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Compatibility Charts of BRB-VD Combined Systems for RC Frames in Ultra-high Seismic Intensity Zones

Shuwei Lan[1]*, Yu Liu [2], Xiang Lan[1], Kechuang Wu[1]

[1] Faculty of Architecture and Civil Engineering, Kunming University, No.2 Puxin Road, Economic and Technological Development Zone, Kunming, Yunnan 650214, China
[2] School of Public Safety and Emergency Management, Kunming University of Science and Technology, No.68 Wenchang Road, Wuhua Zone, Kunming, Yunnan 650093, China

Abstract. The combined seismic energy dissipation of BRB and VD in ultra-high seismic zones can exploit their respective advantages, resulting in a hybrid damping solution with superior performance and broad prospects. Although the potential of such combined damping systems in seismic design is widely acknowledged, the absence of a clear methodology for coordinating their distinct mechanisms of stiffness and damping remains a critical obstacle hindering their efficient application. To solve the compatibility problem between these two damping technologies, a series of computational analyses on reinforced concrete frame structures equipped with BRB-VD combined systems in ultra-high seismic zones is carried out. Key parameters, including the nominal lateral stiffness ratio K of BRBs and the additional damping ratio ξ_a provided by VD, are determined. Furthermore, the K-ξ_a relationship charts illustrating the compatibility between the two dampers under different seismic design groups in ultra-high seismic zones are obtained, which can avoid the inconvenience caused by multiple iterations based on the response spectrum design method. Finally, the accuracy and practicability of the K-ξ_a relation charts for combined seismic energy dissipation design are verified by engineering examples, which provides a convenient manual calculation tool for structural engineers, and offers valuable references for global similar high seismic regions.

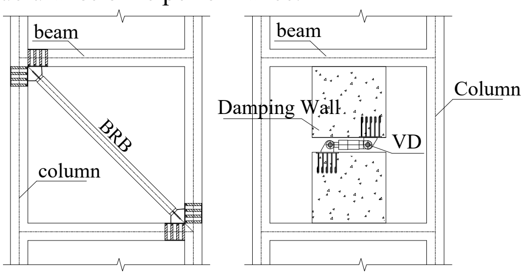
Key words: combined seismic energy dissipation, buckling-restrained braces, viscous dampers, performance-based seismic design, damper compatibility; the K-ξ_a relationship charts

