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Recent applications of high-damping hysteretic devices for the seismic isolation of buildings and bridges

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Abstract

Seismic isolation is a technique in which a structure is decoupled from earthquake-induced ground motions. To control the displacement of the isolated structure, dampers are often included as major components of the isolation system. The most common energy absorption mechanism used for these devices is the hysteretic damping due to the plastic deformation of lead or steel.

In this paper we describe the characteristics of the lead devices and present applications of hysteretic dampers to seismic isolation in Italy, USA, Japan and New Zealand.

1. Introduction

High-damping hysteric devices, relying on the plastic deformation of steel or lead, have many engineering and industrial applications, such as the seismic isolation of buildings, bridges and delicate or hazardous equipment. Another use is in the control of vibration such as in the 'rail' of the magnetically levitated train at present undergoing tests in Japan.

Seismic isolation is a technique in which a structure is decoupled from earthquake-induced ground motions. In Italy, USA, Japan and New Zealand this technique has now advanced to the point where it is often considered for the protection of both new and existing buildings, bridges and, to a lesser extent, industrial plant.

Our studies of seismic isolation began in 1968 as the synthesis of two groups working on materials science and engineering seismology respectively. Our research has had three main components: experiments, theoretical work and application of seismic isolation devices. Devices invented and developed in our laboratory, and successfully applied in real seismic isolation systems, include various designs of the steel damper, the lead-extrusion damper and the lead-rubber bearing.

Because the values of the hysteretic damping for devices based on the plasticity of metals are so high, the damping of these devices becomes difficult to describe in terms of normal damping parameters. For example, the lead rubber bearing has a decrement of the order of 10% to >50% while for lead extrusion, damper values for the decrement are >1 at amplitudes as small as 1 mm.

A paper [1] describing this work was delivered at the 8th ICIFUAS conference in 1985 and a book "*An Introduction to Seismic Isolation*" [2] describing the technique and devices in detail has recently (1993) been produced.

This paper describes developments in the field in the intervening 8 years, which are characterized by an extremely rapid technology transfer.

2. Flexibility and damping

Although hysteretic damping devices can be used on their own in some energy-absorption applications, their use in seismic isolation systems requires that there should also be some means by which a restoring force is exerted on the system, giving rise to damped cyclic motions. Seismic isolation systems have two important functions:

(1) The period of the isolated structure is increased to a value beyond that which dominates in a typical earthquake.

(2) The displacement is controlled (to 50–200 mm) by the addition of an appropriate amount of damping (usually 5%–15% of critical).

The increased period (>1.5 s) is achieved via a flexible support which provides a reduction in the 'stiffness' or 'spring constant' between the structure and the ground. Examples are flexible piles and rubber elastomeric bearings. The damping is usually hysteretic, provided by plastic deformation of either steel or lead or 'viscous' damping of high-damping rubber. For these dampers strain amplitudes, in shear, often exceed 100%.

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TABLE 1. Flexibility and damping of common seismic isolators

Property	Linear	Nonlinear
Restoring force (providing spring constant and flexibility)	Laminated rubber bearings	High-damping rubber bearings
	Flexible piles or columns	Lead–rubber bearings
	Springs	Buffers
	Spheres between curved surfaces (gravity)	Stepping (gravity)
Damping	Laminated rubber bearings	High-damping rubber bearings
	Viscous dampers	Lead–rubber bearings
		Lead extrusion damper
		Steel dampers
		Friction (e.g. PTFE)

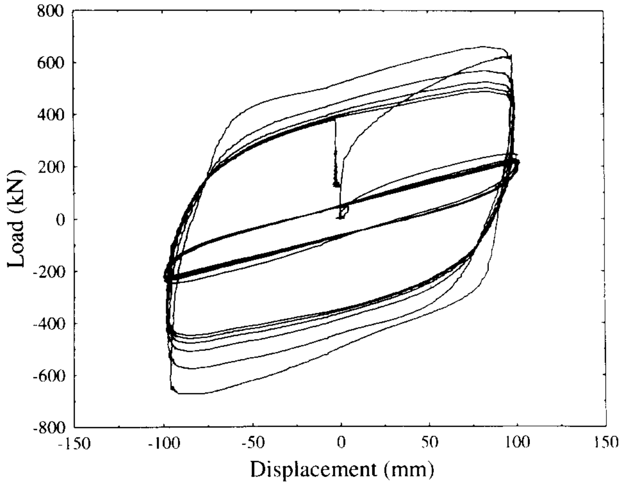

Fig. 1. Hysteresis loops for rubber bearing and lead–rubber bearing.

