Seismic Performance Analysis of Irregular Structures under Combined Action of Base Isolation and Energy Dissipation Braces

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Abstract. Irregular structures are prone to torsional vibration under earthquake action, which aggravates the damage of structures. With the development of energy dissipation technology, LRB and BRB are applied to an irregular steel frame. By comparing and analyzing the seismic response characteristics and laws of the original structure, BRB structure, LRB structure, and LRB + BRB structure, the seismic performance and advantages and disadvantages of each control scheme are obtained, especially the influence on torsion effect, which provides technical reference for the practical application of such projects.

1. Introduction

With the development of economy, the application of irregular building structure is more and more common. For the irregular L-shaped frame structure, due to the eccentricity, the lack of lateral resistance and torsional stiffness, the lateral displacement is larger and the damage degree is greater under the earthquake action[1]. At present, the application of energy dissipation technology is increasingly becoming a new way to control structural torsion effect[2]. In this paper, lead rubber bearing (LRB) and buckling restrained energy dissipation brace (BRB) are applied to irregular structures. It is proposed that the lateral stiffness of the upper structure can be changed by reasonable arrangement of BRB to reduce the tensile stress of isolation bearing under earthquake. The seismic response analysis of four different control schemes of an irregular structure, including the original structure, BRB structure, LRB structure, BRB and LRB joint structure, is carried out. The seismic response characteristics and laws of the structures under different control schemes are compared, especially the analysis of the control torsion effect. The research results can be used as reference for similar projects.

2. Buckling-resistant Energy Dissipation Brace

The buckling-resistant energy dissipation brace (BRB) is a new type of brace, usually composed of yield energy dissipation section ($L_1, A_1$), transition section ($L_2, A_2$) and connection section ($L_3, A_3$), as shown in Figure 1. The sectional area and stiffness of each section of BRB are different[3]. In practical engineering, the cross-section changes of transition section and connecting section are usually not considered for convenience of calculation. The cross-section area of core material along the whole
length is considered as uniform area $A_1$, and the stiffness of BRB is equivalent simplified[4]. The equivalent stiffness of BRB is calculated according to the equation (1).

$$K_{ef}^* = \frac{E_1 A_1}{L_1 + 2L_2 + 2L_3} = \frac{E_1 A_1}{L}$$

(1)

Figure 1. Schematic diagram of buckling restrained brace.

For the BRB structural system, the horizontal seismic effect is first borne by BRB. BRB can significantly improve the ductility and seismic performance of the structural system, and has good energy dissipation capacity, thereby protecting the main structure from damage[5].

3. The Initial Stiffness of BRB and the Lateral Stiffness of the Structure

BRB braces are usually arranged in various ways, such as single oblique direction layout and inverted V-shape layout, as shown in Figure 2.

Figure 2. Schematic diagram of BRB single oblique and inverted V layout.

The initial stiffness of BRB in the figure is calculated according to the equation (2) and equation (3).

$$K_B = \frac{(EA_1) \sin \theta \cos^2 \theta}{h}$$

(2)

$$K_B = \frac{2(EA_1) \sin \theta \cos^2 \theta}{h}$$

(3)

The lateral stiffness of the structure is $K_D$, the ratio between the initial stiffness of BRB brace and the lateral stiffness of the structure is $K_F = K_B/K_D$. Domestic and foreign scholars have conducted qualitative research on the relationship between the lateral stiffness ratio and the main structure, and have achieved corresponding results. For BRB braced frame structure system, $K_F$ needs to be controlled in a reasonable range to effectively reduce the seismic response[3].

4. The Base Seismic Isolation Bearings

The seismic isolation bearing is the main seismic isolation device in the base seismic isolation technology[6,7]. The device not only has the overall automatic reset function, and also can extend the basic period of the building, avoid the main frequency band of the earthquake, significantly reduce the seismic energy input to the structure.

