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Simple design method of structure with metallic yielding dampers based on elastic–plastic response reduction curve

Hua Shen [a,b], Ruifu Zhang [a,*], Dagen Weng [a], Cong Gao [a], Hao Luo [a], Chao Pan [a,c]

[a] *Research Institute of Structural Engineering and Disaster Reduction, Tongji University, Shanghai 200092, China*
[b] *College of Civil Engineering, Nantong Vocational University, Nantong 226007, China*
[c] *College of Civil Engineering, Yantai University, Yantai 264005, China*

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A B S T R A C T

Metallic yielding dampers (MYDs) can effectively improve the seismic performance of structures and are used in many practical engineering applications. In this paper, a simple elastic–plastic design method of a structure with MYDs is proposed based on the elastic–plastic response reduction curve (EPRRC). In widely used traditional design methods based on the elastic response reduction curve, the elastic–plastic behavior of the main structure is neglected. However, such methods may overestimate the vibration control effect of MYDs, especially their effect on acceleration reduction, which is demonstrated in this study. The EPRRC, which can directly reflect the relationship between MYDs' characteristic parameters and the responses of the structure with MYDs in the elastic–plastic range, is proposed to improve the reliability of a structure with MYDs. Then, the corresponding design procedures are presented. To illustrate and verify the effectiveness of the proposed design method, a six-story reinforced concrete frame is analyzed by time history analysis. In conclusion, the proposed design method for the structure with MYDs can adequately satisfy the seismic performance targets under different seismic levels.

1. Introduction

In traditional aseismic structures, seismic energy is absorbed by the plastic deformation of the structural members such as beams, columns and braces, which may cause structural damage under earthquake events [1]. Such damage is usually difficult to check, expensive to repair, and may pose a serious threat to people's lives and properties. To prevent such damage, the concept of control strategies has been introduced into the field of structural engineering. Among the commonly used structure control methods, passive energy dissipation technology has been proven to be an effective method and is widely used in building and bridge structures [2,3].

A metallic yielding damper (MYD) is a type of hysteretic damper made of metal that utilizes the plastic deformation of hysteretic materials, such as mild steel, to dissipate the input seismic energy. Kelly et al. [4] first introduced MYDs into a building structure to dissipate seismic energy after conducting conceptual and experimental studies. In the ensuing years, considerable efforts were made to investigate the seismic performance of the structure with MYDs and use these devices in the field of structural vibration control. It was confirmed that such devices can effectively improve the structural seismic performance [1,5–16]. According to the type of yielding mechanism, MYDs can be categorized into flexural plate systems, torsional bar dampers, yielding ring dampers, extrusion devices, shear panel dampers, etc. [17]. In addition to added damping and stiffness devices and bucking-restrained braces, many new MYDs have been developed in recent years, such as a dual-function metallic damper [18], a shear and flexural yielding damper [19], and dual-pipe dampers [20].

MYDs have been found to have many advantages such as an easy manufacturing process, convenient installation, relatively low cost, and extreme reliability; therefore, they have been adopted in many engineering practices [21–25]. Generally speaking, by incorporating MYDs into a structure, the stiffness and damping of the structure can be significantly adjusted [26]. More seismic energy is absorbed because of the increased damping. Hence, the seismic responses of a structure with MYDs can be clearly reduced. However, according to the response spectrum theory, the added stiffness of the structure with MYDs may result in a decrease in displacement and an increase in acceleration. Because of the great influence of MYDs on the structural performance and the coupling effect of the added damping and stiffness, the practical design of a structure with MYDs is more complex than that of a

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* Corresponding author.
E-mail address: zhangruifu@tongji.edu.cn (R. Zhang).

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structure with viscous dampers, where only the damping characteristic is adjusted [17].

To adopt MYDs in practical engineering applications and meet performance targets, the development of appropriate design methods becomes very necessary. Tsai et al. [8] proposed a design method that incorporates the capacity design concept and the optimal strength ratio of the main structure into MYDs, and Clark et al. [27] suggested using the equivalent static lateral-force provision to design a structure with MYDs. The Japan Society of Seismic Isolation proposed a design method based on the elastic response reduction curve (ERRC) to design a structure with MYDs [28], which has been widely applied. However, these design methods do not consider the inelastic behavior of the main structure. Under a moderate or severe seismic event, the main structure may experience an obvious inelastic behavior, and these design methods may not be suitable in such cases. To overcome these deficiencies, two well-known displacement-based design methods—a coefficient method based on FEMA 273 [29] and a capacity-spectrum method based on ATC-40 [30]—are used to design structures with MYDs. Because of the limitations involved in the application of MYDs to existing structures and the complexity in the static nonlinear analysis of structures with MYDs, the direct displacement-based design method [31–33] was developed. However, structural damage is caused by both the maximum displacement and the accumulated energy dissipation during seismic events. Thus, the energy-based design method was developed for structures with MYDs [34–36]. Considering the actual mechanical interaction between the damper and the brace, Lomiento et al. [37] proposed a graphical design method. Some optimization algorithms and control theories are also used to design structures with MYDs, that is, to determine the number of MYDs along with their locations and characteristic parameters [38–44]. Although some design methods that consider the inelastic behavior of a structure have been proposed, they are still very complex for practical use. Therefore, it is necessary to develop a design method for structures with MYDs that is simpler and more practical but also considers the structural inelastic behavior.

