

Review of Composite Dampers: From Energy Dissipation Mechanisms to Engineering Applications

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Abstract

Composite dampers, which integrate multiple energy dissipation mechanisms-such as metallic yielding, frictional sliding, viscoelastic deformation, and shape memory alloy effects-into a single device, provide an effective solution to the limitations of conventional single-mechanism dampers under multi-level seismic excitations. As a result, they have emerged as a significant research frontier in structural vibration control. Motivated by both theoretical considerations and engineering demands, this review systematically summarizes recent progress in representative composite dampers, including metal-friction, shape memory alloy (SMA)-based, viscoelastic-friction, and lead-viscoelastic composite dampers. The review focuses on their configuration principles, energy dissipation mechanisms, and hysteretic performance characteristics. Furthermore, restoring-force modeling approaches and parameter optimization strategies for composite dampers are discussed. Finally, the remaining challenges and future research directions in this field are outlined.

Keywords

Composite Dampers; Seismic Energy Dissipation; Metallic Yielding; Shape Memory Alloys; Viscoelastic Damping; Self-Centering Behavior.

1. Introduction

Structural energy dissipation and seismic mitigation technology aims to reduce the seismic response of primary structural systems by installing energy dissipation devices at selected locations. These devices are designed to enter an inelastic state prior to the main structural components and dissipate seismic input energy through mechanisms such as frictional sliding, elastoplastic hysteretic deformation, or viscoelastic deformation. According to their energy dissipation mechanisms, conventional dampers can generally be classified into two major categories: displacement-dependent dampers, such as metallic dampers and friction dampers, and velocity-dependent dampers, such as viscous dampers and viscoelastic dampers[1-2].

However, dampers based on a single energy dissipation mechanism have exhibited evident limitations in practical applications. Metallic dampers usually require relatively large yield displacements to activate their energy dissipation capacity. Under minor earthquakes, they often provide only additional stiffness without effectively participating in energy dissipation, and may even amplify the seismic response of the structure due to the increase in stiffness. Similarly, if the slip force of a friction damper is designed according to the requirements of major earthquakes, the damper may not be effectively activated under minor earthquakes. In addition, metallic dampers tend to exhibit significant residual deformation after earthquakes, while the energy dissipation capacity of viscoelastic dampers may decrease substantially under low-frequency and ultra-high-frequency excitations.

The concept of composite dampers has been proposed to address these challenges. Composite dampers integrate two or more types of dampers or energy dissipation materials into a single device through specialized structural configurations[1]. By taking advantage of different energy

dissipation mechanisms, they can achieve multiple performance objectives, such as staged energy dissipation, self-centering capability, and bidirectional energy dissipation. Against the background of rapid developments in information technology, intelligent technologies, and advanced material science, composite damper technology has become an important direction for promoting innovation in energy-dissipating seismic-resistant structures, and is gradually transitioning from laboratory research to engineering applications.

2. Metal-Friction Composite Dampers

Metal-friction composite dampers are among the earliest types of composite dampers to receive research attention[3]. Their core concept is to combine metallic yielding and frictional sliding mechanisms, both of which belong to displacement-dependent energy dissipation systems, in a parallel configuration. By taking advantage of the difference between the yielding displacement of metallic components and the slip displacement of friction components, staged energy dissipation can be achieved.

2.1. Basic Configurations and Energy Dissipation Mechanisms

Zhou et al.[3] first proposed a steel-yielding-friction composite energy dissipation device and established a corresponding trilinear restoring-force model. Under minor earthquakes, the damper mainly provides additional stiffness. Under moderate earthquakes, the friction damper is activated and begins to dissipate energy. Under major earthquakes, the energy-dissipating steel ring yields and enters the energy dissipation stage. This design concept established the basic paradigm of staged energy dissipation for metal-friction composite dampers.

