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Infilled-pipe damper

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ABSTRACT

This paper introduces a new passive control device for protecting structures against earthquakes. The device consists of two welded pipes which have two smaller pipes inside them and the spaces between the pipes are filled with metals such as lead or zinc. The device is loaded in shear and takes advantage of plastification of the outer pipes, the inner pipes and the infilled metals, and the friction between metals as energy absorption mechanisms. Quasi-static cyclic tests are performed on six specimens all showing stable hystereses and high damping. A finite element model is developed and calibrated against test results. The model is used to find the optimum sizes of pipes needed for a better hysteretic response. Equations are given for prediction of key performance parameters of the damper.

1. Introduction

Structures are normally designed for reduced seismic forces based on the notion that energy dissipation takes place in designated structural elements in addition to some inherent damping. Examples of these energy absorbing elements are the plastic hinges in beams, columns and steel braces. This design method has several shortcomings such as considerable strength and/or stiffness degradation in the hysteresis curves of the elements in many cases, low hysteretic damping in the elements and possible severe damage in gravity-load carrying members which may cause collapse of the structure. In addition, rigid frames undergo large inter-story drifts resulting in considerable P–Δ effects and damage to structural and nonstructural elements. Due to these shortcomings, the idea of structural control was envisioned.

Structural control consists of three main categories: active control, passive control and semi-active control. In active and semi-active structural control systems, the structure motions are modified by the action of a control system using external energy supply. Fully active systems add forces to the structure by use of multiple sensors and real-time controlled dampers to control structural deformations, while semi-active systems apply relatively little amount of energy to manipulate certain structural properties during an earthquake [1,2]. Considerable research has been conducted in the field of semi-active and active structural control in the last two decades [3–5].

Passive control systems in effect reduce the input energy to the system and/or increase damping by using either isolation system devices installed at the base of a structure or dissipating devices at floor levels. The objective is to absorb the seismic input energy as much as possible, thus reducing the demands and damage to gravity-load carrying members. Passive control systems may also increase lateral stiffness and strength of structure.

Advantages of passive systems over active and semi-active systems are their simplicity, low cost (initial and maintenance), ease of installation and replacement and not needing external power source. The concept of passive structural control was first applied to buildings in New Zealand and Japan. Application of passive structural control is rapidly growing throughout the world, both in new construction and seismic retrofitting [6–10].

Several mechanisms such as yielding of metals, friction, phase transformation of metals, deformation of viscoelastic materials and fluid orificing have been used to dissipate seismic energy in passive devices during the last four decades. Among these, yielding of metals is the simplest, most economical and most effective mechanism used in dissipative devices. Kelly et al. [11,12] first suggested utilizing this mechanism in the early 1970s. They also developed dissipative devices based on yielding of mild-steel in flexure and torsion and performed cyclic tests on some samples.

Many new hysteretic dissipative devices have been proposed by researchers based on yielding of metals in different modes, during the last four decades. Two most popular devices are X-shaped and triangular steel plate dampers, known as ADAS (added damping and stiffness) and TADAS (triangular ADAS), which are widely used in the USA, Japan and Europe [13,14]. The ADAS and TADAS dampers exploit out-of-plane flexural yielding of steel X-shaped or triangular plates to dissipate earthquake energy. U-shaped steel dampers also apply the out-of-plane flexural plastic deformation of two U-shaped plates to absorb the seismic energy [15]. Honeycomb damper, shear-panel damper and slit

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damper dissipate seismic energy by using in-plane shear or flexural yielding of steel plates [16–18]. Another widely used yielding damper is "buckling restrained brace" which is constituted of a steel core yielding in tension or compression. The yielding core is surrounded by a steel casing filled with mortar or concrete, which prevents the steel core from buckling [19].

Maleki and Bagheri [20,21] proposed a passive dissipative device called the "pipe damper" and proved it to be an effective energy dissipating device through cyclic tests. Stable hysteretic loops and good energy absorption were observed in experiments performed on pipe damper samples. A bi-linear model for the pipe damper hysteresis behavior was also suggested by the authors. According to the results of the experiments, the stiffness and strength of pipe damper are low, compared to some other passive dissipative devices, despite having excellent ductility. Although this may be resolved by using several pipe dampers at each story level to control a typical structure, the available space and architectural aspects may limit the application.

To enhance the performance of pipe damper, Maleki and Mahjoubi [22] introduced the dual-pipe damper (DPD) which is fabricated from two horizontal pipes in contact, welded to each other and to top and bottom supporting plates at certain locations to optimize the performance. DPD dissipates seismic energy by plastic deformation of steel pipe material, mainly in flexural form. A series of experimental quasi-static cyclic tests were performed on four DPD samples by the authors. All damper specimens displayed high ductility and stable hysteresis loops up to relatively large displacements. In addition, a tensile stiffening behavior was observed in the central part of DPDs at large displacements that causes gradual increase of plastic stiffness and strength to a much higher value. This behavior enhances the performance of DPDs in structures subjected to very severe earthquakes and prevents large drifts and P–Δ moments. The DPD was shown to possess advantages over many available metallic dampers namely, light weight, low cost, simple manufacturing, large force to weight ratio, large dissipated energy to weight ratio and large deformation capacity of about 30% to 36% its height.