In this study, while considering the elastic–plastic behavior of the main structure, the existing ERRC is expanded to the elastic–plastic response reduction curve (EPRRC) based on the equivalent linear theory and the response spectrum theory. Within the elastic–plastic range, the EPRRC can directly reflect the relationship between the MYDs' characteristic parameters and the responses of a structure with MYDs. Then, the results of comparisons between the EPRRC and the ERRC are analyzed, and a simple design method based on the EPRRC is proposed. Lastly, the effectiveness of the proposed design method is verified by applying it to a six-story reinforced concrete (RC) frame and performing a time history analysis.

2. Response reduction curve

2.1. Response reduction indexes

The peak responses of an elastic single-degree-of-freedom (SDOF) system can be predicted by a common elastic response spectrum. The mathematical relationship of the peak displacement S_d, pseudo-velocity S_{pv}, and pseudo-acceleration S_{pa} can be expressed as follows [45]:

$$S_d(T,\zeta) = \frac{T}{2\pi} S_{pv}(T,\zeta) = \left(\frac{T}{2\pi}\right)^2 S_{pa}(T,\zeta) \tag{1}$$

where T and ζ are the fundamental period and the damping ratio of the SDOF system, respectively.

The force–displacement relationship of an elastic main structure with an MYD is illustrated in Fig. 1, where the elastic stiffness of the main structure is K_f, and the paralleled MYD is idealized as a bilinear model with elastic stiffness K_a, yielding force F_{ay}, and displacement u_{ay}. The total curve is bilinear with the initial stiffness K_0 calculated by adding the elastic stiffness of the main structure K_f and that of the MYD K_a. Once the MYD reaches its yielding displacement, the corresponding total lateral force is F_y, and the increase in the lateral force is resisted only by the main structure until the maximum displacement $u_{\max}$. The equivalent linear method is adopted herein to consider the inelastic behavior of the structure with an MYD. Hence, the bilinear system can be substituted with an equivalent linear model with stiffness K_{eq}, as shown in Fig. 1. Then, the seismic response of the structure with the MYD can be estimated using the design response spectrum with the equivalent period T_{eq} and the damping ratio ζ_{eq}. This estimation procedure is discussed further in this section.

The equivalent period T_{eq} can be determined as:

$$T_{eq} = T_f\sqrt{\frac{K_f}{K_{eq}}} = T_f\sqrt{\frac{\mu_a}{\mu_a + K_a/K_f}} \tag{2}$$

where $\mu_a = u_{\max}/u_{ay}$ is the maximum ductility coefficient, and T_f is the period of the main structure.

Considering the inherent damping ratio ζ_0 and the hysteretic damping ratio of the MYD ζ_a, the total equivalent damping ratio of the elastic structure with the MYD ζ_{eq} can be expressed as follows:

$$\zeta_{eq} = \zeta_0 + \zeta_a \tag{3}$$

where ζ_0 is usually set to 5% for an RC structure and 2% for a steel structure. The term ζ_a can be calculated as follows [30]:

$$\zeta_a = \frac{E_D}{4\pi E_S} \tag{4}$$

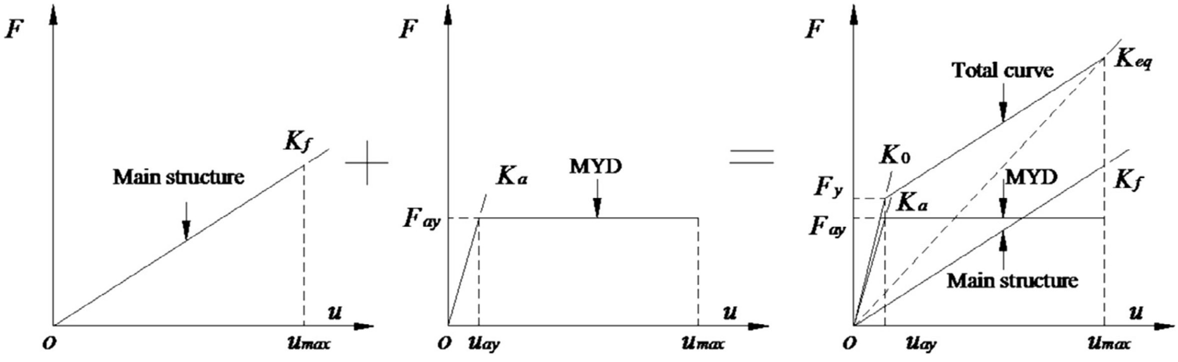

Fig. 1. Force–displacement relationship of the elastic structure with the MYD.