In recent years, continuous progress has been made in the configuration innovation and performance optimization of metal-friction composite dampers. Duan et al.[4] proposed a metal-dual-friction-hinge composite damper by combining a flexural metallic damper with a relatively large yield displacement and a rotational friction damper with a relatively small activation displacement. Experimental results showed that, within the deformation range corresponding to the yield displacement of the metallic damper, energy dissipation was mainly provided by the friction mechanism. Compared with conventional metallic dampers, the proposed composite damper exhibited fuller hysteresis loops and a significantly improved equivalent viscous damping ratio. A restoring-force model for the composite damper was also proposed, indicating that performance-based design can be achieved by adjusting the parameters of the metallic damper and the dual-friction-hinge damper.

Yang et al.[5] developed a friction-metal hybrid asynchronous dual-stage shear damper (FMHADSD), which consists of two friction units and one asynchronously activated metallic yielding unit. The device exhibits a clear dual-stage working mechanism. Theoretical equations for a quadrilinear skeleton curve were proposed, and the dual-stage mechanical behavior was verified through full-scale damper tests. More importantly, a corresponding uniaxial material model was developed in OpenSees, providing an effective numerical tool for seismic response analysis of structures equipped with composite dampers.

The friction-metal-yielding composite damper proposed by Yang et al.[6] demonstrates another ingenious configuration strategy. In this device, energy is dissipated through friction under small to moderate displacements, while metallic yielding is activated under large displacements. The metallic yielding component also provides additional hardening stiffness after degradation of the frictional stiffness. By varying parameters such as the bolt pretension force and the width of short steel tubes, the study found that optimal performance could be achieved when the ratio of radial yield force to friction force ranged from 1.1 to 5.6 and the ratio of radial yield displacement to the designed slip displacement ranged from 1.0 to 1.7.

2.2. Composite Application with Buckling-Restrained Braces

Buckling-restrained braces (BRBs) are an important type of displacement-dependent damper. Combining friction mechanisms with BRBs can not only compensate for the limited energy dissipation capacity of BRBs under minor earthquakes, but also enable dual-stage yielding and energy dissipation. Cheng Runyu et al.[7] combined a friction damper with a BRB to develop a dual-yielding buckling-restrained brace (DYBRB). The results showed that the component exhibited stable and full hysteresis loops with clear dual-yielding characteristics. Even after fracture of the core plate, the device was still capable of dissipating energy. Moreover, a larger friction damping force led to stronger energy dissipation capacity.

2.3. Composite Dampers with Yielding Reserve Stiffness

Zhang et al.[8] proposed a composite damper with yielding reserve stiffness, referred to as a yielding reserve stiffness damper (YRSD). The device consists of a friction unit and a metallic yielding unit, and its unique collaborative energy dissipation mechanism enables the damper to provide reserve yielding stiffness when the structure approaches its limit state. Experimental results showed that when the bolt pretension force increased by 100%, the enclosed area of the rectangular hysteresis loop of the YRSD increased by 107.3%. When the thickness of the X-shaped steel plate increased by 2 mm, the resistance of the damper increased by 26.2%, while the post-yield stiffness increased by 37.9%. The discrepancy between numerical simulation and experimental results was less than 10%, confirming the reliability of the proposed model.

3. SMA-Based Composite Dampers

Shape memory alloys (SMAs) have introduced a new dimension of self-centering capability into the development of composite dampers because of their unique superelasticity and shape memory effect[9-10]. During loading, SMA materials can dissipate energy through stress-induced martensitic phase transformation. Upon unloading, they can recover their original shape automatically, thereby reducing or even eliminating residual deformation. By combining SMAs with friction, viscoelastic, viscous, or metallic dampers, composite devices can be designed to achieve the dual objectives of energy dissipation and self-centering.

3.1. SMA-Friction Composite Dampers

SMA-friction composite dampers are among the earliest developed SMA-based composite dampers. Xue Sufeng et al.[11] installed SMA wires on the basis of a Pall friction damper and developed a novel composite damper. When applied to the vibration control of spatial grid structures, the device showed effective control of both nodal displacements and member internal forces. Qian Hui et al.[12] developed a self-centering SMA friction damper, referred to as the HSMAFD. In this device, the relative sliding between friction plates drives the SMA wires to undergo tension and compression, thereby generating both frictional energy dissipation and SMA deformation-induced energy dissipation. Coupled translational-torsional shaking table tests verified its effectiveness in controlling both translational displacement and torsional angular displacement.