1. INTRODUCTION

Ultra-high seismic intensity zones refer to regions where ground motion intensity (typically represented by peak ground acceleration, PGA, or seismic intensity) reaches or exceeds a specific high threshold. With reference to seismic design codes from Europe [1], the United States [2], Japan [3], Iran [4], Turkey [5] and other countries, such areas are defined as ultra-high seismic intensity zones. In such zones, the individual application of Buckling-Restrained Braces (BRB) or Viscous Dampers (VD) presents significant limitations. Although BRBs are effective in limiting structural lateral deformations, their seismic energy dissipation capacity is relatively limited. Conversely, VDs demonstrate high efficiency in energy dissipation but contribute minimally to limit lateral deformations. By integrating BRB and VD technologies, a hybrid damping system can be developed that leverages the respective advantages of each device, resulting in a superior seismic energy dissipation system with enhanced overall performance. At present, seismic energy dissipation of buildings mainly focuses on the application of a single type of damper. The structure with combined seismic energy dissipation using two types of dampers is rather complex in analysis and design, and it is necessary to consider how to match the two types of dampers to achieve optimal performance in seismic energy dissipation. The research and application on the compatibility between the two types of dampers in combined seismic energy dissipation structures are not yet mature. Lan [6] conducted a finite element calculation study on reinforced concrete structures with combined seismic energy dissipation using BRB and VD, and carried out a preliminary study on the collaborative working mechanism of the two dampers. The research results show that the combined seismic energy dissipation structure can effectively improve the seismic performance. Alemdar [7] investigated the working performance of BRB and VD combined energy-dissipation under frequent, moderate, and rare earthquake intensity levels. Hansu [8] evaluated steel frames incorporating BRBs and viscous dampers through nonlinear time-history analyses, demonstrating their efficacy in significantly reducing seismic deformations and enhancing structural serviceability. Castellano [9] conducted experiments on reinforced concrete frames with BRB-VD combined systems, comparing them to undamped frames. The results demonstrated superior seismic performance of the combined system, confirming its effectiveness. Chen [10] discussed design methodologies for BRB-VD combined systems, detailing their implementation and comparing their performance to the standalone BRB or VD systems. Their studies validated that combined systems achieve both improved displacement reduction and seismic shear mitigation. Sun [11] explored BRB-VD combined applications in practical engineering, showing that hybrid damper systems outperform single-damper systems in metrics such as cross-sectional dimensions, seismic shear forces, and steel consumption under identical inter-story drift ratios, thereby better achieving targeted seismic energy dissipation objectives. Guo [12] applied BRB and VD in a coordinated manner to the seismic reinforcement of existing buildings. The former provides a certain rigidity for the structure and limits the inter-story displacement of the structure within the allowable level of the current seismic code, while the latter is used to reduce seismic action and make the original reinforcement meet the requirements of the current code. This combined approach resulted in a significant enhancement of the building's seismic performance. Miani [13] evaluated the seismic retrofit of irregular RC buildings using BRBs and viscous dampers, demonstrating their effectiveness in enhancing energy dissipation and torsional stiffness. Hosseini [14] implemented a hybrid damping system combining BRB and VD in a high-rise building. This combined system significantly enhanced the seismic performance, effectively mitigating damage to both the primary structural and non-structural components. Javaid [15] respectively studied the seismic performance of steel-reinforced concrete frames and reinforced concrete frames with BRB and VD types of dampers for seismic energy dissipation, and compared and analyzed the seismic energy dissipation effects of the two types of dampers. Yang [16] investigated the application of a hybrid damping system, combining BRB and VD, in precast frame and steel frame structures, respectively. Cai [17] proposed a displacement-based design method for steel frames with hybrid BRB and VED systems, demonstrating its effectiveness in optimizing damper capacities and controlling drifts, though performance varies with seismic intensity levels. This approach achieved complementary advantages, enabling the structures to fulfill multi-level seismic design objectives and demonstrating effective seismic energy dissipation performance. While the above-mentioned research has made beneficial explorations in the field of combined seismic energy dissipation, they are subject to notable limitations. Most studies on BRB and VD combined seismic energy dissipation mainly focus on the energy dissipation effect with in-depth analyses of the collaborative and compatibility principles between the two damper types under complex loading conditions remaining scarce. Moreover, prevailing design methodologies largely rely on iterative trial calculation processes based on response spectrum analysis, lacking universal guidelines for compatible damper design. Furthermore, research on the applicability and optimal design of this combined system for ultra-high seismic intensity zones with Peak Ground Acceleration $\alpha \geq 0.4g$ is exceedingly limited, and relevant literature is rarely reported, thereby hindering their broader implementation in these extreme seismic conditions. Addressing the currently unclear working mechanisms and compatibility principles of the two damper types in combined seismic energy dissipation structures, this study focuses on a reinforced concrete frame structure located in a region with a peak ground acceleration of 0.4g. A seismic energy dissipation scheme combined BRB and VD is adopted, and a series of computational analyses are conducted to investigate the working mechanisms and compatibility relationships between the two damper types. A general chart for the optimal collaborative working compatibility of the two types of dampers in combined seismic energy dissipation, which can avoid the inconvenience brought by the iterative trial calculation of the conventional response spectrum design method. These charts provide direct and reliable theoretical tools for seismic design in the ultra-high intensity zone, significantly enhancing the design feasibility and engineering applicability of hybrid damping systems while advancing performance-based seismic design practices.

2. WORKING PRINCIPLE OF COMBINED BRB AND VD SEISMIC ENERGY DISSIPATION SYSTEMS

The use of BRB and VD for seismic energy dissipation is to install two different types of dampers on the structure at the same time. The buckling restrained brace (Fig. 1a) is mainly used to provide stiffness for the structure, effectively limit lateral deformations of the structure, and control its elasticity to maintain under the frequent earthquakes, and to yield to dissipate the energy prior to the structure under the moderate and rare earthquakes. The viscous dampers (Fig. 1b) are primarily employed to mitigate seismic forces, enabling both components to fully leverage their respective advantages. Through synergistic interaction under seismic excitation, they facilitate phased energy dissipation and collectively enhance the structural seismic performance.



(a). Buckling Restrained Brace (b). Viscous Damper

Fig.1. Schematic diagram of damper

2.1. The Nominal Lateral Stiffness Ratio of the Bucking Restraint Brace, *K*

Zhang [18] proposed the concept of nominal lateral stiffness ratio, which is the ratio of the elastic lateral stiffness K_b of the buckling restrained braces t to the elastic lateral stiffness K_f of the frame, viz:

$$K = K_b / K_f \tag{1}$$

When the bucking restraint brace is a monoclinic arrangement (Fig. 2a) $K_b = K_{be} \cos^2 \theta$; when the bucking restraint brace is a herringbone arrangement (Fig. 2b) $K_b = 2K_{be} \cos^2 \theta$ where K_{be} is the axial stiffness of the bucking restraint brace. The nominal lateral stiffness ratio K is an important parameter for determining the cross-sectional area of the core unit of the buckling restrained brace in the seismic design of the structure.