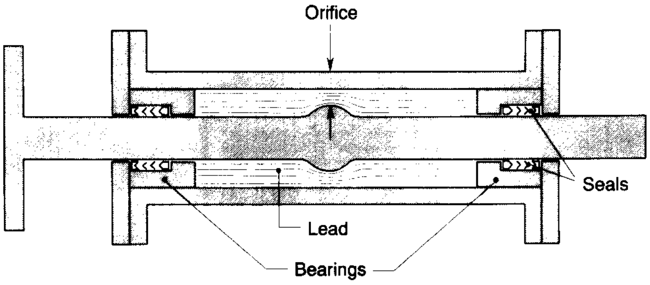

Fig. 2. 'Bulged shaft' type lead extrusion damper.

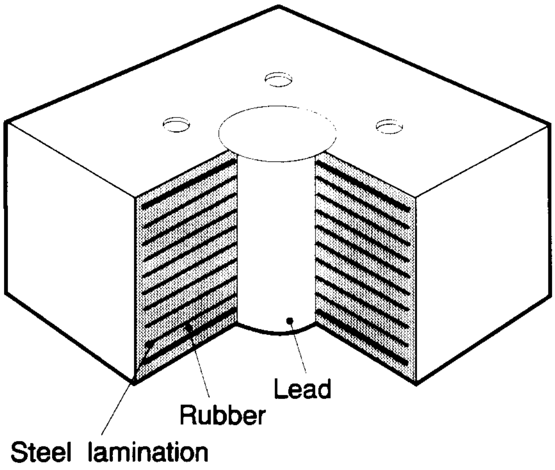

Fig. 3. Lead–rubber bearing.

This high damping has the effect of reducing the displacement by a factor of up to 5 from unmanageable values of ~1 m to large but reasonable sizes of <200 mm. Table 1 groups common devices according to whether they are linear or nonlinear. A system which has linear damping and linear elastic restoring force will give rise to a force–displacement hysteresis loop as shown in the inner loop of (Fig. 1), while a characteristic nonlinear system is illustrated by the outer loops.

3. Devices based on the plasticity of lead

Table 1 shows a variety of devices but we describe here only two:

3.1. The lead extrusion damper

This comprises a lubricated shaft which, when moved, forces a bulge on the shaft through the lead contained in a cylinder (Fig. 2). This device is similar to that shown at ICIFUAS 8 [1] but is the 'bulged shaft' version whereas the latter was the 'constricted tube' [3]. The 'bulged shaft' extrusion damper is easier to manufacture than the 'constricted tube' damper. In both types of device the process of plastic deformation is rapidly followed by the interrelated processes of recovery, recrystallization and grain growth. These processes are

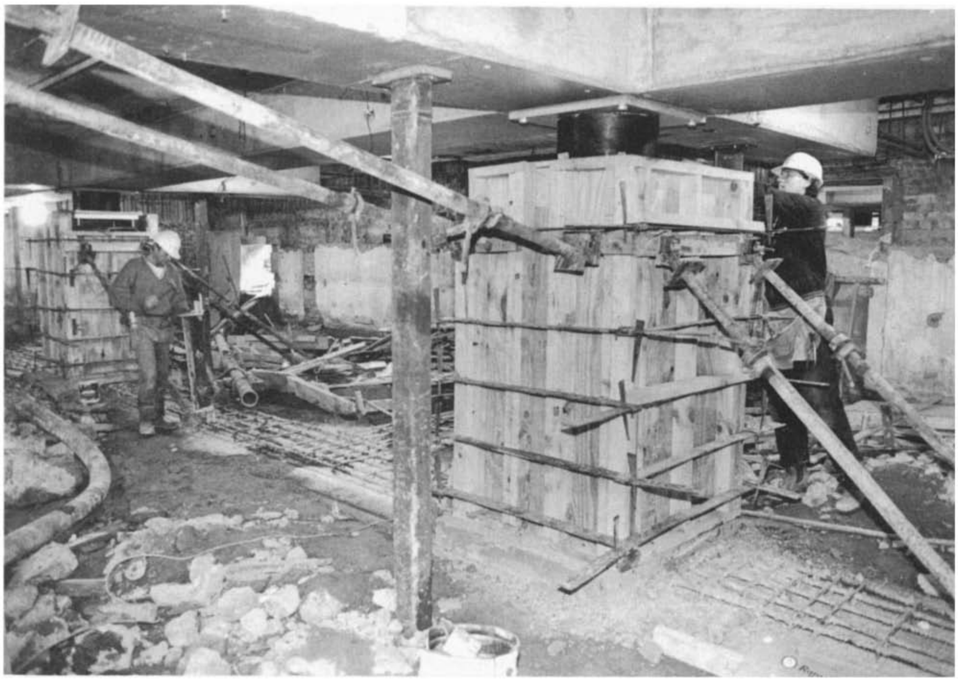

Fig. 4. Lead–rubber bearings being retrofitted under New Zealand Parliament Building, 1993.

