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HYSTERETIC DAMPERS FOR PROTECTING STRUCTURES DURING EARTHQUAKES

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Abstract. The cyclic plastic deformation of steel and lead can be used to absorb the energy of motion of a base isolated structure during an earthquake. Hysteretic dampers made of steel and lead have been developed at our laboratory and tested over a wide range of conditions. In particular the lead extrusion damper and the lead-rubber bearing have been tested with satisfactory results at frequency of $10^{-6}$ to $50$ Hz and at engineering strains as high as 200% The force-displacement hysteresis loop due to the lead is found to be rectangular and at ambient temperatures the lead is able to be "hot worked" over many cycles. At high cyclic strains, unrestrained lead cylinders are found to be unstable due to the application of "simple" shear rather than "pure" shear.

INTRODUCTION. The destructive effect of earthquakes which often contain components of acceleration in the range 1 to 5 Hz, can be reduced by mounting the structure on a base isolation system in the form of ball bearings, sliding bearings, or more practically flexible rubber bearings. The compliant base has the effect of decreasing the resonant frequency of the structure, which may have a Q of $\sim 10$, to a value far less than the earthquake thereby in effect enabling the earthquake to interact only weakly with the structure. However, without any damping the displacement of the base isolated structure during an earthquake could approach $0.5$ m and furthermore the structure would be set into motion by wind gusts. To provide protection against these dynamic loads, >20 bridges and 1 building in New Zealand, and 3 bridges and 1 building in California, have been base isolated and fitted with steel or lead hysteretic dampers.

STEEL HYSTERETIC DAMPERS. The first hysteretic damper developed at our laboratory was a torsional beam device designed for the Rangitikei Railway Bridge /1/. The damper consisted of a flat plate of mild steel ($\sim 600 \times 50 \times 3000$ mm) which was held firmly in place by two heavy lever arms (Figure 1). During an earthquake the 60 m tall bridge piers step slowly and in doing so cause the flat plate to be twisted via a second set of lever arms. This steel damper plastically deforms when a force of $\sim 450$ kN is applied and has a range of movement of $80$ mm resulting in a strain amplitude of $\sim 3%$. The damper is found to operate satisfactorily over many hundreds of cycles which is far greater than the $\sim 5$ cycles needed to be sustained during a major earthquake.
Other steel dampers developed are in the form of round and flat cantilevers with and without tapers, round bars in the form of loops and flexural beams. With all of the steel devices the major problem is one of avoiding placing welds at points of high strain. In fact, the heavy welds required contribute strongly to the cost of the devices. However, steel dampers have to date been used in two bridges, one tall building and for one tall rocking chimney.

Figure 1. Steel Torsion Beam Damper (45 tonne).

**LEAD EXTRUSION DAMPERS.** The process of extrusion is an old one. Possibly the first design of an extrusion press was that of Joseph Bramah who in 1797 was granted a patent for a press "for making pipes of lead or other soft metals of all dimensions and of any given length without joints". The process of extrusion consists of forcing or extruding a material through a hole or orifice thereby changing its shape (Figure 2). If the extrusion ratio (ER) is defined as the ratio of the original cross-sectional area divided by the extruded area then experimentally it is found that

$$p = k \ln(ER) + p_0$$

where $p$ is the extrusion pressure while $k$ and $p_0$ are constants.

A longitudinal extrusion damper is shown in Figure 2. It consists of a thick-walled tube co-axial with a shaft which carries two pistons. There is a constriction on the tube between the pistons, and the space between the pistons is filled with lead. The lead is separated from the tube by a thin layer of lubricant kept in place by hydraulic seals around the pistons. The central shaft extends beyond one end of the tube. During operation axial loads are applied with one attachment point at the protruding end of the central shaft and the other at the far end of the tube. The damper is fixed between two points on a structure during an earthquake. As the attachment points move to and fro the pistons move along the tube and the captive lead is forced to extrude back and forth through the orifice formed by the constriction in the tube /2/.