The selection of isolation bearing needs to meet the requirements of minimum size and horizontal yield capacity [8,9]. The vertical compressive stress of rubber isolation bearing of class C building under the representative value of gravity load should not exceed 15MPa. First, calculate the area of the column base bearing according to the formulas $A = F/\sigma$ and $F = 1.0G + 0.5Q$, and then calculate the minimum diameter of the bearing required at the bottom of each column according to the formula $D = 2\sqrt{A/\pi}$. Finally, according to the specification that the total yield force of the seismic isolation
layer is not less than 2% of the base reaction force under the action of the representative value of gravity load, the total yield force of the seismic isolation layer is estimated.

5. Engineering Case Analysis

A project is a 12-story steel frame with an L-shaped layout, as shown in Figure 3. The frame is 51m long from north to south and 83m long from east to west. The total height of the building is 43.8m. It belongs to the Class A high-rise building. The height of the bottom floor is 4.2m, and the rest is 3.6m.

The floor dead load and live load are both 2.0kN/m², and the load on the beam is 4.5kN/m. The self-weight of the floor slab is automatically calculated by the program. The seismic fortification intensity of the project is 8 degrees, the design basic earthquake acceleration is 0.3g, the design earthquake group is the first group, the seismic class is three, and the site category is class II. The cross-sectional dimensions of the main structural members are shown in Table 1.

![Table 1. Cross-section sizes of the main structural components.](image)

| Component name  | Section size (unit: mm) | Material type |
|-----------------|-------------------------|---------------|
| Frame column z1 | 400×400×12              | Q345          |
|                 | 350×350×12              |               |
| Frame column z2 | 500×500×16              | Q345          |
|                 | 450×450×16              |               |
| Beam            | 600×250×12×24           | C30           |
| Floor           | Cast-in-place thickness is 100mm |               |

*The column is a box-shaped section, and the section size is: side length × side length × wall thickness.

*The beam has an I-shaped cross-section, and the dimensions are: height × width × web thickness × flange thickness.

5.1. Different Seismic Control Solutions

In order to analyze the impact of BRB, LRB and their combined application on the seismic response of irregular steel frames, seismic control schemes are divided into four types, as shown in Figure 4. Considering comprehensively, the BRB of this project adopts (8-12) m TJ energy dissipation buckling
brace (Q235), adopts single oblique layout, and BRB is hinged with beam and column. Two types of Zhentai lead rubber bearing LRB800 and LRB900 are selected for LRB. For the L-shaped structure, when the number of BRB is the same at the limb and corner of the structure, better damping effect can be obtained. Considering the torsional effect, the displacement around the structure may be slightly larger. Considering the overall consideration, LRB900 is arranged along the periphery, and LRB800 is arranged in the middle, as shown in scheme 3.

5.2. Structural Modal Analysis

Midas/gen analysis software is used to analyze the mode of four different control schemes. The maximum number of vibration modes used in the analysis is 18, which meets the requirement of the code. The results are shown in Table 2.

| Structure type | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 |
|----------------|----------|----------|----------|----------|
| Mode number    | 1        | 2        | 3        | 1        |
| Period T/s     | 1.983    | 1.896    | 1.856    | 1.446    |
| UX(%)          | 1.780    | 61.642   | 18.323   | 22.872   |
| UY(%)          | 45.468   | 13.667   | 21.920   | 63.663   |
| RZ(%)          | 33.337   | 6.244    | 41.656   | 0.007    |
| Period ratio   | 0.936    | 0.716    | 0.820    | 0.864    |

From the above table, the period of the first mode is reduced by 27.08% in scheme 2 compared with scheme 1, Scheme 3 and 4 is 42.68% and 33.02% higher than scheme 2, Scheme 4 is 14.43% lower than scheme 3. This shows that BRB can improve the lateral stiffness of the irregular structure and effectively reduce the natural vibration period of the structure. The LRB can effectively increase the natural vibration period of the structure. Because the lateral stiffness of the upper part is much larger than that of the isolation layer, the effect of scheme 4 on the natural vibration period is not significant.

