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Experimental and analytical study of telescopic lead yielding damper

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ABSTRACT

In this study, a novel type of passive energy dissipation device called a Telescopic Lead Yielding Damper (TLYD) is proposed and analyzed. This device comprises co-axial steel cylinders and lead rings, such that these rings act as shear locks between the steel cylinders. TLYDs dissipate energy through the plastic shear deformation of lead metal. The telescopic mechanism used in TLYDs allows these small-sized dampers to tolerate large axial displacements with low fatigue. For each telescopic level, a yield plateau is added to the hysteresis behavior of TLYD devices. Each yield plateau resists a different performance level, namely design-based and maximum credible earthquakes. Seven single-yield level and two multi-yield level TLYDs were manufactured and tested in a quasi-static manner to investigate the hysteresis behavior of such devices. The tests indicated that these devices are rate independent, can tolerate large displacements, and are low-cycle, large-displacement fatigue resistant. In addition, a finite element (FE) model was developed to determine the accuracy of the experimental results. Since the finite element and experimental results were in good agreement, the FE analysis can be used for further studies. Furthermore, to analyze the structures equipped with TLYD devices, a telescopic model was developed in the OpenSees software. Afterwards, the cumulative dissipated energies of the specimens were calculated. The results showed that in loops where the telescopic mechanism activates, the dissipated energy grows faster. Finally, the effective damping and stiffness of TLYD specimens were calculated, and it was concluded that the damping capacity of TLYD devices was high.

1. Introduction

The energy dissipation capacity of a structure highly enhances structural performance during seismic excitations. Infrastructures such as nuclear power plants and dams are designed to remain elastic, during earthquakes, possessing high strength levels [1]. These high strength levels lead to increased construction costs; however, such feature is uneconomical for regular structures, for which seismic loads are instead reduced through the elevation of damping capacity. The required damping is initially achieved via plastic deformation in structural elements, but this approach causes costly damage to both structural and non-structural components. This problem is overcome by the use of additional structural elements and devices that can dissipate energy and increase damping capacity. These features prevent structural and non-structural damage that is due to reductions in structural story drift and acceleration [2]. They can also be easily replaced after earthquakes and therefore eliminate the need for major structural repairs [3,4].

Three main categories of energy dissipation devices are passive, active, and semi-active devices [5]. Active and semi-active energy dissipation devices are unpopular not only because computers and power sources are vital for their operation but also their fabrication comes with exorbitant costs. Passive energy dissipation devices involve low fabrication and maintenance costs and do not require any computers or power sources to operate. This category is divided into frictional dampers [6,7], viscous and viscoelastic dampers [8,9], and material yielding dampers [10,11].

Material yielding devices, such as steel slit dampers (SSDs) [5] and pipe dampers (PDs) [6], absorb energy through plastic deformation of specially shaped steel members. In SSDs and PDs, energy dissipation occurs through plastic deformation in Vierendeel truss elements and steel pipes, respectively. Recently, the use of lead metal as a yielding material has been widely accepted for two main reasons [7]. First, lead metal recrystallizes at room temperature after plastic deformation, that results in the recovery of the metal's mechanical properties [3]. Second, it has high fatigue resistance that prevents low-cycle, large-displacement fatigue in lead parts. Unlike most other metals, however, lead is susceptible to premature failure due to creeping [12]. Creeping is critical when a member is subjected to sustained loading, but because energy dissipation devices are exposed to cyclic loading once in their lifetime, the creep behavior of yielding materials is unimportant [10,13].

Robinson and Greenbank [3] proposed the first lead yielding energy dissipation device, which induces large plastic deformations in lead that

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extrudes in a back and forth motion through an orifice and tolerates up to 1000 loading cycles with no strength degradation. Monti and Robinson [8] put forward another lead yielding energy dissipation device called the Penguin Vibration Damper (PVD), in which lead undergoes shear plastic deformation during ground motion excitations. A standard PVD can tolerate displacements in the range of ±2 μm under wind forces and up to ±10 mm during earthquakes. Lead yielding dampers (LYDs) that can withstand large deformations are also large in size. An example is Cousins and Porrit's [10] lead yielding device, which has a length of 2 m and a diameter of 25.4 cm; the device withstands displacements of up to ±225 mm. Nevertheless, some exceptional metallic yielding damping devices can resist large deformations even with their small sizes; a case in point is the U-shaped damper developed by Suzuki et al. [14]. Curadelli and Riera [4] proposed a lead yielding device that withstands shear deformations and axial displacements of up to ±10 mm.

