

# Adaptability Between Structural Characteristics and Additional Effective Damping Ratio Calculation Methods

Qiong Yao, Chao Yang \*, Yingying Liang, Jinzhu Lu, Jiannan Jin

Liuzhou Orient Engineering Rubber Products Co., Ltd., Liuzhou 545025, Guangxi Province, China.

\* Correspondence: yangc@ovm.cn

**Abstract:** To investigate the significant influence of structural characteristics on the calculation of additional effective damping ratios in seismic energy dissipation structures, this study examines four typical structural types: steel frames, concrete frames, concrete frame–shear walls, and concrete shear walls. Additionally, the compatibility between the structural features and three calculation methods—the code method, energy ratio method, and time-variant method—is analyzed. Results show that the optimal method depends strongly on the structural type. For steel frames with low inherent damping and high ductility, the energy ratio method proves to be the most accurate. In the case of concrete frames, all three methods yield small calculation errors; however, the code method is recommended because its computational efficiency and accuracy are comparable to those of the time-variant method. For concrete frame-shear walls with notable stiffness variations, the time-variant method achieves the highest precision, although the code method remains a practical primary alternative. Regarding concrete shear walls, the code method tends to overestimate the damping effects, making the energy ratio method or time-variant method the preferred choice. This study establishes clear adaptation guidelines between structural characteristics and calculation methods, effectively resolves applicability issues, improves computational accuracy and design efficiency, and provides an important basis for the engineering application of viscous dampers.

**Keywords:** viscous fluid damper; additional effective damping ratio; seismic-damped structures; compatibility of calculation methods; different calculation methods

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## 1 Introduction

Energy dissipation technology protects primary structures by dissipating seismic energy through dampers, with its design core relying on accurate calculation of the additional effective damping ratio. Although the code-recommended strain energy method outlined in the current Technical Specification for Seismic Energy Dissipation of Buildings (JGJ 297—2013) [1] is widely adopted, its iterative process is complex and highly dependent on empirical estimates of damper deformation. Particularly, when structures enter the nonlinear stage or when damper layouts are complex, calculation errors can exceed 20% (Ding et al.) [2]. To improve the computational efficiency, researchers have proposed alternative methods such as the time-variant method (Zhou et al.) [3,4] and cumulative energy ratio method (Weng et al., Duan et al.) [5,6]. However, these methods have limitations: the time-variant method requires intensive tracking of dynamic time-history responses, resulting in high computational costs, while the cumulative energy ratio method, despite its clear physical meaning and ability to depict the damping ratio variation trend throughout the process, struggles to reflect the time-varying characteristics of local energy dissipation within a structure. More critically, existing research has predominantly focused on optimizing algorithms for single structural types (e.g., frames or shear walls), overlooking the differential impact of structural characteristics on the suitability of calculation methods. In a comparative study on effective damping ratio calculation methods for frame–shear wall structures with viscous dampers, He et al. [7] reported that different methods yield varying additional effective damping ratios.

They emphasized that the ratio calculation should consider factors such as the structural form, damper story placement, and different ground motion records. Wu et al. [8] demonstrated that the error of the code method for frame structures can be controlled within 5%, while for frame–shear wall structures, owing to abrupt stiffness changes and complex deformation coordination, the error for the same method can reach 15%. This finding indicates that the accuracy of a given method varies across structures, likely related to their inherent characteristics. Song [9] found that stiffness significantly influences the calculation of the additional effective damping ratio. Hu et al. [10] observed discrepancies in the estimation accuracy of different methods for steel frame structures. Lu et al. [11] investigated differences in the additional effective damping ratio calculation methods among Chinese, American, and Japanese codes for steel and concrete frame structures and proposed more reasonable accuracy requirements tailored to different structures. Most current studies have evaluated the validity of a calculation method using a single structural type, thereby neglecting the influence of structural characteristics. Consequently, considering that inherent structural features such as the low damping and high ductility of steel frames, stiffness interactions and abrupt changes in the frame–shear wall structures, and concentration of plastic deformation at the base of concrete shear walls [12] alter damper energy dissipation paths, the universal applicability of any single calculation method must be further investigated.

However, a systematic “structural characteristic–calculation method” adaptation framework is yet to be established. This gap leads to situations where the same calculation method may demonstrate completely opposite levels of accuracy for different structural systems. Consequently, engineering designs lack a quantitative basis for method selection, which may not only result in insufficient seismic protection owing to overestimated damping ratios but also cause resource waste from redundant configurations due to underestimation. Addressing the design risks arising from the current lack of an adaptation framework, the innovation of this paper lies in developing a quantifiable system for evaluating method compatibility. Moving beyond simple comparisons across structural types, this study aims to reveal the underlying mechanisms affecting the calculation accuracy and to establish a universal, quantifiable selection framework linking structural characteristics to calculation methods. Through systematic analysis and validation across four typical energy-dissipation structures—steel frames, concrete frames, frame–shear walls, and shear walls—this research transforms discrete empirical selection into a quantifiable decision-making process based on key structural parameters. This framework not only provides a precise and reliable basis for selecting calculation methods in engineering designs, thereby fundamentally mitigating the risks of underprotection or overdesign, but also advances the standardization and refinement of the analysis of energy-dissipation structures.

