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Seismic performance evaluation and design of steel structures equipped with dual-pipe dampers

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ABSTRACT

Dual-pipe damper (DPD) is a metallic yielding device for passive control of structures, introduced recently by the authors. The objective of the current study is to provide guidelines for implementing DPDs in actual steel buildings, evaluate and compare their performance against other metallic dampers. In this study, a representative load–displacement model for DPDs is proposed for the first time, and assessed based on previous experimental cyclic tests. Guidelines for the design of DPD devices are also presented. Three steel moment resisting frames of 5, 10 and 20 stories are designed and then equipped with DPDs of various properties. The responses of the frames to seven earthquake excitations are investigated using dynamic nonlinear time-history analyses. Performance of the DPD devices is then evaluated through various response parameters including the normalized energy ratios. The results prove the effectiveness of the DPD devices in dissipating a considerable portion of the input seismic energy and significantly reducing the non-structural and structural damage. The responses of a 10-story frame equipped with DPDs are compared to those of the frame with TADAS devices. The results show that the structure equipped with DPD, with its unique secondary hardening portion in force-displacement, results lower structural and non-structural damage compared to TADAS.

1. Introduction

The traditional concept of designing building frames for seismic loads is based on the plastification of the main elements of a structure such as beams, columns, and braces. As a result, the energy dissipation in frame members can lead to undesirable structural damage to the load-carrying elements. Moreover, most structural elements exhibit strength degradation and low damping after the very first cycles of an earthquake excitation. To avoid these deficiencies, the concept of structural control was proposed and developed by several researchers during the last four decades [1,2]. Yielding of metals was first suggested by Kelly et al. [3] in the early 1970s as a mechanism for structural control. It was soon proved to be one of the most economical and effective mechanisms of passive control. Several yielding metallic dampers have been developed for structural application during the last two decades; among which, the most popular devices have been the X-shaped ADAS device [4], triangular TADAS device [5], honeycomb damper [6], shear-panel damper [7] and buckling-restrained braces (BRB) [8].

Recently, pipe damper was introduced by Maleki and Bagheri [9,10] as a simple passive device, using a steel pipe loaded in shear. Despite its excellent ductility, the device demonstrated low stiffness and strength compared to some other passive dissipative devices. To enhance the effectiveness and performance of the pipe damper, Maleki and Mahjoubi [11] introduced a dual-pipe system connected with a special welding scheme. This new passive device was called the dual-pipe damper or DPD. The device consists of two horizontal pipes in contact, welded to each other and to top and bottom supporting plates at certain locations (see Fig. 1). Later in 2014, an in-filled version of DPD, called the infilled pipe damper (IPD), was proposed by the authors [12] to enhance the performance even further.

Experimental quasi-static cyclic tests were performed on four DPD specimens [11], all displayed high ductility and stable hystereses up to relatively large displacements. Fig. 2 displays the deformed shape of a DPD specimen made with 110 mm diameter, 4.1 mm thick pipes, after failure. DPD devices dissipate seismic energy through plastic deformation of steel pipes, mainly in flexural form. At large deformations, a stiffening behavior was observed in the hystereses of the DPD specimens [11]. The stiffening behavior is attributed to a tensile-flexural action formed in the central part of the DPD in relatively large deformations (see Fig. 2). This causes gradual increase of plastic stiffness and strength to a much higher value. This behavior can prevent large drifts and P-Δ moments in structures subjected to severe earthquakes.

Advantages of the DPD over many available metallic dampers, such as its light weight, low cost, simple manufacturing, large force to weight ratio, large dissipated energy to weight ratio and large deformation capacity (30% to 36% its height) make it an economical and effective

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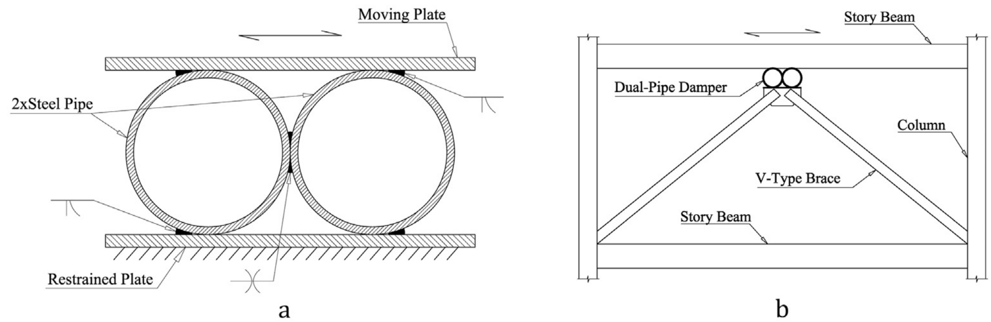

Fig. 1. a) Dual-pipe damper configuration; and b) installation configuration for DPD.

solution for passive energy dissipation in both new structures and structures to be retrofitted [11].