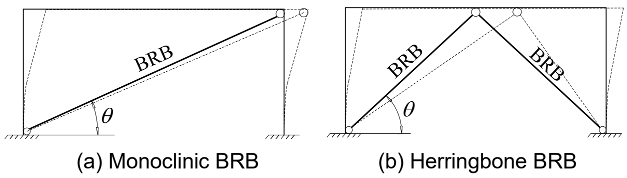


Fig.2. Schematic diagram of two types of BRB

2.2. Equivalent Damping Ratio of combined Energy Dissipation Structures

According to the Code for Seismic Design of Buildings [19], the effective damping ratio of the energy dissipating components attached to the structure is calculated by the formula:

$$\xi_a = \sum_j W_{cj} / (4\pi W_s) \tag{2}$$

Where, W_{cj} is defined as the energy dissipated by the j-th energy dissipation device undergoing one complete cycle at the structure's anticipated inter-story drift. W_s is defined as the total strain energy of the structure equipped with energy dissipation devices at the expected displacement.

Under frequent earthquakes, both the structure and the buckling restrained brace remain elastic, and only the viscous dampers act as the sole source of energy dissipation, at which time the equivalent damping ratio of the structure is:

$$\xi_{eff} = \xi_0 + \xi_{a1} = \xi_0 + \sum_j W_{cj} / (4\pi W_s) \tag{3}$$

Under moderate and rare earthquakes, the structure will enter the elastic-plastic deformation stage, at this time, both viscous dampers and buckling restraint bracing are involved in the energy dissipation, for viscous dampers, the energy dissipated one cycle after the structure enters the elastic-plastic stage. The additional damping ratio of the viscous damper ξ_{a1} can be determined by substituting it in Eq. (2). According to reference [20] the additional damping ratio of the buckling restraint bracing to the structural is obtained as ξ_{a2} :

$$\xi_{a2} = \sum_{i=1}^{n} [\xi_{i.eq} h_i \theta_i \sum_{j=i}^{n} G_i H_i] / \sum_{i=1}^{n} [h_i \theta_i \sum_{j=i}^{n} G_i H_i] \tag{4}$$

Where, h_i is defined as the height of the i-th floor of the structure; H_i is the calculated height of the i-th floor; G_i is defined as the gravity load of the i-th floor; θ_i is defined as the displacement angle between the i-th floors; $\xi_{i.eq}$ is defined as the additional effective damping ratio of the i-th floor of the structure; at this time, the equivalent damping ratio of the structure is:

$$\xi_{eff} = \xi_0 + \xi_{a1} + \xi_{a2} \tag{5}$$

Current design codes provide methodologies for calculating the nominal lateral stiffness ratio of buckling restrained braces and the equivalent damping ratio of the structure. However, their engineering implementation remains challenging. The determination of the stiffness ratio is sensitive to the brace's sectional design and requires multi-parameter coordination. Furthermore, estimating the equivalent damping ratio involves a complex, displacement-dependent procedure that must account for stage-wise elastoplastic behavior and the coupled energy dissipation of the damping system. This reliance on difficult-to-predict parameters leads to a protracted and inefficient iterative design process. Therefore, establishing a straightforward and practical design alternative is imperative to improve the efficiency and reliability of applying combined seismic energy dissipation structures.

3. RESEARCH METHODOLOGY FOR THE COMPATIBILITY OF BRB AND VD COMBINED ENERGY DISSIPATION STRUCTURES

According to the Chinese seismic design code, the compatibility between the two types of dampers involved in the structures combined energy dissipation varies with different seismic intensities and different seismic groupings, and therefore concrete frame structures with BRB and VD combined seismic energy dissipation are designed in the ultra-high intensity zone ($\alpha = 0.4g$) under the Class II site ,corresponding to seismic groupings of Group II and Group III. The detailed analytical process of this investigation is illustrated in Figure 3.