## 2 Calculation Methods for Additional Damping Ratio of Velocity-Dependent Viscous Dampers

### 2.1 Fundamental Calculation Principles

According to the energy balance criterion specified in the Code for Seismic Design of Buildings [13], the additional effective damping ratio of an energy-dissipated structure is determined by the ratio of the energy dissipated by dampers to the strain energy of the structure as follows:

$$\xi_a = \sum_j W_{cj} / (4\pi W_s) \quad (1)$$

where  $\xi_a$  is the additional effective damping ratio contributed by energy-dissipation components,  $W_{cj}$  is the energy dissipated by the  $j$  energy dissipation component in one cycle under the expected interstory displacement, and  $W_s$  is the

total strain energy of the structure equipped with energy-dissipation components under the expected displacement.

Based on the energy balance criterion, this paper employs three methods—the code-specified method, time-variant method, and energy ratio method—to calculate the additional effective damping ratio of an energy-dissipation structure.

### 2.2 Code-Specified Method

To avoid iterative calculations and displacement estimation errors, the code-specified method employs time-history extreme values for energy computation: the structural strain energy is determined by the maximum product of the story shear and interstory displacement over the entire time history, while the energy dissipated by dampers is calculated using the maximum product of the damper force and displacement over the full duration. The calculation formulas are as follows:

$$W_{s,max} = (1/2)\sum F_{i,max}u_{i,max} \tag{2}$$

$$W_{cj,max} = \lambda_1 F_{cj,max}u_{cj,max} \tag{3}$$

$$\xi_{a,max} = \sum_j W_{cj,max} / (4\pi W_{s,max}) \tag{4}$$

where  $W_{cj,max}$  represents the maximum energy dissipation of a single damper,  $\lambda_1$  denotes a function of the damping exponent,  $F_{cj,max}$  and  $u_{cj,max}$  are the maximum force and maximum displacement, respectively, over the time history,  $W_{s,max}$  indicates the maximum strain energy of the structure; and  $F_{i,max}$   $u_{i,max}$  represent the maximum story shear and maximum interstory displacement, respectively.

### 2.3 Time-Variant Method

The time-variant method proposed by Zhou Yun et al. [3,4] calculates the additional equivalent damping ratio through instantaneous energy integration. Its core formulas are as follows:

$$\xi_a = \frac{1}{T} \int_0^T \frac{\sum_{j=1}^m W_{cj}(t)}{4\pi W_s(t)} dt \tag{5}$$

Instantaneous strain energy of a structure is given as follows:

$$W_s(t) = \frac{1}{2} \sum_{i=1}^n F_{i,t}(t) \cdot u_{i,t}(t) \tag{6}$$

Instantaneous energy dissipated by a damper is given as follows:

$$W_{cj}(t) = \lambda(\alpha_j) \cdot F_{cj,t}(t) \cdot u_{cj,t}(t) \tag{7}$$

$$\lambda(\alpha_j) = \pi C_j |\dot{u}_{cj}(t)|^{\alpha_j - 1} \tag{8}$$

where  $F_{i,t}$  represents the story shear at the  $i$ -th story at time  $t$ ,  $u_{i,t}$  denotes the interstory displacement at the  $i$ -th story at time  $t$ ,  $\lambda(\alpha_j)$  is the velocity exponent correction function,  $F_{cj,t}$  indicates the damping force of the  $j$  damper at time  $t$ , and  $u_{cj,t}$  represents the relative displacement of the  $j$  damper at time  $t$ .

### 2.4 Energy Ratio Method

The energy ratio method [5,6], based on the principle of modal energy conservation, calculates the additional damping ratio using the ratio of structure's inherent damping ratio to the relative energy dissipation contribution of dampers.

The ratio of the cumulative energy dissipated by dampers to the cumulative strain energy of a structure is calibrated as follows:

$$\xi_a = (\sum_j W_{c,j,a} \cdot \xi) / W_{s,a} \quad (9)$$

In the formula,  $\sum_j W_{c,j,a}$  denotes the cumulative energy dissipated by the  $j$  damper in one complete cycle throughout the entire time history,  $W_{s,a}$  represents the cumulative total strain energy of the structure equipped with dampers over the entire time history, and  $\xi$  indicates the inherent damping ratio of the structure.

### 3 Rationality Verification of Additional Effective Damping Ratio

To systematically evaluate the seismic mitigation effectiveness of velocity-dependent nonlinear viscous dampers in different structural systems, this study selected four typical structural types as analytical objects: steel frame structures, concrete frame structures, concrete frame–shear wall structures, and concrete shear wall structures. A comparative analysis was conducted using the code-specified method, time-variant method, and energy ratio method, with nonlinear time history analysis employed to verify the applicability of these additional damping ratio calculation methods. All structures were equipped with viscous dampers, with a particular focus on their energy dissipation performance under design-based earthquake conditions.