In recent years, research on SMA-friction composite dampers has become more refined and comprehensive. The recentering variable friction damper (RVFD) proposed by Ozbult et al. incorporates piezoelectric actuators in addition to SMA elements and a friction device. The piezoelectric actuators are used to regulate the normal force of the friction device, enabling simultaneous control of peak displacement and acceleration responses of the structure. A 2025 experimental study further investigated the failure behavior and reparability of SMA cable-friction damping devices under extreme deformation, providing important durability evidence for the practical engineering application of SMA-based composite dampers.

3.2. SMA-Metal Composite Dampers

Combining SMAs with metallic dampers can compensate for the excessive residual deformation commonly observed in conventional metallic dampers after earthquakes. Naeem et al. arranged SMA bars diagonally on both sides of a steel slit damper to form an SMA-based composite steel slit damper. Analytical results showed that the proposed damper could significantly reduce both residual deformation and maximum inter-story drift of the structure.

Sun Zhiguo et al.[13] proposed a novel SMA-mild-steel hybrid damper, referred to as the SMA-MSHD. In this device, SMA bolts are used as self-centering components, while X-shaped metallic dampers are arranged in parallel to enhance energy dissipation capacity. The hysteresis loops of the damper exhibit a typical flag-shaped behavior, indicating excellent energy dissipation capacity together with stable self-centering performance. The theoretical model, experimental results, and finite element simulations were found to be in good agreement.

3.3. SMA-Viscoelastic and SMA-Viscous Composite Dampers

SMA-viscoelastic composite dampers are primarily intended to address the reduction in energy dissipation capacity of viscoelastic dampers under low-frequency and ultra-high-frequency excitations, as the mechanical performance of SMA materials is relatively less sensitive to loading frequency. Yao Yuan et al. installed SMA wires on the outer surface of a viscous damper cylinder to develop an SMA-viscous damper. The device was considered suitable for long-period, long-span cable-stayed bridges, and showed better displacement control performance than conventional viscous dampers. Zhao Xiang et al.[14] used pulleys to amplify the displacement by a factor of N , enabling the deformation of SMA elements to reach N times the structural deformation. The resulting hybrid shape memory alloy viscous damper (HSMAMD) integrates both displacement amplification and self-centering capabilities.

Baikuntha et al. combined viscoelastic devices with SMA wires and proposed a superelastic viscous damper (SVD). The seismic responses of six-story and nine-story steel frame structures equipped with SVDs were systematically investigated under multi-level earthquakes and aftershock sequences. The results demonstrated that the SVD could effectively mitigate seismic responses and improve post-earthquake functionality. Consequently, the structures equipped with SVDs also exhibited significantly enhanced resistance to aftershocks.

3.4. Systematic Reviews of SMA-Based Composite Dampers

Recent review studies have provided a systematic theoretical framework for SMA-based composite dampers. The review and comparative study titled A Review and Comparative Study on the Performance of Self-Centering Damping Devices Based on SMA classified SMA-based self-centering damping devices into four categories: tension-type, shear-type, rotational-type, and isolation-bearing-type devices. It also proposed a new evaluation index, namely the synergistic optimization coefficient of energy dissipation capacity and self-centering capability. This index provides a unified criterion for performance comparison and design optimization of SMA-based composite dampers with different configurations.

Meanwhile, research on SMA cable-based self-centering devices has established a multi-level framework covering material, component, and structural scales. This framework includes key mechanical issues such as SMA cable anchorage systems, cyclic stability, temperature effects, fatigue performance, and stress relaxation. These studies provide systematic theoretical and experimental support for the engineering application of SMA cables in self-centering braces.

4. Viscoelastic-Friction Composite Dampers

Viscoelastic-friction composite dampers combine two different energy dissipation mechanisms: velocity-dependent viscoelastic deformation and displacement-dependent frictional sliding.