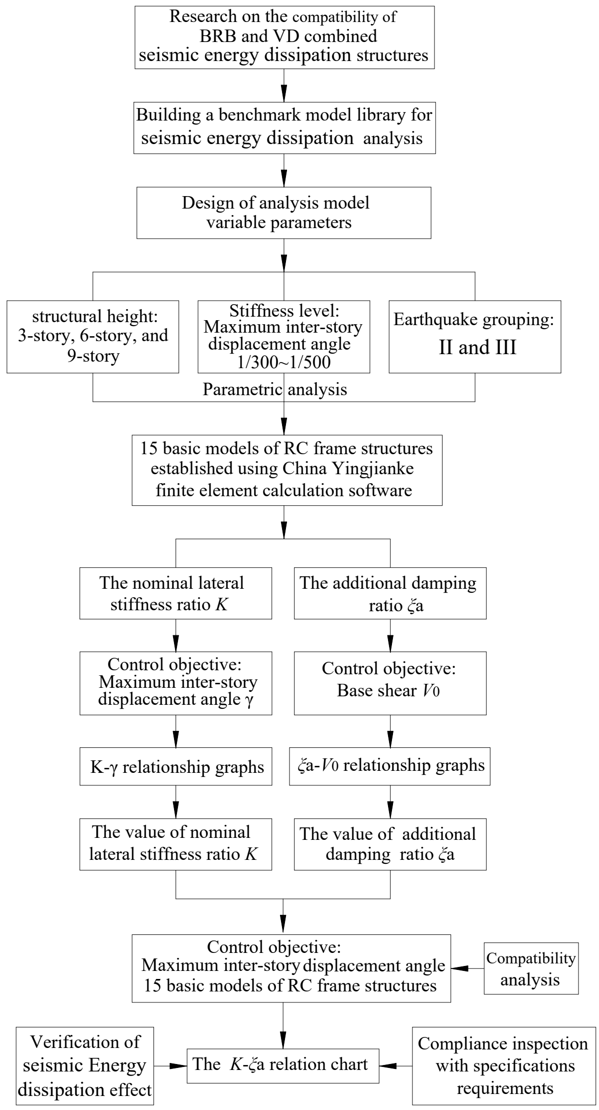


Fig.3. The roadmap of relevant compatibility analysis research

In view of the fact that the compatibility between the two types of dampers and the structure may vary with the number of stories and the lateral stiffness of the structure. Three types of concrete frame structures with three, six and nine floors are designed respectively. For each frame height, five levels of lateral stiffness are considered, corresponding to inter-story drift limits of 1/300, 1/350, 1/400, 1/450, and 1/500, resulting in a total of fifteen structural models. The models are named according to the rule illustrated by "3FS300": where "3" denotes the number of stories, and "300" indicates the inter-story drift limit of 1/300. The full set of models includes: 3FS300, 3FS350, 3FS400, 3FS450, 3FS500, 6FS300, 6FS350, 6FS400, 6FS450, 6FS500, 9FS300, 9FS350, 9FS400, 9FS450 and 9FS500. The lateral stiffness of the primary structure varies uniformly along the height, with comparable stiffness in both principal directions and no significant weak story. The dampers are arranged in plan according to the principles of "uniformity, dispersion, and symmetry". In the vertical distribution, dampers are first assigned to the story with the maximum inter-story drift angle. This placement process is repeated iteratively until all dampers are allocated, with the exact number determined based on specific structural requirements.

3.1. Determination of the Value of the Nominal Lateral Stiffness Ratio *K*

The nominal lateral stiffness ratio K of buckling restrained brace is set to take a set of values: 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, 1.0, 1.5, 2.0, 3.0, and according to this, fifteen concrete frame structure models are calculated respectively under different seismic groupings of the ultra-high intensity zone ($\alpha = 0.4g$), and the buckling restraint braces are arranged in the maximum story displacement, and the top and bottom are arranged successively, and the maximum inter-story displacement angle change is taken as the control target. The arrangement of buckling restraint bracing is arranged at the maximum floor displacement, and the upper and lower floors are arranged consecutively, with the change of the maximum inter-story displacement angle as the control target, and the relationship between the nominal lateral stiffness ratio K and the change of the maximum inter-story displacement angle γ is calculated, see Fig. 4 and Fig. 5.

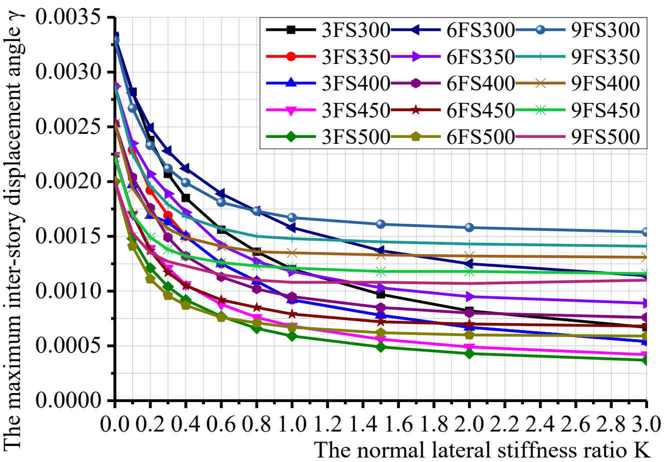


Fig.4. Group II relationship graphs of the normal lateral stiffness ratio and maximum interlayer displacement angle