#### 3.1 Project Overview

Analysis covered four typical types of building structure. The steel frame structure had four stories with plan dimensions of 42.9 m × 42.3 m. Columns and beams were constructed of Q355 steel. The primary column sections were box sections: □600×600×25 and □500×500×20. The main beams were I-sections: H500×300×10×20 and H600×350×12×25 (height × flange width × web thickness × flange thickness). The concrete frame structure was two stories high, with plan dimensions of 52.2 m × 42.0 m. The concrete strength grade of columns and beams was C30. The main column sections were rectangular (750×750), and the primary beam sections were rectangular (400×750 and 500×900). The concrete frame–shear wall structure had six stories and plan dimensions of 46.8 m × 20.4 m. The concrete strength grade was C35 for columns and walls and C30 for beams. The main column sections were rectangular (750×750). The shear wall thicknesses were 300, 350, and 400 mm. The primary beam sections were rectangular (250×650 and 300×800). The concrete shear wall structure comprised three stories with plan dimensions of 31.2 m × 13.5 m. The concrete strength grade for walls and beams was C40. The shear wall thicknesses were 250 and 300 mm, and the beam sections were rectangular (300×700 and 250×600).

Structural models of the energy-dissipation systems were developed in ETABS v22. An elastic modeling approach was employed, with rigid diaphragm assumptions applied at each floor level. Beams and columns were modeled using frame elements, slabs were modeled as membrane elements, and walls were modeled as shell elements. Dampers were simulated using nonlinear damper–exponential link elements. Analysis was conducted using the fast nonlinear analysis (FNA) method. The key structural parameters are summarized in Table 1, wherein the inherent damping ratio is specified as 0.04 for the steel structure and 0.05 for the concrete structures.

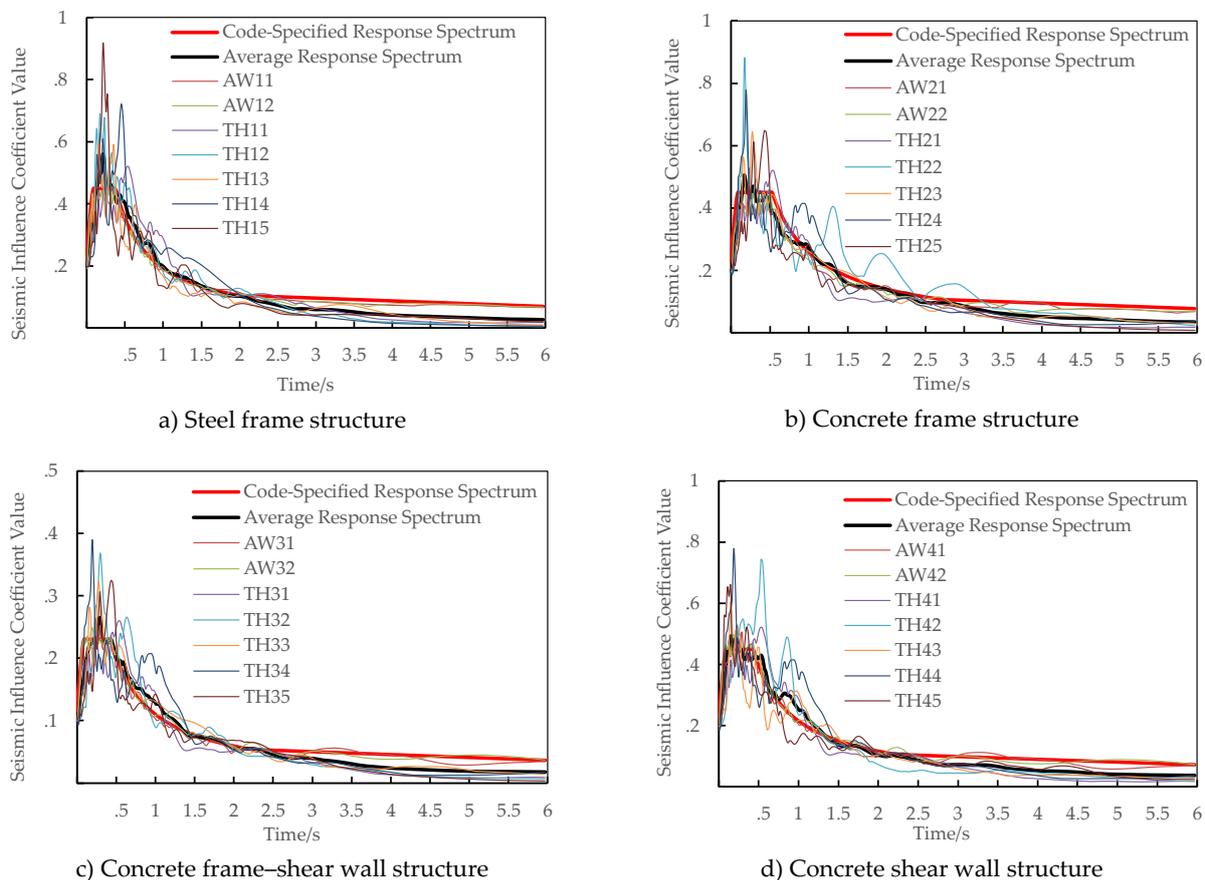
The seismic input consisted of five recorded strong ground motions and two artificially simulated waves, all satisfying the requirements for the peak ground acceleration (PGA), frequency spectrum, and duration (as shown in Figure 1). The constitutive behavior of dampers was simulated using the Maxwell model.

