_{eff} / T_0$, by calculating it in accordance with 2.4, the additional damping ratio of the viscous damper $\xi_{a1}$ can be determined. According to reference [6] for the use of the base shear force to the multi-degree of freedom structure of meet the use of the base shear force, the additional damping ratio $\xi_{a2}$ provided viscous dampers:

$$\xi_{a2} = \sum_{i=1}^n \left[ \xi_{i,eq} h_i \theta \sum_{j=1}^n G_j H_j / \sum_{i=1}^n h_i \theta \sum_{j=1}^n G_j H_j \right]$$  \hspace{1cm} (2.4)

In the above formula, $h_i$: the height of the $i$ layer, $H_j$: the calculation height of the $i$ layer, $G_j$: the gravity load of the $i$ layer, $\theta$: the displacement angle of the $i$ layer, $\xi_{i,eq}$: the additional effective damping ratio of the $i$ layer. At this time, the equivalent damping ratio of the structure is:

$$\xi_{eq} = \xi_0 + \xi_{a1} + \xi_{a2}$$  \hspace{1cm} (2.5)

3. The Matching Research of The United Energy Dissipation Structure

The united energy dissipation structure of BRB and viscous damper is mainly used in high seismic region. To control the axial compression ratio of frame column, the structure should have some initial stiffness. In view of the two types of dampers involved in the united energy dissipation matching the structure may be due to the number of layers of the frame structure, Therefore, this paper designs 6-layer and 9-layer frame structures. The seismic precautionary intensity of the project is 8 degrees, and the design basic acceleration of ground motion is 0.3g; the design of the earthquake group is the second group, and site category is the class two. Considering the two types of dampers involved in the
united energy dissipation matching the structure may be due to frame structure stiffness, so this paper set up five frame structure stiffness levels which contain maximum displacement angle 1 / 300, 1 / 350, 1 / 400, 1 / 450 and 1 / 500 and a total of ten concrete frame structure modes 6F-S300, 6F-S350, 6F-S400, 6F-S450, 6F-S500, 9F-S300, 9F-S350, 9F-S400, 9F-S450 and 9F-S500. The lateral stiffness of the structure changes uniformly along the height, and the stiffness of the structure is similar in both directions. There is no obvious weak layer.

3.1. The Value of The Normal Lateral Stiffness Ratio $K$ and The Additional Damping Ratio $\xi_a$

Assuming that the normal lateral stiffness ratio of the buckling restrained brace $K$ take a set of values: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, the above ten concrete frame structures are calculated separately. The relationship between the normal lateral stiffness ratio $K$ and the maximum interlayer displacement angle is calculated to be obtained by using the maximum interlayer displacement angle as the control target, as shown in Figure 5.

![Figure 5](image)

It can be seen from Figure 5 that along with the normal lateral stiffness ratio $K$ increases, the maximum interlayer displacement angle decreases gradually, and the reduction effect is obvious in the range of $K \leq 1.5$, that is, along with the normal lateral stiffness ratio $K$ changes the effect of shock reduction is obvious; The amount of change is not large, that is, along with the normal lateral stiffness ratio $K$ changes the effect of shock absorption is not obvious in the range of $K \geq 1.5$. Considering the united energy dissipation structure requires the stiffness of the buckling restrained brace to control the displacement of the structure, the normal lateral stiffness ratio $K$ should not be too small, Therefore, the value of the normal lateral stiffness ratio $K$ should be $0.05 \leq K \leq 1.5$.

Assuming that the additional damping ratio of viscous dampers under small earthquakes $\xi_a$ take a set of values: 0.03, 0.05, 0.07, 0.10, 0.12, 0.15, 0.17, 0.20, 0.22, 0.25, the above ten concrete frame structures by only using BRB for shock absorption are calculated separately. The relationship between the additional damping ratio $\xi_a$ and base shear force is calculated to be obtained by using base shear force as the control target, as shown in Figure 6 and Figure 7.
Figure 6 $\xi_a$ and X base shear force relation chart

Figure 7 $\xi_a$ and Y base shear force relation chart

It can be seen from Figure 6 and Figure 7 that along with the additional damping ratio of viscous dampers $\xi_a$ increases, base shear force decreases gradually, and the reduction effect is obvious in the range of $\xi_a \leq 18$, that is, along with the additional damping ratio of viscous dampers $\xi_a$ changes, the effect of shock reduction is obvious; The amount of change is not large in the range of $\xi_a \geq 18$, that is, along with the additional damping ratio of viscous dampers $\xi_a$ changes, the effect of shock absorption is not obvious. Considering the united energy dissipation structure requires viscous dampers to reduce base shear force of the structure, the additional damping ratio $\xi_a$ should not be too small, Therefore, the value of the additional damping ratio $\xi_a$ should be $3 \leq K \leq 18$.