Compared with metal-friction composite dampers, their distinctive advantage lies in the fact that viscoelastic materials can contribute to energy dissipation even under small displacements. This feature compensates for the limitation of displacement-dependent dampers, which are often ineffective under micro-amplitude vibrations.

Wu et al.[15] conducted a systematic experimental and numerical investigation on a novel viscoelastic-friction composite damper. The study provided a detailed analysis of the device configuration and summarized the relevant research background with 70 references. Their work further demonstrated the potential of integrating viscoelastic and frictional mechanisms to improve the adaptability of dampers under different vibration amplitudes and loading conditions.

Another important engineering application of viscoelastic-friction composite dampers is their integration with buckling-restrained braces. Zhou Ying et al.[16] designed a viscoelastic composite buckling-restrained brace in which viscoelastic materials were arranged at both ends of the brace and connected in parallel with the energy-dissipating core. This configuration ensures that, even when the core remains elastic, the viscoelastic materials can still provide damping and energy dissipation. Moreover, after fracture of the core, the viscoelastic components can continue to function and contribute to structural vibration control. A similar configuration proposed by Marshall et al. incorporated slotted holes as displacement limiters, ensuring that the core could participate in energy dissipation under large displacement demands.

5. Lead-Viscoelastic Composite Dampers

Lead, as a metallic material with excellent deformation-tracking capability and high energy dissipation efficiency, has been widely used in composite dampers. However, direct exposure of lead to air may cause environmental pollution. Therefore, encapsulating lead within steel tubes or viscoelastic materials has become a key technical issue in the development and application of lead-based composite dampers.

Zhou Yun's research team has conducted systematic and in-depth studies on lead-viscoelastic composite dampers. Lead-viscoelastic dampers dissipate energy through the combined action of shear or extrusion-induced plastic deformation of the lead core and shear hysteretic deformation of the viscoelastic layer. As a result, they exhibit composite characteristics associated with both displacement-dependent and velocity-dependent energy dissipation mechanisms. Fan-shaped lead-viscoelastic dampers can be directly installed at beam-column joints in frame structures, offering advantages such as compact size, convenient installation, and easy replacement.

Research conducted in 2024 further advanced this field. Zhou et al.[17] proposed a rotational lead-viscoelastic damper (RLVD) with resistance capacity. The device consists of laminated rubber and lead cores and can be used for rotational energy dissipation at beam-column joints. Studies on the use of lead-viscoelastic dampers to enhance the seismic performance of steel-tube-confined reinforced concrete column joints showed that increasing the diameter of the lead core can significantly improve the energy dissipation capacity of the damper. It was recommended that the number of lead cores be set to two, and that the ratio of the lead-core area to the composite viscoelastic-layer area be controlled within the range of 6%-8%. In addition, a rotational lead-viscoelastic damper with separated flexural and shear functions has also been proposed and applied to beam-column joints in prefabricated structures. ABAQUS finite element analysis verified the rationality of its working mechanism.

6. Numerical Modeling and Design Methods for Composite Dampers

6.1. Development of Restoring-Force Models

Restoring-force models provide the theoretical basis for characterizing the mechanical performance and optimizing the design of composite dampers. Different configurations of composite dampers generally correspond to different types of restoring-force models. For example, the steel-yielding-friction composite energy dissipation device can be represented by a trilinear restoring-force model. The restoring-force model of the metal-dual-friction-hinge composite damper is established based on the parallel combination of the metallic damper and the friction hinges. For the friction-metal hybrid asynchronous dual-stage shear damper, theoretical equations for a quadrilinear skeleton curve have been proposed to describe its staged mechanical behavior.