In scheme 1, the first mode is mainly Y-direction translation with large torsion, the second mode is X-direction translation, and the third mode is torsion. The period ratio of the first scheme is 0.936, which is 0.9 higher than that of the code, and the torsion period of the third mode is close to that of the translation period of the first and second modes. However, after setting BRB or LRB, the period ratio of scheme 2, 3 and 4 decreases, among which scheme 2 is the smallest, the participation coefficient of torsional mass of mode 1 is reduced, and the torsional effect of mode 1 and 2 is reduced. It can be seen that reasonable arrangement of BRB can enhance the torsional performance of the structure, adjust the eccentricity of the upper structure and reduce the period ratio of the structure.

5.3. Dynamic Time History Analysis of Each Control Scheme

El-Centro wave, Taft wave and Lanzhou wave are selected to analyze the frequent earthquake response of structures. Due to space limitation, only the analysis results of El-Centro wave are listed.

5.3.1. Interlayer displacement angle. The comparison results are shown in Figure 5 and 6. In scheme 1, the inter-story displacement angle is relatively large, and the local overrun in Y direction does not meet the seismic code [10]. Compared with scheme 1, scheme 2, 3 and 4 all reduce to varying degrees and meet the requirements. The reduction degree of scheme 2 and 4 is more obvious than that of scheme 3, and scheme 4 is more reduced. This shows that the upper lateral stiffness can be significantly enhanced and the inter-story displacement angle can be reduced by reasonably setting BRB for high-rise structures with long natural vibration period. If only LRB is set, the effect is not obvious. Therefore, it is necessary to increase the lateral stiffness of the upper part reasonably, and then set LRB, such as scheme 4, which can significantly reduce the inter-story displacement angle, reflecting the advantages of joint setting of BRB and LRB.
5.3.2. **Floor shear.** The comparison results are shown in Figure 7 and 8. Compared with scheme 1, the shear forces of each floor in X and Y directions in scheme 2 are increased, while those in scheme 3 and 4 are smaller. By calculating the ratio of story shear of scheme 3 and scheme 1, the maximum horizontal damping coefficient $\beta$ is 0.395 in X direction and 0.402 in Y direction. After isolation, the structure can be reduced by one degree for design calculation. It is shown that the setting of BRB increases the upper lateral stiffness and increases the shear force of each floor. Setting LRB can weaken the seismic action of the upper part and reduce the shear force of each floor effectively. The joint setting of LRB and BRB can also reduce the shear force of each floor, and make the upper BRB brace more uniform, which is more conducive to BRB energy consumption.

5.3.3. **Maximum horizontal displacement of floor.** The comparison results are shown in Figure 9 and 10. Compared with scheme 1, the maximum horizontal displacement of the top floor in X and Y directions is reduced in scheme 2, 3 and 4. The maximum reduction is 63.8% in scheme 2 and 4, and only 22.7% in scheme 3. It shows that the horizontal displacement can be reduced by setting BRB. If only LRB is set, the maximum horizontal displacement cannot be effectively controlled. If the LRB and BRB are set together and the lateral stiffness of the upper part is enhanced by BRB, the maximum horizontal displacement of the floor can be well controlled, which reflects the advantages of the joint application.
6. Conclusion
By analyzing the seismic performance of an L-shaped irregular high-rise steel frame structure, the lead rubber isolation bearing and the buckling restrained energy dissipation brace are combined in the irregular structure, and the reasonable arrangement of braces in the upper part of the high-rise foundation isolation is proposed to improve the seismic performance of the structure. Through the comparative study of different schemes, the advantages of the combined application are obtained. The results show that:
(1) In the irregular structure, reasonable BRB brace can improve the lateral stiffness of the upper structure, adjust the eccentricity of the upper structure, weaken the torsional effect of the structure, reduce the natural vibration period of the structure, the inter story displacement angle and the horizontal displacement of the floor, but the shear force of each floor will be increased.
(2) Reasonable setting of LRB bearing can weaken the seismic energy transmitted into the superstructure, reduce the inter story displacement angle, horizontal displacement and shear force of each floor, but it will greatly prolong the natural vibration period of the structure.
(3) Adding BRB brace to the upper structure of LRB with base isolation bearing and combining LRB bearing with BRB brace can avoid the shortage of separate application and give full play to the advantages of both. Meanwhile, the structural indexes can meet the requirements of the code, especially for irregular high-rise building structures in high-intensity areas.

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