The current investigation proposes a small-sized lead yielding energy dissipation device that can tolerate large deformations with negligible fatigue. The design of this novel device draws inspiration from the device put forward by Curadelli and Riera [15]. A new telescopic mechanism was used to increase the allowable axial deformation of the device presented in the current work, and each telescopic level was intended to add a separate yield plateau to the device's hysteresis behavior. Each yield plateau can be activated at different structural lateral forces. Seven single-yield plateau specimens or LYDs were fabricated and tested, after which two LYD specimens equipped with the novel telescopic mechanism, called Telescopic Lead Yielding Damper (TLYD), were manufactured and tested to study the behavior of telescopic devices. In addition, finite element studies were conducted to numerically investigate the performance of the LYDs and TLYDs. The effects of the telescopic mechanism on the cumulative dissipated energy of the specimens were also examined. Finally, the effective damping and stiffness of the specimens were calculated, and an OpenSees model was constructed to illustrate the behavior of the TLYDs.

2. LYD and TLYD configurations

This section presents the configurations and details of the LYD specimens with single and multiple yield plateaus.

2.1. LYD configuration

The general configuration of the LYD specimens (Fig. 1) is characterized by two coaxial steel cylinders and lead rings working as shear locks. Devices designed with this configuration can be fixed onto structures with one attachment point at the end of a central cylinder (Plate A) and the other at the far end of an outer cylinder (Plate B) (Fig. 1). When the steel cylinders undergo relative axial deformation along the central axis of the damper, a combination of shear and compressive stresses act on the lead rings. These stresses cause the lead rings to yield and dissipate energy.

As previously stated, the LYD design in this work is the enhanced version of the lead damper introduced by Curadelli and Riera [15]. In contrast to their device, the LYD put forward in the present research has a steel–lead interface that was roughened in saw-tooth form to prevent slippage between lead and steel and increase lead confinement. The dimensions of the lead rings were also modified to achieve a more appropriate hysteresis behavior for the damper.

2.2. TLYD configuration

To increase the displacement and load bearing capacity of the LYD specimens, a novel telescopic mechanism was introduced and used to fabricate TLYDs with multiple yield plateaus. The three-level TLYD depicted in Fig. 2 comprises four coaxial steel cylinders and three sets of lead rings at the interface of adjacent cylinders. The relative axial displacements between nearby cylinders, except for the outer cylinder, are restricted to a finite extent by two sets of lock mechanisms. The number of lead rings and their geometries in each ring set should be selected in a way that increases the corresponding yield strength through movement from the inner to outer sets of lead rings. This feature guarantees the successive yielding of lead ring sets.

3. Test program

3.1. Test apparatus and set-up

The test was performed via a DARTEC universal machine with 1000kN capacity. To obtain the post peak behavior of the force-displacement curves the tests were conducted in a displacement-control manner [16] (Fig. 3). The load was applied at the top of the inner cylinder of specimens through the cap plate of the machine, while the outer cylinder was laid on a set-up cylinder supported by a deck (see Fig. 3).

3.2. Materials

3.2.1. Lead

Two batch of lead materials with different maximum allowable stresses, denoted as LM1 and LM2, were used to manufacture the specimens. In order to determine the mechanical properties of each lead material, direct tension tests were conducted on specimens with the dimensions of 250 mm × 20 mm × 4.0 mm and five replicates. The direct tension tests were performed by an INSTRON 1193 universal device equipped with an extensometer (Fig. 4). The strain-stress diagrams obtained for both lead materials are depicted in Fig. 5(b). For the numerical modeling, idealized true stress-strain curves were utilized [11] that are presented in Fig. 5(a). In these idealized diagrams, the maximum tolerable stress for lead materials LM1 and LM2 are denoted as F_{yh1} and F_{yh2}, respectively. The maximum tolerable stress and its

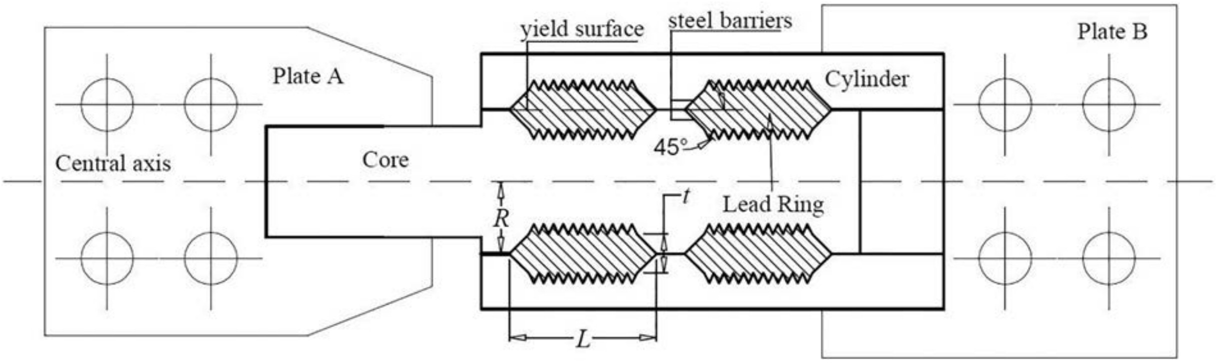

Fig. 1. LYD configuration.