3.2. The Matching Value of The Normal Lateral Stiffness Ratio $K$ and The Additional Damping Ratio $\xi_a$

In this paper, the above ten concrete frame structure model is calculated, and the matching value of the normal lateral stiffness ratio $K$ and the additional damping ratio $\xi_a$ is shown in Table 1. According to the matching value of table 1, the seismic performance of the united energy dissipation structure of BRB and viscous damper under earthquake and large earthquake is checked. The results meet the structural damping target and the united energy dissipation effect is good.

| Layer | Stiffness type | 0   | 0.10 | 0.200 | 0.300 | 0.400 | 0.500 | 0.600 | 0.800 | 1.000 | 1.500 |
|-------|----------------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 6F    | 6F-S300        | -   | -    | 19    | 13    | 8     | 6     | 4     | 2     | -     | -     |
|       | 6F-S350        | -   | -    | 16    | 10    | 6     | 3     | 1     | -     | -     | -     |
|       | 6F-S400        | 10  | 5    | 2     | -     | -     | -     | -     | -     | -     | -     |
|       | 6F-S450        | 10  | 4    | 2     | -     | -     | -     | -     | -     | -     | -     |
|       | 6F-S500        | 4   | 1    | -     | -     | -     | -     | -     | -     | -     | -     |
| 9F    | 9F-S300        | -   | -    | 22    | 15    | 10    | 7     | 4     | 2     | -     | -     |
|       | 9F-S350        | -   | -    | 14    | 7     | 4     | 2     | -     | -     | -     | -     |
|       | 9F-S400        | 21  | 12   | 6     | 2     | 1     | -     | -     | -     | -     | -     |
|       | 9F-S450        | 13  | 5    | 3     | -     | -     | -     | -     | -     | -     | -     |
|       | 9F-S500        | 6   | 1    | -     | -     | -     | -     | -     | -     | -     | -     |
Considering the range of the nominal lateral stiffness ratio $K$ and the additional damping ratio $\xi_a$, According to $K - \xi_a$ matching relationship table can be obtained the $K - \xi_a$ matching relationship chart, as shown in Figure 8.

![Figure 8 The $K - \xi_a$ Matching Relationship Chart](image)

4. **Engineering Examples**

4.1. **Project Overview**

The project is located in Jianshui County, Yunnan Province, is a large integrated commercial building, which is a six-story frame structure with the building height of 28.90m. The seismic precautionary intensity of the project is 8 degrees, and the design basic acceleration of ground motion is 0.3g, the design of the earthquake group is the second group, and site category is the class II. In order to meet the requirements of building function and to control the beam and column section effectively, the design of the united energy dissipation structure of BRB and viscous damper is adopted. The structure of the shock absorption target is in table 2. The lateral stiffness of the structure changes uniformly along the height, and the stiffness of the structure is similar in both directions. There is no obvious weak layer. Taking into account the building use function, the damper arrangement is shown in Figure 9. The performance specifications of BRB are shown in Table 3.

![Figure 9 The diagram of damper arrangement](image)
Tab.2 The Target of Structural Energy Dissipation

| structure type | Parameter         | Specification | Damping targets |
|---------------|------------------|---------------|-----------------|
| Frame         | Displacement angle | small 1/550   | 1/610           |
|               |                  | large 1/50    | 1/100           |
|               | Base shear force  | -              | Reduced by 15%  |

Tab.3 The Performance Specification of BRB

| Number | Equivalent section :mm² | Yield bearing capacity :KN | Yield displacement :mm |
|--------|--------------------------|----------------------------|------------------------|
| BRB1   | 10000                    | 1950                       | 6.0                    |
| BRB2   | 19600                    | 3350                       | 4.6                    |

4.2. The Matching Value of $K$ and $\xi_a$

The maximum interlayer displacement angle of the non-damping structure is 1/442 (the second layer), the lateral stiffness of the two-layer X-direction is 6143400kN / m, and the Y-direction stiffness is 6180600kN / m, and the stiffness in the two directions is similar. With reference to the equivalent cross-section of the BRB specification in Table 3, according to Formula 2.1, the normal lateral stiffness ratio of the buckling restrained brace $K$ can be calculated, and $K = 1.2$ can be obtained. According to the $K - \xi_a$ relation chart, $\xi_a = 0.05$ can be obtained. With reference to Formula 2.1, the equivalent damping ratio of the united energy dissipation structure of BRB and viscous damper structure can be obtained, that is $\xi_{eff} = 0.05 + 0.05 = 0.10$.