Considering the similar response patterns observed under bidirectional seismic excitation and for conciseness, this paper presents results for the primary X direction only; the response trends in the Y direction is fundamentally consistent.

**Table 1** Summary of structural engineering models

Structural type	Seismic fortification intensity	Design PGA (g)	Design earthquake group	Site class	Fundamental period /s	Damper configuration
Steel frame	8	0.20	Second	II	0.40	Chevron brace
Concrete frame	8	0.20	Second	III	0.55	Wall-mounted
Concrete frame–shear wall	7	0.10	Third	II	0.45	Wall-mounted
Concrete shear wall	8	0.20	Third	II	0.45	Wall-mounted

Note: The number of dampers is 8, the velocity exponent  $\alpha$  is 0.2, and the damper coefficient is  $400 \text{ kN}\cdot(\text{s/m})^\alpha$ .



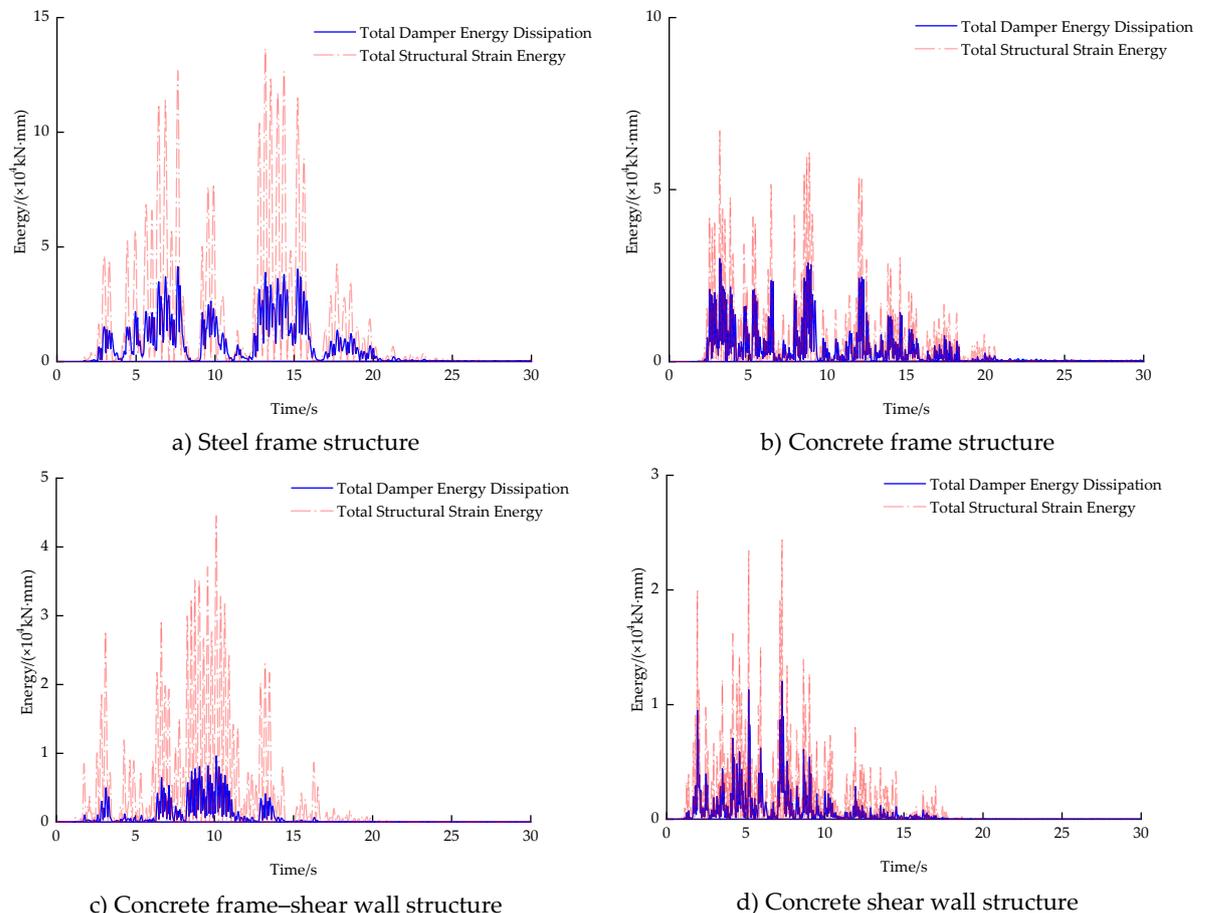
**Figure 1** Comparison of earthquake response spectra and code response spectra (Note: AW: artificial wave; TH: nature wave)