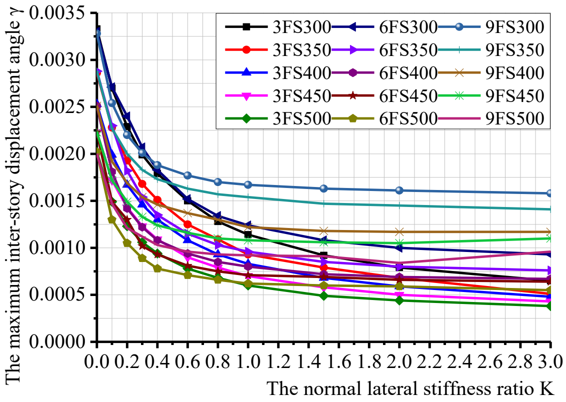


Fig.5. Group III relationship graphs of the normal lateral stiffness ratio and maximum interlayer displacement angle

As shown in Fig. 4 and Fig. 5, when $K \leq 1.0$, the maximum inter-story displacement angle of the floor decreases more obviously, and the damper stiffness play efficiency increases with the increase of K value; In contrast, when $K > 1.0$, the maximum inter-story displacement angle of the floor tends to change gently, and the damper stiffness play efficiency does not change obviously with the increase of K value. Under this condition, adding more buckling restrained braces has limited effect on restraining structural lateral displacement and may not lead to further reductions in displacement. Moreover, the efficiency of stiffness utilization remains low at this range. In the combining seismic energy dissipation, the buckling restraint brace is used to limit the structural lateral deformations, in order to ensure the efficiency of the buckling restraint brace stiffness in combined seismic energy dissipation, the nominal lateral stiffness ratio of the buckling restraint brace is suggested to be: $K \leq 1.0$.

3.2. Determination of the value of additional damping ratio ξ_a

A series of values of 0.00, 0.03, 0.05, 0.07, 0.10, 0.12, 0.15, 0.17, 0.20, 0.22, 0.25 are set for the additional damping ratio of viscous dampers under the action of frequent earthquakes, respectively, to calculate the seismic reduction calculation model of fifteen concrete frame structures with a single buckling restrained bracing (BRB) under different seismic subgroups in the ultra-high intensity zones ($\alpha = 0.4g$), and the relationship between the additional damping ratio ξa and the change of base shear force V_0 is calculated in Fig. 6 and Fig. 7. With the change of base shear as the control objective, the relationship between the additional damping ratio ξ_a and the change of base shear V_0 is calculated and shown in Fig. 6 and Fig. 7. Due to the fact that the stiffness of the structure in both directions is close to each other and the difference of base shear is within 3%, the article is limited to the length of the article and only lists the X-direction base shear, and the base shear in the figures refers to the X-direction base shear.

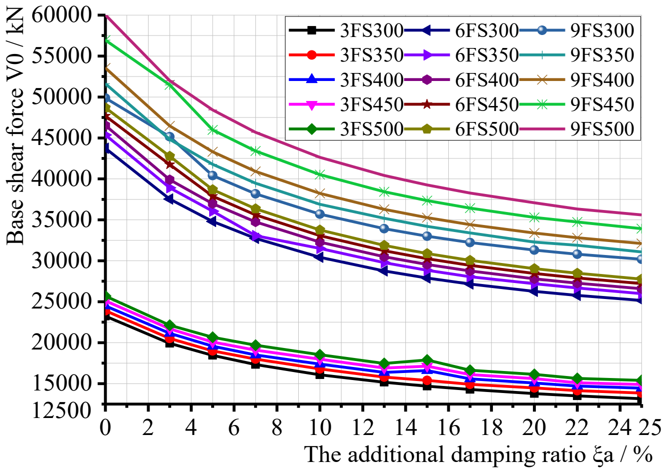


Fig.6. Group II relationship graphs of the additional damping ratio and base shear force