6.2. Finite Element Analysis and Numerical Simulation

Finite element analysis plays an indispensable role in the performance investigation of composite dampers. From early simulations using ANSYS to the recent development of specialized material models in OpenSees, numerical methods have not only provided efficient tools for configuration optimization of composite dampers, but also laid a technical foundation for seismic response analysis of entire structures equipped with composite damping devices. Through finite element modeling and nonlinear dynamic analysis, key mechanical behaviors such as staged activation, stiffness degradation, hysteretic energy dissipation, residual deformation, and failure modes can be systematically evaluated.

6.3. Performance-Based Design Philosophy

One of the core advantages of composite dampers lies in their parameter adjustability and design flexibility. Duan Shukun et al. pointed out that performance-based design can be achieved by adjusting the parameters of the metallic damper and friction hinges, thereby satisfying the seismic requirements of different application scenarios. Zhang et al. further revealed that when the energy dissipation capacities of the friction unit and the metallic yielding unit are approximately equal, the overall energy dissipation performance of the composite damper reaches an optimal level. These findings provide important guidance for the rational design and engineering application of composite dampers.

7. Engineering Applications and Future Prospects

7.1. Applications in Bridge Engineering

Preliminary progress has been achieved in the application of composite dampers in bridge engineering. Studies on the SCMYD-LRB bearing connection system for double-column bridges have shown that, after the installation of shape-optimized composite metallic dampers, damage to bridge bearings and shear keys can be significantly reduced. This system can effectively decrease the risk of transverse girder unseating, thereby improving the seismic safety of bridge structures.

7.2. Key Issues Remaining

Although considerable progress has been made in the study of composite dampers, several key issues remain to be addressed:

(1) Design specifications are still lacking. Unified technical guidelines for the design methods and performance indicators of composite dampers have not yet been established. Simplifying structural systems and clearly defining qualitative and quantitative performance indicators are essential for promoting engineering applications.

(2) Material-structure collaborative design remains insufficient. Although intelligent materials such as SMAs have demonstrated excellent self-centering capability, their constitutive relationships, fatigue performance, and environmental sensitivity under complex stress states still require systematic investigation. In addition, novel composite materials, such as interpenetrating metallic-multiphase composites with grid-like architectures, have shown outstanding damping performance and energy dissipation potential. However, their application in seismic mitigation for civil engineering structures remains at an early stage.

(3) The generality of numerical models is limited. Most existing numerical models for composite dampers have been developed for specific configurations, and a generalized material model capable of uniformly describing different composite energy dissipation mechanisms is still lacking.

(4) Engineering application experience remains insufficient. At present, relatively few building structures in China have adopted composite dampers. Demonstration projects should therefore be strengthened to help designers and the public better understand and gradually accept this advanced seismic design concept.

7.3. Future Research Directions

Future research on composite dampers can be further advanced in the following directions:

(1) Innovative development of multifunctional composite dampers should be emphasized. Against the background of the integration of intelligent technology, new energy technology, and advanced material technology, new composite dampers that combine multiple functions-such as self-centering, staged energy dissipation, and multidirectional energy dissipation-should be explored.

(2) Greater attention should be paid to the application of intelligent materials and novel composite materials. By deeply integrating SMAs, piezoelectric materials, and magnetorheological materials with metallic and viscoelastic materials, new intelligent composite dampers with adaptive and semi-active control capabilities can be developed.

(3) Composite dampers should be synergistically applied with resilient structural systems. Combining composite dampers with rocking structures and self-centering structural systems may lead to more comprehensive earthquake-resilient structural systems with enhanced post-earthquake recoverability.

(4) Life-cycle-oriented design theories should be developed. By comprehensively considering the initial cost, maintenance cost, and post-earthquake repair cost of composite dampers, life-cycle-cost-based optimization design methods can be established.

8. Conclusions

By ingeniously integrating different energy dissipation mechanisms into a single device, composite dampers exhibit significant advantages in resisting multi-level seismic actions, achieving staged energy dissipation, and providing self-centering capability. They have therefore become an important direction in the development of structural energy dissipation and seismic mitigation technologies. From metal-friction composite dampers to SMA-based composite dampers, and from viscoelastic-friction composite dampers to lead-viscoelastic composite dampers, substantial progress has been achieved in configuration innovation, performance characterization, numerical simulation, and design methods.