### 3.2 Influence of Structural Energy Dissipation Differences on Additional Effective Damping Ratio Calculation

By analyzing differences in the characteristics and energy dissipation of different structural types, the energy dissipation paths and efficiencies of various structures under seismic action differ significantly. Owing to space limitations, this paper only presents the time-history curves of the strain energy and damper energy

dissipation for the four structural types under Artificial Wave 1, as shown in Figure 2. Analysis of the strain energy and damper energy dissipation time histories reveals that the steel frame structure, with its low damping and high ductility, exhibits intense time-varying energy dissipation, where the damper energy consumption far exceeds the structural strain energy, dominating the energy dissipation process. The concrete frame structure, owing to its relatively uniform stiffness, shows higher damper energy dissipation than but close to the structural strain energy. Meanwhile, the concrete frame–shear wall structure demonstrates similar levels of the damper energy dissipation and structural strain energy because of the stiffness variations caused by frame–shear wall interactions and energy sharing by shear walls. The shear wall structure, characterized by highly concentrated stiffness, exhibits the energy dissipation behavior of the shear wall itself absorbing and dissipating the majority of input energy during the elastoplastic phase, resulting in a relatively lower total energy dissipation by dampers. These fundamental differences in the energy dissipation mechanisms of these structures lead to asynchrony between the peak values of the structural strain energy and damper energy dissipation, causing deviations in the calculated additional effective damping ratio, with maximum values often lagging behind energy peaks.

Therefore, given the complexity of structural characteristics, a single method cannot be used for all structural types. To more accurately evaluate the actual seismic mitigation effect of dampers in various structures and guide their optimized designs, this study develops an evaluation framework for additional effective damping ratio calculation methods targeting major structural types, aiming to improve the computational accuracy and rationality.

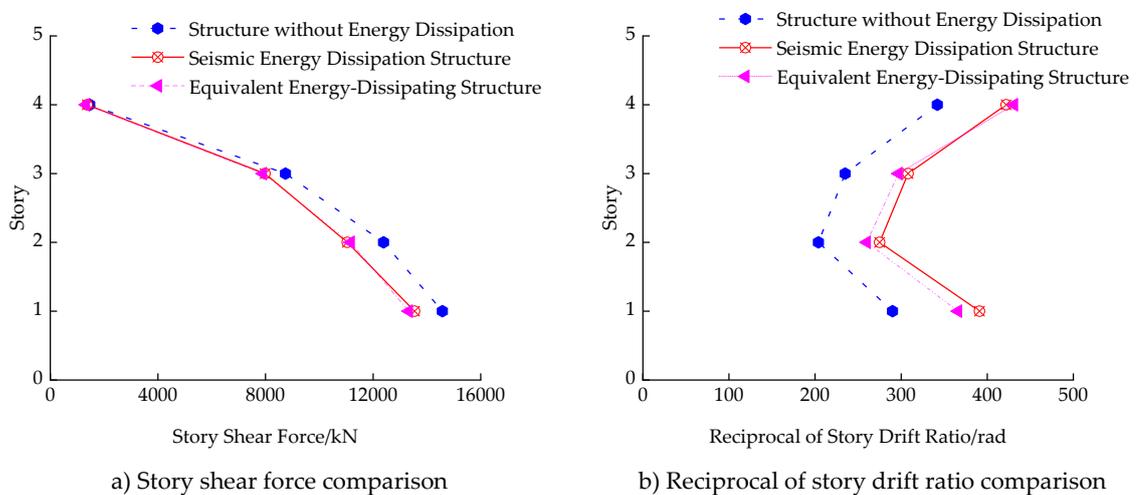


**Figure 2** Time history of structural strain energy and damper energy dissipation

### 3.3 Validation of Additional Effective Damping Ratio for Energy Dissipation Structures Using Equivalent Model

To evaluate the seismic mitigation effect of a damper-equipped structure, determining its additional effective damping ratio is necessary. Because this parameter cannot be directly measured, this study employs an equivalent model [2,3] approach for validating its value. By inputting a hypothetical additional effective damping ratio into the original energy-dissipation structure, an “equivalent structure” is constructed. Subsequently, by comparing key response indicators—the story shear forces and interstory drift ratios—between the energy-dissipation structure and equivalent structure, the additional effective damping ratio is derived and validated. The damping ratios and time-history responses presented here are the mean values obtained from the seven ground motion records.