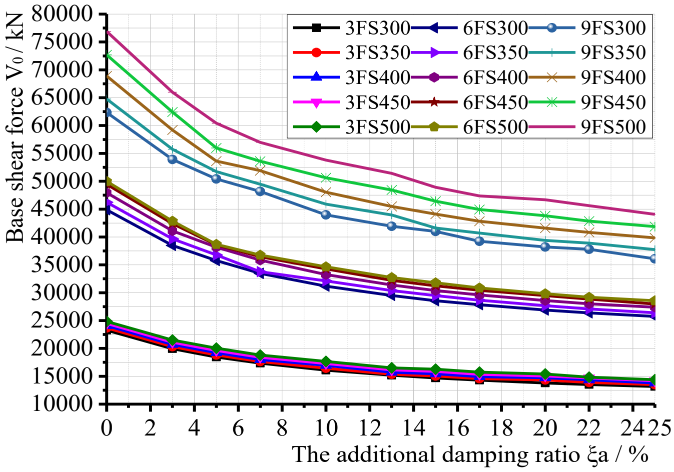


Fig.7. Group III relationship graphs of the additional damping ratio and base shear force

As shown in Fig. 6 and Fig. 7, with the increase of additional damping ratio, the base shear gradually decreases. when $\xi_a \leq 18\%$, the base shear reduction is more obvious, and the damper damping efficiency improves with the increase of ξ_a. However, when $\xi_a > 18\%$, the change of the floor base shear tends to flatten out, and the damping efficiency of the damper does not change much with the increase of the ξ_a value, and the effect of seismic reduction is not obvious. Under such conditions, adding more viscous dampers results in only marginal reduction in structural base shear. Therefore, it is recommended that the additional damping ratio ξ_a for viscous dampers in combined seismic energy dissipation structures is suggested to be taken as $\xi_a \leq 18\%$.

3.3. Determination of the Compatibility Relationship between Nominal Lateral Stiffness Ratio and Additional Damping Ratio

To ensure the efficiency of both the buckling bestrained braces and the viscous dampers, it is recommended that for reinforced concrete frame structures with combined seismic energy dissipation systems in ultra-high seismic intensity zones ($\alpha = 0.4g$),the nominal lateral stiffness ratio of the BRB should not exceed 1.0, and the additional damping ratio provided by the viscous dampers should be limited to 18%.

Based on the aforementioned fifteen concrete frame models designed for ultra-high seismic intensity regions, analyses are conducted with the objective of controlling the maximum inter-story drift angle within code-specified limits under different earthquake groups. Using the nominal lateral stiffness ratio K of the buckling-restrained braces as the variable parameter, the corresponding additional damping ratio ξ_a to be provided by the viscous dampers is determined. The resulting paired values of K and ξ_a are subsequently verified under both moderate and severe intensity levels. The verification results confirm that the selected parameters satisfy the structural performance objectives, demonstrating effective and well-performing seismic energy dissipation. With K as the horizontal axis and ξ_a as the vertical axis, the data are plotted to generate the K-ξ_a relationship diagrams (Fig. 8 and Fig. 9), which characterize the compatibility between buckling restrained braces and viscous dampers in reinforced concrete frame structures with combined seismic energy dissipation.

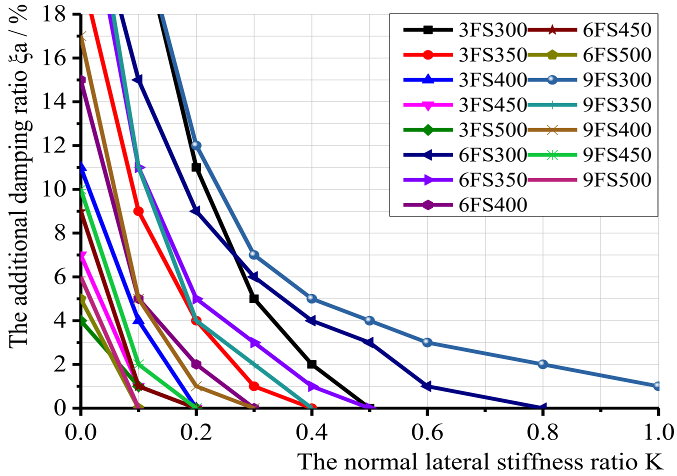


Fig.8. Group III relationship graphs of the normal lateral stiffness ratio and additional damping ratio