TABLE 2. Applications of seismic isolation devices in New Zealand, Japan, USA and Italy

Year/country	Structure(s)	Damping system(s)
1974 to 1985		
New Zealand	bridges	19 LRB, 2 LED, 4 Steel
	buildings	1 LRB, 1 Steel
Japan	buildings	1 Friction
Italy	bridges	19 Elastomeric, 9 Viscous
1985 to 1993		
New Zealand	bridges	18 LRB, 1 LRB+LED, 3 Steel
	buildings	1 LED, 4 LRB
Japan	buildings	17 LRB, 17 Steel, 7 Friction, 5 Viscous, 9 Elastomeric
	bridges	12 LRB, 3 Elastomeric
USA	buildings	9 LRB, 1 Friction 3 Elastomeric
	bridges	23 LRB
Italy	bridges	6 LRB, 75 Steel, 29 Viscous, 14 Elastomeric
	buildings	4 Elastomeric

Key: LRB = Lead–rubber bearing; LED = lead extrusion damper; steel includes cantilevers, beams, *etc.* undergoing plastic deformation; elastomeric includes rubber and neoprene bearings, high damping rubber bearings plus other elastomers; friction includes PTFE sliding bearings plus other sliding supports.

particularly efficient at ambient temperatures because of the low melting point of lead (327 °C). The almost rectangular elastic–plastic force–displacement hysteresis loop typical of such dampers as shown in Fig. 6 of the ICIFUAS 8 paper [1] and in refs. 2 and 3.

3.2. *Lead–rubber bearing*

The lead–rubber bearing [4] comprises a lead insert inside a laminated elastomeric bearing of the type commonly used in bridges to accommodate thermal expansion. Figure 3 shows schematically a typical lead–rubber bearing. It has been found that to a good approximation the total force to shear a lead–rubber bearing, $F(\text{LRB})$, is given by

$$F(\text{LRB}) = F(\text{rubber}) + F(\text{lead}) \tag{1}$$

where $F(\text{rubber})$ and $F(\text{lead})$ are the forces required to shear the rubber and lead. This equation is illustrated by the hysteretic loops shown in Fig. 1 where the difference between the inner loops, $F(\text{rubber})$, and the outer loops, $F(\text{LRB})$, is due to the force needed to plastically deform the lead. $F(\text{lead})$ is, to a reasonable approximation, given by the yield stress of lead times its cross-sectional area. The total force $F(\text{LRB})$ is independent of velocity and vertical load. For the results shown in Fig. 1 the axial force representing the weight of the structure was 1.5 MN (150 tonne). The respective values of the significant parameters for the lead–rubber and rubber bearings are: decrements of >50% and 10%; the energy absorbed in one cycle of 80 kJ and 13 kJ; the mean damping force as a fraction of the weight on the bearing of 7% and 0.7%. By careful selection and placement of lead–rubber and rubber bearings, it is possible for the complete structure to have the required isolation characteristics while controlling the maximum shear force applied to any part of the structure. This approach is particularly important when seismically isolating existing structures with relatively fragile components.

4. Applications of these devices

Table 2 is a summary of the current application of seismic isolation devices, presented in such a way as to highlight the progress which has been made since the previous ICIFUAS paper [1] was presented in 1985. There has been extremely rapid transfer of the technology in Italy, Japan, USA and New Zealand.

Seismic isolation has been installed in both new structures and retrofits: in New Zealand current work in progress is the installation of lead–rubber bearing systems in the existing Parliament Buildings and the New Museum of New Zealand being built on the Wellington waterfront. Figure 4 shows the lead–rubber bearings being retrofitted to seismically isolate the New Zealand Parliament Building, a building of historic significance. This process involves the repiling of the building with lead–rubber bearings and rubber bearings in the supports, and cutting a seismic gap in the 500 mm thick concrete walls. During an earthquake the building will be able to move in any direction on a horizontal plane up to distances of 300 mm.

Another historic building is the Salt Lake City and County Building, Utah, USA completed in 1894. This massive five-storey unreinforced masonry and stone structure with a 76 m high central clock tower, is 3 km from the Wasatch fault and was retrofitted with a lead–rubber bearing isolation system in 1988.

5. Conclusion

The hysteretic damping due to the plastic deformation of steel and lead has, to date, been used in over two-thirds of the applications of seismic isolation. These devices have the advantages of being maintenance-free and relatively robust.

The popularity of the lead-based hysteretic devices in applications such as seismic isolation has been, in part, due to the advantages offered by the concept underlying these devices. For example, the lead–rubber bearing combines in one compact unit the flexibility and damping required of a seismic isolation device; also, installation of the lead core into a standard elastomeric bearing already used in many bridges for the accommodation of thermal stresses is a practical way of conferring earthquake resistance as well. However, the success of the devices can essentially be attributed to the fact that lead, with its lack of fatigue at operating temperatures, is such an ideal material for these applications.

As discussed in a recent book [3], an emerging trend is for these devices to be used in conjunction and combination, thereby conferring even better isolation and damping characteristics.

Acknowledgments

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