Nevertheless, the design specifications for composite dampers remain incomplete, and engineering application experience is still relatively limited. In the future, with the continued development of intelligent materials, advanced manufacturing technologies, and resilient structural system theories, composite dampers are expected to make greater contributions to enhancing the seismic resilience of building structures.

References

- [1] Yan X Y, Wang X, Cao C, et al. Research progress of composite dampers[J]. *Earthquake Engineering and Engineering Dynamics*, 2020, 40(3): 54-70. (in Chinese)
- [2] Wen L. Research progress on energy dissipation and seismic mitigation technology and dampers for building structures[J]. *Sichuan Building Science*, 2020, 46(4): 423-432. (in Chinese)
- [3] Zhou Y, Deng X S, Liu J. Performance study of a steel-yielding-friction composite energy dissipation device[J]. *Earthquake Engineering and Engineering Dynamics*, 1999, 19(1): 127-131. (in Chinese)
- [4] Duan S K, Tang L, Huang G, Zhang Y B, Zhang X Q, He J T. Experimental study on metal-dual-friction-hinge composite dampers[J]. *Earthquake Engineering and Engineering Dynamics*, 2025, 45(3): 222-231. (in Chinese)
- [5] Yang C T, Xie L L, Sun H, et al. Theoretical, experimental, and numerical investigations on friction-metallic hybrid asynchronized-type double-stage shear damper[J]. *Thin-Walled Structures*, 2025, 202: 113107.
- [6] Yang X W, Li M Y, Zhang Y Q, et al. Development and Experimental Research on Friction-Metal Yield Composite Damper[J]. *KSCE Journal of Civil Engineering*, 2025, 29(11).
- [7] Cheng R Y, Shi W L, Ma L G, Zhu P J. Experimental study on mechanical properties of mixed friction buckling-restrained brace[J]. *Noise and Vibration Control*, 2025, 45(5): 273-278. (in Chinese)
- [8] Zhang X R, Zhu L H, Liu L B, et al. Hysteretic performance of composite damper with yielding reserve stiffness[J]. *Buildings*, 2024, 14(12): 3931.
- [9] Zhou Y, Ali A, Shi F, et al. Research progress on SMA cable-based self-centering devices and structures[J]. *Engineering Mechanics*, 2026, 43(3): 1-20. (in Chinese)
- [10] A review and comparative study on the performance of self-centering damping devices based on SMA[J]. *Structures*, 2025, 71: 108027.
- [11] Xue S F, Wang L, Zhuang P. Design and performance study of an SMA composite friction damper[J]. *World Earthquake Engineering*, 2006, 22(2): 1-6. (in Chinese)
- [12] Qian H, Li H N, Ren W J, et al. Design and experimental study of a shape memory alloy composite friction damper[J]. *Journal of Building Structures*, 2011, 32(9): 58-64. (in Chinese)
- [13] Duan J X, Zhang S H, Qian H. Research on the hysteretic performance of self-centering shape memory alloy-mild steel hybrid damper[J]. *Journal of Vibration and Shock*, 2025, 44(20): 28-39. (in Chinese)
- [14] Zhao X, Liu Z H, Wang S L, et al. Design and analysis of a shape memory alloy composite viscous damper[J]. *Earthquake Engineering and Engineering Dynamics*, 2016, 36(6): 72-78. (in Chinese)
- [15] Wu Q Y, Jia C Y, Liu W G, et al. Experimental and numerical study on a novel viscoelastic-friction composite damper[J]. *Structures*, 2025: 108840.
- [16] Zhou Y, Hu Q, Wu R L. Experimental study on seismic performance of composite energy-dissipating braces[J]. *Journal of Central South University (Science and Technology)*, 2018, 49(7): 1726-1733. (in Chinese)
- [17] Zhou Y, Hong J X, Zhang Q, et al. A rotary lead viscoelastic damper with force-resisting capacity: Experimental verification and parametric analysis[J]. *Structures*, 2024, 62: 106219.