Figure 2. Lead Extrusion Damper.
Since at 20°C the lead is being hot worked during the operation of the damper the lead is continually returning to its initial state via the interrelated processes of recovery, recrystallization and grain growth. Furthermore, the device is a stable in that during continuous operation its temperature will rise causing a decrease in extrusion pressure together with more rapid recovery and recrystallization.

The prototype extrusion damper for two Wellington bridges was tested satisfactorily for many thousands of cycles at ~1 Hz. The manufactured dampers operated plastically at 150 kN and had extrusion ratios of ~1.2 (Figure 3).

Another device using this principle is the torsional extrusion damper in which lead inside a cylinder is continually extruded by the rotation of a cam on a shaft.

**LEAD SHEAR DAMPERS.** Initially in an attempt to reduce the cost of manufactured hysteretic dampers a cylindrical lead shear damper was developed with its ends soldered to steel plates. However, during cycling at strain amplitudes of ~25% the lead was found to pump from the sides into the region of maximum tensile stress.

This thinning of the shear cylinders was caused by the fact that the lead cylinder was under "simple" shear rather than "pure" shear. To overcome this problem and difficulties of soldering lead cylinders ~100 mm in diameter to steel plates, the lead plugs were placed in elastomeric bearings. These elastomeric bearings are commonly used to enable bridge decks to expand and contract and they consist of a sandwich of steel plates and rubber layers vulcanized to form one unit (Figure 4).

As was the case for the lead extrusion devices, the lead in the lead rubber bearing is being "hot worked" and readily deforms plastically. Thus the resultant force displacement hysteresis loop consists of an elastic component due to the rubber plus a plastic component due to the lead shearing at a shear stress of 10.5 MPa (Figure 5). During the testing of the lead rubber bearing a vertical load appropriate to the structure is applied by four 100 tonne hydraulic jacks. The maximum engineering shear strain the bearings have been tested at is +200% at 0.9 Hz /3,4/.

The rate dependence of the lead in shear satisfies an equation of the form (Figure 6)

\[ \alpha_{(Pb)} = a \dot{\gamma}^b \]  

(1)

where below a strain rate \( \dot{\gamma} = 3 \times 10^{-4} \) s\(^{-1} \), \( b = 0.15 \) and above \( b = 0.035 \). For the lead extrusion damper the same equation was satisfied with \( b = 0.12 \) and \( 0.03 \) while for slow creep other authors conclude that \( b = 0.13 /5/\).
These results indicate that the lead-rubber bearing has little rate dependence at strain rates of $3 \times 10^{-4}$ s$^{-1}$ to $10$ s$^{-1}$, which includes typical earthquake rates of $10^{-1}$ to $1$ s$^{-1}$, and in fact in this region an increase of rate by a factor of ten causes an increase in force of only 8 percent.

Below strain rates of $4 \times 10^{-4}$ s$^{-1}$, the dependence of the shear stress on creep rate is greater, with a 40 percent change in force for each decade change in rate. However, this means that a creep displacements of $\sim 1$ mm/h for a typical bearing 100 mm high, that is $\dot{\gamma} \sim 3 \times 10^{-6}$ s$^{-1}$, the shear stress has dropped to 35 percent of its value at typical earthquake rates ($\dot{\gamma} \sim 1$ s$^{-1}$).

To satisfy the requirements of the civil engineers who were keen to use the lead-rubber bearing, full scale dampers were tested under a range of conditions including temperatures of $-35$ to $+45^\circ$C, 11000 cycles at $\pm 3$ mm and six large artificial earthquakes with 5 minute intervals. The effect of the 5 minute interval is interesting in that during this time the initial properties at the lead rubber bearing are recovered. This recovery is mainly governed by the cooling of the lead via the transfer of heat to the surrounding steel plates (Fig. 4).

CONCLUSIONS. The steel and lead hysteretic dampers are suitable for absorbing the energy of motion of a base isolated structure during an earthquake. Because of its cheapness, simplicity and multiple functions of vertical support, elastic restoring force and damping, the lead-rubber bearing was found to be the most appropriate device for this task and is at present being installed in buildings and bridges in New Zealand and California.

REFERENCES.