4.3. Elastic Time History Analysis In Small Earthquakes

In the elastic time history analysis, the selection of five natural waves and two artificial waves, base shear force of the structure calculated for each wave meet the regulatory requirements. The additional damping ratio $\xi_a$ provided the viscous dampers in small earthquake meet the requirement of $\xi_a = 0.05$ obtained by the $K - \xi_a$ matching relationship chart.

Tab.4 The Damping Ratio of Story Drift Angle

| Time-history Analytical method | X direction | Y direction |
|-------------------------------|-------------|-------------|
|                               | Drift angle | Damping ratio | Drift angle | Damping ratio |
| Wave 32                       | 1/1084      | 51%          | 1/838       | 33%          |
| Wave 56                       | 1/655       | 15%          | 1/616       | 10%          |
| Wave 72                       | 1/823       | 32%          | 1/850       | 34%          |
| Wave 93                       | 1/743       | 25%          | 1/726       | 23%          |
| Wave 99                       | 1/920       | 39%          | 1/814       | 31%          |
| WaveR01                      | 1/1242      | 55%          | 1/1183      | 53%          |
| WaveR02                      | 1/1079      | 48%          | 1/1188      | 53%          |
| Average                      | 1/894       | 38%          | 1/844       | 34%          |
| CQC                          | 1/626       | 11%          | 1/615       | 10%          |

Tab.5 The Damping Ratio of Base Shear Force

| Time-history Analytical method | X direction | Y direction |
|-------------------------------|-------------|-------------|
|                               | Drift angle | Damping ratio | Drift angle | Damping ratio |

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It can be seen from Table 4 that the damping rate of the average interlayer displacement angle calculated for the time-history analysis is 34%, which is greater than the 11% damping rate in the response spectrum analysis. From Table 5, it can be seen that the damping rate of the average base shear is 37%, which is greater than the 24% damping rate in the response spectrum analysis. It can be concluded that the actual damping effect of the viscous damper satisfies the preset damping target and the damping effect is good.

4.4. Elastic Time History Analysis under Large Earthquakes

In order to study the seismic performance of the structure under large earthquakes, the finite element analysis software SAP2000 is used to analyze the elastic time history analysis. On the basis of the elastic time history analysis, the results of the three waves are calculated as: wave 33 X to 1/127, Y to 1/124; wave 99 X to 1/122, Y to 1/119; wave R02 X to 1/142, Y to 127. The above analysis shows that the maximum interlayer displacement angle is 1/119, which satisfies the preset damping target 1/100 requirements in large earthquakes, and layer shear force is also significantly reduced. The damping effect of the damper is good. The supplementary calculation results show that the beam hinges appear before the column hinge, and the frame around the damper meet the "strong column weak beam" and "strong shear weak bend". The structure has a reasonable energy dissipation mechanism to meet the "big earthquake does not fall".

5. Conclusion

(1) A series of computational analysis is carried out on the united energy dissipation design of the concrete frame structure with buckling restrained brace and viscous dampers. The calculation results show that the value of the normal lateral stiffness ratio $K$ and additional damping ratio $\xi$ provided the viscous dampers. The $K - \xi$ relation chart between the two damper matching rules is obtained, which avoids the inconvenience caused by multiple iterations based on the response spectrum design method.

(2) The accuracy and practicability of the $K - \xi$ relation chart in the design of the united energy dissipation of the concrete frame structure with BRB and viscous dampers are verified by the engineering example. The results show that the calculated parameters of the united energy dissipation structure meet the requirements of the specification. In large earthquake, the energy consumption of two types of dampers is obvious, which effectively improves the seismic performance of the whole structure. The $K - \xi$ relation chart has good practical application value, which can provide some reference for the structure design in high seismic region.

References

[1] Koetaka Y., Narihara H., and Tsujita O. Experimental study on buckling restrained braces. In proceedings of sixth pacific structural steel conference, Beijing, China,2001:15-17

[2] Watanbe A., Hitomi Y., and Wada A.et al. Properties of braces encased in buckling-restraining concrete and steel tube. In:9th World Conf. on Earthquake Engineering, Vol. IV, Japan,1988:719-724

[3] Cheng, X, Li, T and Chen, Y. Application of buckling restrained brace and viscous dampers in
Seismic Strengthening [J]. Journal of Civil Engineering and Engineering Management, 2011, 28 (3): 329 ~ 331

[4] Guo D, Pei X. Study on Seismic Effect of Steel Frame Structure with Metal and Viscous Dampers [J]. Engineering Earthquake and Reinforcement, 2010, 32(6): 42-47

[5] Zhang X, Huang K. Application of buckling restrained braces in High-rise Steel Frames [J]. Steel Structures, 2008, 23 (10): 5 ~ 9

[6] Geng P, Pan Y. Design and analysis of the united energy dissipation steel frame with viscous dampers and BRB [D]. Southwest Jiao tong University Master’s degree thesis, 2012: 47 ~ 52