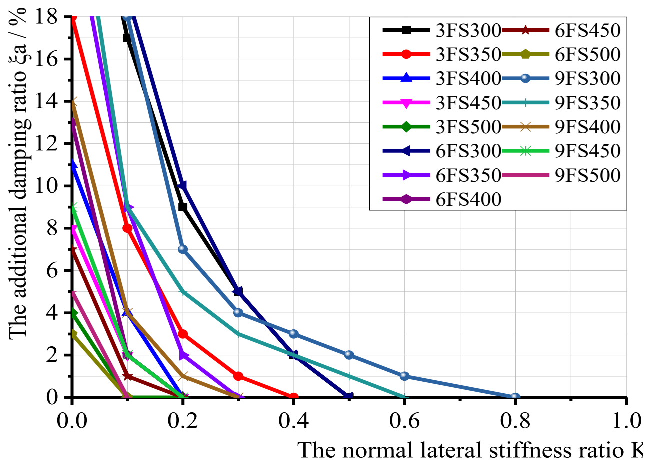


Fig.9. Group III relationship graphs of the normal lateral stiffness ratio and additional damping ratio

4. APPLICATION AND ANALYSIS

This study presents the design of a five-story commercial office building in Lancang County, Yunnan Province, China. The structure adopts a reinforced concrete frame equipped with a combined seismic energy dissipation scheme incorporating both buckling restrained braces and viscous dampers. The first and second floors, with a story height of 3.6 m each, are designated for commercial use, while the third to fifth floors, with a uniform story height of 3.0 m, are allocated for office functions. The total building height of 16.20 m remains well below the code-specified maximum allowable height of 24 m for this structural type. The basic seismic acceleration is 0.4g, belonging to the ultra-high intensity zone, and the design seismic grouping is Group III; the site category is Class II, and the site characteristic period is 0.45s. The structural floor beams and columns have uniform cross-section changes, and there is no local load concentration. The dampers are strategically positioned to accommodate architectural functional needs and facade design requirements, in accordance with the principles of "uniform, dispersed, and symmetrical" layout, as illustrated in Figure 9. The performance specifications of the proposed buckling restrained brace (BRB) are shown in Table 2.

TABLE 1. Structural seismic energy-dissipation objectives

Seismic energy dissipation objectives				
Structural category	Items	Specification		Damping targets
Reinforced concrete frame structure	the maximum inter-story displacement angle	frequent earthquakes	1/550	1/610
		rare earthquakes	1/50	1/100
	Base shear force	/		15 percent reduction

TABLE 2. Performance Specifications of Buckling Restraint braces

The number of BRB	Equivalent section	Yield capacity /kN	Yield displace-ment /mm	Maximum output for rare earthquake/ kN	Maximum axial force for frequent earthquake /kN	Maximum displace-ment for rare earthquake /mm
BRB1	10000	1950	6.0	2035	1803	22.70

Remarks: the BRBs are arranged continuously in one and two layers, total 32 pcs; Core material grade: Q235.

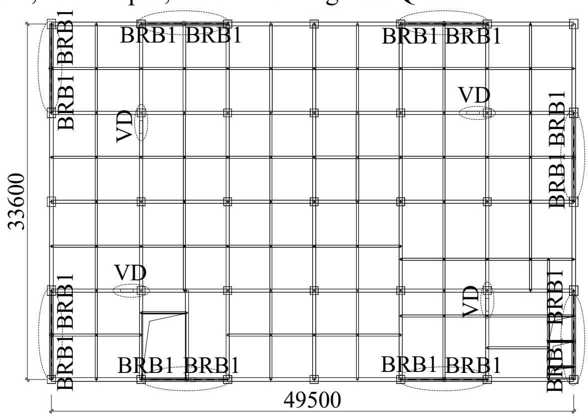


Fig.10. Layout of dampers

4.1 Determining the values of K and ξa for the combined seismic energy dissipation structures

The maximum inter-story displacement angle of the non-seismically damped structure is 1/375 (second floor), and the maximum Y-direction inter-story displacement angle is 1/371 (second floor) in the preliminary trial calculation; the X-direction story shear stiffness of the second floor is 13,688,000 kN/m, and the Y-direction story shear stiffness is 13,615,000 kN/m, and there is not much difference in the inter-story displacement angle and story stiffness in the two directions. According to the equivalent cross-section described in the specification of BRB of buckling restrained brace in Table 2, the total stiffness of buckling restrained brace is calculated in accordance with Eq. (1), and the ratio of its total stiffness value to the second story shear stiffness is taken to derive the nominal lateral stiffness ratio K=0.13, which is carried out according to the relationship graphs of K-ξ_a in Fig. 9. According to the 3FS350~6FS350 and 3FS400~6FS400 the linear interpolation of the number of floors takes the additional damping ratio ξ_a =0.04, and the total damping ratio of the structure is 0.05+0.04=0.09. According to this, the calculation under the frequent earthquakes is carried out, and the maximum inter-story displacement angle is calculated to be 1/649, which meets the established seismic energy dissipation objectives in Table 1.