Taking the steel frame structure as an example, the code-specified method, time-variant method, and energy ratio method were first used to calculate the additional effective damping ratio, yielding values of 2.7%, 3.4%, and 2.2%, respectively. Given this range of values, an intermediate value of 2.7% was selected as the initial additional damping ratio for the equivalent structure. However, comparative analysis reveals that the story responses of the equivalent structure are significantly smaller than those of the energy-dissipation structure, indicating that the 2.7% damping ratio is overestimated. Through iterative adjustment of the input value and reduction in the additional effective damping ratio, when the equivalent model input damping ratio was set to 2.1%, the story shear responses of the equivalent structure essentially matched those of the energy-dissipation structure, as shown in Figure 3. Additionally, errors in the interstory drift ratios remain within an acceptable range. Accordingly, the additional effective damping ratio of this energy-dissipation structure is considered to be approximately 2.1%. This validation method was extended to other structural types.



**Figure 3** Response comparison between energy-dissipated structure and equivalent structure by story

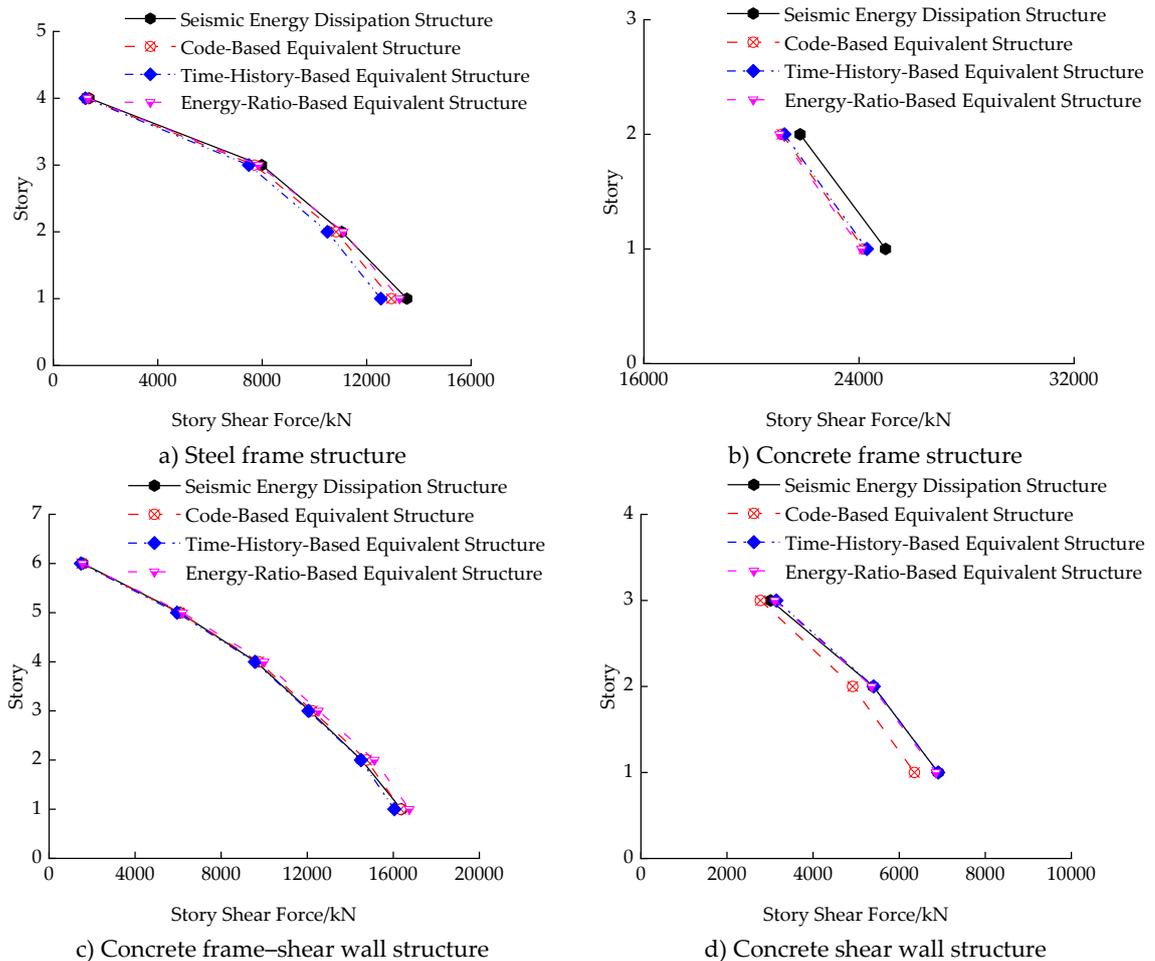
### 3.4 Adaptability Verification of Additional Effective Damping Ratio Calculation Methods