Several researches have been performed in the fields of response evaluation, optimization and design of structures with hysteretic dampers of different types [13–24]. Xia and Hanson [13] carried out a parametric study on two 10-story building frames equipped with ADAS devices to find out their performance and response to seismic loading. They identified the yield displacement, strain-hardening ratio, ratio of the device stiffness to the bracing member stiffness and ratio of the device stiffness to the story stiffness as the most important parameters, distinguishing the performance of yielding dampers in frames.

Curadelli and Riera [14] considered 6-story concrete and 9-story steel moment resisting frame structures with metallic dampers. They calculated the fragility curves of the structures with and without passive devices and concluded that the probability of failure of the structures may be decreased to 1/5 of the initial value by introducing external metallic dampers in the cases studied.

Kim and Choi [17] investigated energy dissipation capacity and nonlinear dynamic response of two five- and ten-story steel structures equipped with buckling-restrained braces and proposed a design procedure to meet a given target displacement. Oviedo et al. [24] studied the earthquake response of a ten-story reinforced concrete building structure with hysteretic dampers. The three parameters considered were damper to frame strength and stiffness ratios and yield drift ratio; however, only two of the parameters were independent. They concluded that structures with low yield story drift ratio demonstrate the largest reduction in the inelastic demand and permanent damage to the main frame.

The objective of the current study is to guide designers in implementing DPDs in actual steel buildings and to evaluate the DPD performance in reducing the seismic responses of steel frames. Considering the second hardening branch observed in force-displacement of DPDs, the other goal of this study is to evaluate the effect of this specific property of DPDs on preventing damage to the building frames. First, a simple load–displacement model for DPDs is suggested to be used in nonlinear analyses, for the first time. Design guidelines for DPDs are also proposed. The responses of three steel structures equipped with DPDs of various yield strengths are obtained using nonlinear dynamic time-history analyses and compared to those of bare frames. Energy dissipation of dampers and frames subjected to the earthquake motions is evaluated and discussed. The results show that DPD devices can prevent destructive damage to main frame elements by dissipating almost all the hysteretic energy which would be imposed to a building in an earthquake.

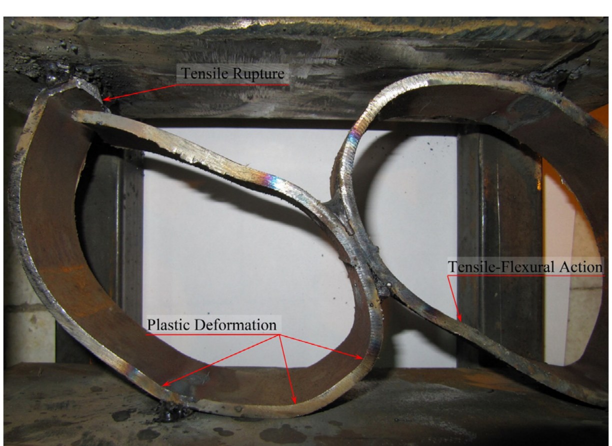

Fig. 2. Deformed shape of a DPD specimen with 110 mm diameter and 4.1 mm thickness.

2. Simplified force-displacement model of DPDs

The following relationships are recommended for mechanical properties of DPDs, based on tests and numerical studies [11]. In these relationships: $100 \le D \le 350$ mm and $20 \le D/t \le 35$. The material considered is ASTM A-36 steel.

$$\Delta_y = 0.0001\,(4.75D - 8.2)\left({}^{D}/_{t}\right) \tag{1}$$

$$K_0 = 3156L\left({}^{D}/_{t}\right)^{-3.14} \tag{2}$$

$$\mu = 333\left({}^{D}/_{t}\right)^{-0.8} \tag{3}$$

$$E_D = 0.015L\ .\ t^{1.77} \tag{4}$$

in which Δ_y, K_0, μ and E_D denote DPD yield displacement (mm), DPD elastic stiffness (kN/mm), DPD ultimate ductility and total energy dissipated by DPD (kJ), respectively. D, t and L are the pipes diameter, thickness and length in mm. Note, however, the total dissipated energy and ductility of a passive damper depend also on material properties and loading history. The values calculated by Eqs. (3) and (4) are approximate in nature and may be used as a reference value.

Having the parameters K_0, Δ_y and μ, one can easily calculate the parameters P_y (yield force) and Δ_u (ultimate displacement) by basic mechanics.

Herein, a trilinear characteristic model is proposed to represent the DPDs inelastic behavior for further analytical investigations (see Fig. 3). The model is simple, yet able to consider the strain hardening and the second hardening branch of DPDs. The elastic stiffness (K_e) of the trilinear model can be calculated from Eq. (2). The equivalent yield displacement in the trilinear model is assumed 1.5 times of that calculated by Eq. (1), on the basis of the experimental and FE study results [11].

The nonlinear stiffness (K_p) and large deformation stiffness (K_l) values are suggested to be 6% and 25% of the DPD elastic stiffness,