4.2 Analysis of elastic time course under frequent earthquakes

In the elastic time-range analysis, five natural waves and two artificial waves are selected, and the base shear force of the structure calculated from each time-range curve meets the code requirements. The effective damping ratio of the viscous damper added to the structure under frequent earthquakes meets the requirements of K-ξ_a relationship curve Fig. 9 to find the additional damping ratio ξ_a = 0.04. It can be concluded that the actual energy dissipation effect of viscous dampers meets the preset seismic energy dissipation objectives, and the effect of seismic energy dissipation is good.

4.3 Analysis of elastic time course under rare earthquakes

The finite element analysis software SAP2000 is used to carry out the elastic-plastic time-history analysis, and two natural waves and one artificial wave are selected to carry out the calculation and analysis of a total of three seismic waves, and the maximum inter-story displacement angle of the floor obtained from the envelope under the action of three seismic waves is 1/119, which meets the preset seismic energy dissipation objectives of 1/100, and the dampers have a good the seismic energy dissipation effect. The overall seismic performance of the structure under the rare earthquakes has been significantly improved.

This case study demonstrates that the the combined seismic energy dissipation structures enables significant reductions in beam and column cross-sections compared to conventional structural systems, thereby providing greater flexibility in architectural space.A structure equipped exclusively with buckling restrained braces would require numerous BRB installations, which would substantially compromise the open space requirements typical of commercial buildings. Furthermore, this approach would significantly increase structural stiffness, resulting in higher total seismic base shear demands compared to the combined seismic energy dissipation structures.Conversely, a structure relying solely on viscous dampers would necessitate an impractically high additional damping ratio, leading to a substantial increase in the number of dampers required and consequently poor economic efficiency.In comparison to these single-device solutions, the combined seismic energy dissipation structures incorporate considerably fewer devices of both types. Relative to a conventional structure without damping devices, the combined seismic energy dissipation structures not only enhance structural stiffness and effectively limit lateral deformations but also reduces the total seismic base shear-a key indicator of overall seismic action. Additionally, it achieves these performance objectives at reduced construction costs while successfully meeting predetermined seismic performance objectives.

5. CONCLUSIONS

(1) This study systematically elucidates the combined seismic design mechanism incorporating buckling restrained braces and viscous dampers for reinforced concrete frame structures in ultra-high seismic intensity zones. The combined use of buckling-restrained braces and viscous dampers in reinforced concrete frame structures located in ultra-high seismic intensity zones enables full utilization of their respective advantages. BRBs can effectively limit lateral deformations, while VDs contribute through efficient energy dissipation under seismic excitation. This complementary interaction allows the combined seismic energy dissipation system to fulfill multi-level and multi-stage seismic design objectives, achieving significant reductions in both structural displacements and seismic shear forces. As a result, the combined application of BRBs and VDs substantially enhances the seismic performance of the structure.

(2) The findings demonstrate that to ensure adequate stiffness efficiency of the BRBs, the nominal lateral stiffness ratio should be limited to $K \leq 1.0$. Meanwhile, to fully utilize the energy dissipation capacity of viscous dampers, the additional damping ratio is recommended not to exceed $\xi_a \leq 18\%$. This parameter combination facilitates an effective synergistic interaction between stiffness and damping, thereby enhancing the overall seismic performance of the structure.

(3) A design chart based on the K–ξa relationship that reflects the compatibility between buckling restrained braces and viscous dampers is proposed, which can avoid the inconvenience of the previous design method based on response spectra due to the need for a number of the iterative trial calculations, and provides an intuitive and fast reference tool for the design of seismic energy dissipation of reinforced concrete structures in the ultrahigh-intensity zones. The accuracy and practicability of the K-ξ_a relationship diagram for the seismic energy dissipation design are verified by the application examples, which can provide a theoretical basis and practical guide for the seismic energy dissipation design of reinforced concrete frame structures in ultra-high intensity zones.

(4) The compatibility design charts developed in this study are specifically established for certain types of reinforced concrete frame structures, based on three key parameters: number of stories, lateral stiffness characteristics, and seismic grouping categories. However, the current applicability of these charts is subject to certain limitations. They have not yet been extended to other structural systems, such as steel structures or shear wall structures. Furthermore, the modeling assumptions did not account for variations in story height, joint behavior, or the extent of material nonlinearity development, which may consequently affect their accuracy in practical engineering applications. Future research should focus on developing generalized design methodologies that encompass a wider range of structural types and more comprehensive design parameters, while also further validating the applicability boundaries of the model across different nonlinear phases, so as to enhance the adaptability and reliability of this tool in complex engineering contexts.

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