This study aims to verify the adaptability of different additional effective damping ratio calculation methods to structural characteristics and evaluate the accuracy and rationality of their results. The specific procedure is as follows. The additional effective damping ratios calculated by various methods were superimposed on the structural inherent damping ratio to obtain the total damping ratio. Subsequently, viscous dampers in the original energy-dissipation structure were removed to construct the corresponding equivalent damping structural model. Finally, through nonlinear time history analysis, the seismic responses of the equivalent model were compared with those of the original energy-dissipation

structure. The damping ratios and time-history responses represent the mean values from the recorded seven ground motions, as shown in Figure 4. Based on the verification of the response consistency of the equivalent models, the results of the three calculation methods were further compared and analyzed with the additional effective damping ratio derived from the response matching of the equivalent models, as presented in Table 2. By applying different calculation methods to compute the additional effective damping ratio for various types of energy-dissipation structures, this study systematically evaluated the applicability and accuracy of these different calculation methods across different structural types, thereby clarifying their adaptability relationships with structural characteristics.

**Table 2** Computation results of average additional effective damping ratios

Additional effective damping ratio calculation	Structural type							
	Steel frame	Relative errors (%)	Concrete frame	Relative errors (%)	Concrete frame–shear wall	Relative errors (%)	Concrete shear wall	Relative errors (%)
Code-based method	2.7%	28.6	4.3%	13.2	1.2%	-14.3	5.9%	68.6
Time-history-based method	3.4%	61.9	4.1%	7.9	1.5%	7.1	3.4%	-2.9
Energy-ratio-based method	2.2%	4.8	4.2%	10.5	0.8%	-42.9	3.6%	2.9
Seismic-energy-dissipation structure	2.1%	/	3.8%	/	1.4%	/	3.5%	/



**Figure 4** Comparison of story shear forces between equivalent structures and energy dissipation structures

To address the significant discrepancies in calculating the additional effective damping ratio of energy-dissipation structures using the code-specified method, time-variant method, and energy ratio method, a systematic analysis of the four typical structural types was conducted to derive the calculated additional effective damping ratio across different structural systems. This enabled the establishment of the quantitative adaptation criteria between structural mechanical characteristics and calculation methods. The results indicate the following.

- (1) As shown in Table 2, the additional effective damping ratio for the steel frame energy-dissipation structure is 2.1%. Comparing the results obtained from the different calculation methods reveals that the relative error of the time-variant method reaches 62% and that of the code-specified method is 28.6%; notably, the energy ratio method demonstrates the smallest relative error of only 4.8%. Furthermore, Figure 4a) indicates that the story shear response calculated using the energy ratio method-based equivalent model closely matches that of the energy-dissipation structure. This fully demonstrates that the energy ratio method is more suitable and yields more reasonable results for calculating the additional effective damping ratio of steel frame energy-dissipation structures.
- (2) As indicated in Table 2, the additional effective damping ratio for the energy-dissipated concrete frame structure is 3.8%. A comparison of the results obtained from the different calculation methods reveals that the relative error of the code-specified method is 13%, while that for both the energy ratio method and time-variant method are less than 11% (10.5% and 7.9%, respectively). Furthermore, Figure 4b) shows that the story shear responses calculated using the equivalent models of all three methods closely match the results from the corresponding energy-dissipated structures. This indicates that, for calculating the additional effective damping ratio of energy-dissipation concrete frame structures, the code-specified method and energy ratio method are preferred for conventional concrete frames. For structures with higher complexity or when further verification is needed, the time-variant method can be employed for supplementary analysis.
- (3) As shown in Table 2, the additional effective damping ratio of the energy-dissipation concrete frame-shear wall structure is 1.4%. Comparing the results of the different calculation methods reveals that the relative error of the energy ratio method is 43% and that of the code-specified method is 14.3%; meanwhile, the time-variant method has the smallest relative error of only 7.1%. Figure 4c) indicates that the story shear response calculated using the time-variant method-based equivalent model closely matches that of the energy-dissipation structure, and the error of the code-specified method-based equivalent model is also small. This suggests that for calculating the additional effective damping ratio of energy-dissipation concrete frame-shear wall structures, the time-variant method offers higher accuracy and applicability. However, considering the computational efficiency, the code-specified method is recommended as the primary approach; meanwhile, when further verification is needed, the time-variant method can be used for supplementary calculations.
- (4) As shown in Table 2, the additional effective damping ratio for the energy-dissipation concrete shear wall structure is 3.5%. Comparing the results obtained from the different calculation methods reveals that the relative error of the code-specified method reaches 69%, while that of the energy ratio and time-variant methods are both 2.9%. Additionally, Figure 4d) shows that the story shear responses calculated using the energy ratio method-based and time-variant method-based equivalent models closely match those of the energy-dissipation structure. This indicates that for calculating the additional effective

damping ratio of energy-dissipation concrete shear wall structures, the energy ratio and time-variant methods demonstrate high accuracy and strong applicability, and their combined use is recommended.