Despite the excellent performance of the DPD, the authors decided to make it even more efficient by using two additional pipes inside the main pipes and filling the space between them with an infill (Fig. 1). The infill material can be metallic, nonmetallic or composite and can be chosen depending on the property that needs to be enhanced.

In this research, only metallic infill is considered. Two metals are chosen, namely lead (Pb) and zinc (Zn). These metals are easily melted and cast into the space between the pipes and have adequate stiffness and ductility. Lead has been used in lead-rubber bearings as an isolation device for years and has an excellent seismic energy absorption capability.

The new device is called the "infilled-pipe damper" or IPD and adds both strength and stiffness to structures in addition to energy dissipation capability. The added strength and stiffness and energy dissipation of IPD are much more than an equivalent DPD damper. Especially, the lead-IPD shows a superior performance due to energy absorption property of lead. Pure zinc also dissipates energy by its plastic deformation, having high elongation of up to 65%. Another source of energy dissipation in the IPD is the friction between the infill and the steel pipes and the cover plates (if used). This gives a unique advantage to the IPD that uses multiple energy dissipation mechanisms in one device, namely steel (both main pipes and inner pipes) plastification, lead or zinc plastification and friction. Therefore, IPD possesses almost all of the advantages of DPD and more.

In the next sections, the design of IPD is discussed in detail first. Next, the results of experimental quasi-static tests performed on six samples of IPD are presented. Further, a finite element (FE) model of the IPD, considering nonlinearity, large deformation, contact (including friction) and steel material damage with ABAQUS [23] software is introduced and is calibrated against the test results. Finally, a parametric study is performed on different pipe sizes and damper lengths using the proposed FE model. Recommendations for optimum sizes are given. Equations are proposed for prediction of key performance parameters of the damper.

2. IPD configuration

The main part of IPD is similar to DPD and is made up of two horizontal pipes in contact (hereinafter called the "main pipes") welded to each other and to top and bottom supporting plates at certain locations (see Fig. 1). The six lines of weld used in the fabrication of IPD include two flare V groove welds between the pipes and four flare bevel groove welds between the pipes and supporting plates.

Two additional pipes of smaller diameter (hereinafter called the "inner pipes") are held inside the main pipes. The spaces between the main and inner pipes are filled with molten lead or zinc. The infill material should completely fill the space between the pipes even after cooling and contraction. In cyclic loading, due to Poisson's effect, the infilled metal tends to squeeze out of the pipes. Lead, because of its high Poisson's ratio (0.44 against 0.25 for zinc), is more vulnerable to this effect. This may lead to degradation in hysteresis loops of the damper. To prevent the lead from protruding the damper, two plates (hereinafter called the "cover plates") are installed at the two sides of the damper and connected to each other via two steel rods bolted at both ends. Note that, the cover plates are not welded to anything and do not interfere with the deformation of the pipes. The corners of the cover plates must be beveled and lubricated to avoid jamming with the supporting plates. An alternative design could use the supporting plates with slightly lower width than the IPD, so that the cover plates do not come into contact with the supporting plates. In this case, there is no need to bevel and lubricate the cover plate corners. Cover plates are not necessary for the zinc infill.

Pipe material should be mild steel with a minimum of 25% elongation in tensile coupon test to guarantee ductile and stable behavior of the damper. Seamless pipes have a slightly better performance. The seam in ordinary pipes should not be placed in plastic hinge locations.

The four different possible installation methods of DPDs are also applicable to IPDs. These methods of installation are shown in Fig. 2. The main installation method of IPD is on top of an inverted-V brace as shown in Fig. 2a and b in a framed structure. The IPD may be installed within a diagonal brace (as configured by Gray et al. [24] for slit damper) as shown in Fig. 2c. It can also be installed in a connection on top flange of beam to make a semi-rigid energy absorbing connection similar to that tested by Sang-Hoon et al. [25] for slit damper (Fig. 2d).

3. Experimental study

3.1. Test specimens

Quasi-static cyclic loading tests were performed on six specimens to evaluate the energy absorption capacity, cyclic performance and the behavior of IPDs. Table 1 shows the properties and dimensions of the damper specimens tested experimentally in this study. The main pipes in all specimens are seamless steel pipes with 220 mm outside diameter and 9.2 mm thickness, except for the DP-140-I-75 specimen in which 140 mm outside diameter and 5.1 mm thickness is used. The inner pipe for specimens DP-220-I-140-1, DP-220-I-140-2 and DP-220-I-140-3 has 142 mm diameter and 6.5 mm thickness. The difference among the three is that the specimen DP-220-I-140-2 has no cover plates and the length of pipes in specimen DP-220-I-140-3 is 150 mm, while for the other two is 100 mm. The inner pipe for specimen DP-220-I-115 is a 115 mm diameter pipe with 6.2 mm thickness and the length of specimen is 100 mm. Specimen DP-220-I-160-Zn has a zinc infill with 160 mm diameter inner pipe with 6.0 mm thickness and a length of 100 mm.