### 3.5 Influence of Parameter Variation on Calculation Method Compatibility

In practical engineering, damper parameters are often adjusted according to specific structural requirements. If research is conducted based solely on a single set of parameters, conclusions regarding the suitability of calculation methods may fail to encompass complex and variable working conditions. This limitation can not only diminish the practical value of the research but also potentially lead to compatibility deviations in real-world applications. Therefore, to enhance the reliability and generalizability of our findings, this study supplements the main analysis with computational validation under two additional sets of damper parameters: a damping coefficient of  $C = 500(\text{kN}\cdot(\text{s}/\text{m})^\alpha)$  with a damping exponent of  $\alpha = 0.3$  and a damping coefficient of  $C = 300(\text{kN}\cdot(\text{s}/\text{m})^\alpha)$  with a damping exponent of  $\alpha = 0.1$ . By calculating the additional effective damping ratio for a concrete frame structure under these two parameter sets, the influence of the variation in the damper parameters on the compatibility of the calculation methods was systematically analyzed. This provides a more comprehensive and reliable reference for engineering applications.

**Table 3** Influence of parameter variation on the additional effective damping ratio

Concrete frame additional effective damping ratio	$C=400(\text{kN}\cdot(\text{s}/\text{m})^\alpha)$	$C=300(\text{kN}\cdot(\text{s}/\text{m})^\alpha)$	$C=500(\text{kN}\cdot(\text{s}/\text{m})^\alpha)$
	$\alpha=0.2$	$\alpha=0.1$	$\alpha=0.3$
Code-based method	4.3%	3.8%	4.6%
Time-history-based method	4.1%	4.1%	4.2%
Energy-ratio-based method	4.2%	3.6%	4.9%
Seismic-energy-dissipation structure	3.8%	3.5%	4.4%

As shown in Table 3, for the energy-dissipated concrete frame structure, the deviations among the additional effective damping ratios calculated by the three methods remain small even when the damper parameters are adjusted. This finding indicates that for this type of structure, variations in the damper parameters do not significantly affect the results of the additional effective damping ratio. Therefore, in practical applications, prioritizing the use of the code method and cumulative energy ratio method for conventional concrete frame structures is recommended. If the structural system is more complex or if result verification is required, the time-variant method can be employed as a supplementary analysis approach.

## 4 Conclusions

A systematic analysis of four types of energy-dissipation structures—steel frames, concrete frames, concrete frame–shear walls, and concrete shear walls—reveals that the calculation accuracy of the additional effective damping ratio is highly dependent on structural characteristics and that the selection of a suitable calculation method must align with the structure type. For steel frame structures, the cumulative energy ratio method should be prioritized as its equivalent model closely matches the story shear response of the energy-dissipation structure. For concrete frame structures, the efficient code method and cumulative energy ratio method are recommended, with the time-variant method being used for supplementary verification under complex conditions. For concrete frame–shear wall structures, the code method is recommended as the primary approach, while the time-variant method should be adopted when high precision is required. For concrete shear wall

structures, either the cumulative energy ratio method or time-variant method must be selected, and the code method is not suitable.

In summary, the compatibility guidelines between energy-dissipation structure types and calculation methods for the additional effective damping ratio are established for the first time in this study. Furthermore, this study effectively addresses the significant discrepancies in the results obtained from different methods and enhances calculation reliability. Given that the additional effective damping ratio is influenced by factors such as the damper story placement and ground motion characteristics, this study focuses on conventional damper parameters commonly used in standard structures. Further investigations into other influencing factors will be conducted in the future study.

**Conflict of interest:** All the authors disclosed no relevant relationships.

**Data availability statement:** The data that support the findings of this study are available from the corresponding author, Yang, upon reasonable request.

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AUTHOR BIOGRAPHIES

	<p><b>Qiong Yao</b> M.E., Engineer. She graduated from Xi'an University of Architecture and Technology in 2019. Research Direction: Seismic and Vibration Reduction of Engineering Structures. Email: 1284706180@qq.com</p>		<p><b>Chao Yang</b> D.Eng, Senior Engineer. He graduated from Hunan University of Civil Engineering in 2022. Research Direction: Seismic and Vibration Reduction of Engineering Structures. Email: yangc@ovm.cn</p>
	<p><b>Yingying Liang</b> B.E Sensor Engineer. She graduated from Central South University of Forestry and Technology in 2009. Engaged in R&amp;D of seismic mitigation technologies for structures and emerging fields. Honored with the Guangxi Technological Invention Award (2nd Class), Liuzhou Technological Invention Award (1st Class), multiple national patents, and contributed to several industry and local standards. Email: liangyy@ovm.cn</p>		<p><b>Jinzhu Lu</b> B.E. Engineer. He graduated from Guilin University of Electronic Technology in 2009. Research Direction: Seismic and Vibration Reduction of Engineering Structures. Email: ljz1231@126.com</p>
	<p><b>Jiannan Jin</b> M.E. Senior Engineer. She graduated from Dalian Maritime University in 2013. Research Direction: Seismic and Vibration Reduction of Engineering Structures. Email: 543619729@qq.com</p>		