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LEAD DAMPERS FOR BASE ISOLATION

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SUMMARY

The cyclic plastic deformation of lead can be used to absorb the energy of motion of a base isolated structure during an earthquake. Practical hysteretic dampers are of two forms: firstly, the lead extrusion damper in which lead is extruded back and forth through an orifice and secondly, the lead rubber bearing in which a lead plug contained within a normal elastomeric bridge bearing is sheared. Over the last seventeen years we have conducted many experiments on these devices and in this paper we present some new data and re-interpret some of our old results.

INTRODUCTION

The destructive effect of earthquakes, which often contain components of acceleration in the range of 1-5 Hz, can be reduced by mounting the structure on a base isolation system which can take the form of ball bearings, sliding bearings or more practically, flexible rubber bearings or flexible columns. The compliant base has the effect of decreasing the resonant frequency of the structure, which may have a Q of the order of 10, to a value below the dominant earthquake frequencies thereby 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 could be set into motion by wind gusts. To provide protection against these dynamic loads approximately 30 base-isolated bridges and a number of base-isolated buildings in New Zealand, USA, Japan and Italy have been fitted with lead hysteretic dampers.

LEAD EXTRUSION DAMPERS

The process of extrusion is an old one, possibly the first design of an extrusion device being 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". Extrusion consists of forcing or extruding a material through an orifice thereby changing its shape.

A longitudinal extrusion damper is shown in Fig. 1. It consists of a thick-walled tube coaxial 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 protuding 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 which move relative to one another 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.

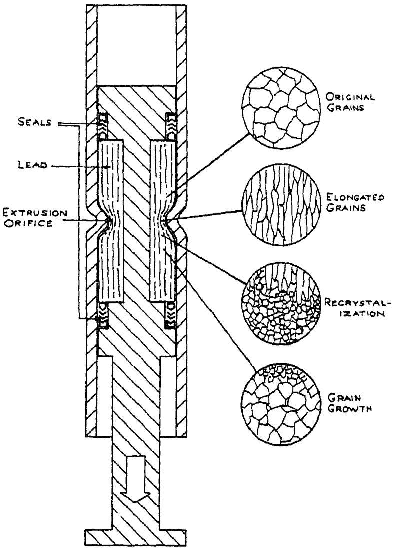

Fig. 1 Longitudinal section of a lead-extrusion damper.

Since at 20°C the lead is being hot worked it is continually returned to its initial state by the interrelated processes of recovery, recrystallisation and grain growth. Furthermore the device is stable in that during continuous operation its temperature will rise causing a decrease in extrusion pressure together with more rapid recovery and re-crystallisation.

During 1976 a prototype extrusion damper for two Wellington bridges was tested for more than 100 cycles at 0.9 Hz. It operated plastically at a force of 140kN. In 1986 the same damper was retested at 0.9 Hz producing a nearly identical hysteresis loop (Fig. 2).

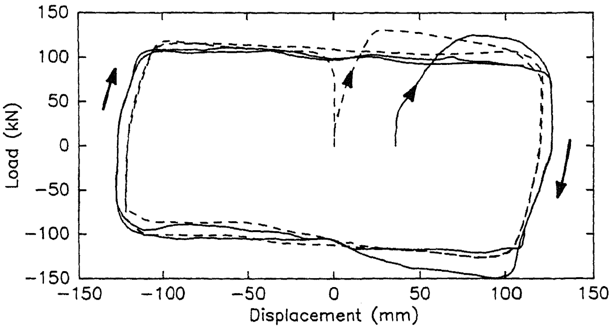

Fig. 2 Comparison of force-displacement hysteresis loops for a 140kN lead-extrusion damper tested in 1976 (solid line) and again in 1986 (dashed line).

The performance of the damper can be put into perspective by comparing the laboratory test conditions with the motions to be expected if the Wellington bridges protected by the damper were to be attacked by a 1.5 times El Centro 1940 NS component (Ref. 1). The estimated extrusion distance during the 1.5 times El Centro attack is a total of 460 mm in 3 complete cycles, the largest being +25 mm to -55 mm, the average power consumption is 13 kW, and the peak 36 kW. Corresponding values from the laboratory tests are 1 to 3 m of extrusion travel in 2 to 6 cycles of ± 125 mm, the average power consumption is 48 kW, and the peak 85 kW.

By the end of the most recent series of tests the damper had been taken through a total of 148 cycles, mostly at a displacement of ± 125 mm and rate of 0.9 Hz, and the lead plug had travelled a total distance of 62.5 m backwards and forwards through the extrusion orifice. This is equivalent to approximately 40 times the cycles and 140 times the extrusion travel to be expected during one moderate-large earthquake. Despite such severe testing the damper has shown no signs of impending failure, which is not surprising as an early 15 kN device was still performing satisfactorily after 3400 cycles of continuous testing (Ref. 2).

In 1988 an extrusion damper of capacity 150 kN ± 200 mm for the Bannockburn bridge in the South Island of New Zealand was tested and it produced a very rectangular hysteresis loop (Fig. 3). The effect of heating during cycling can be observed in Fig. 3, with the force decreasing by 15% over 3 cycles. As mentioned before, continuous cycling causes heating of the lead and consequently a decrease in the extrusion pressure and an increase in the rate of recovery.

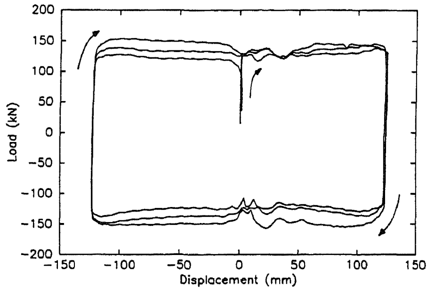

Fig. 3 First three force-displacement loops for a 150 kN lead-extrusion damper cycled at 0.9 Hz, ± 125 mm.

The lead extrusion damper has very little rate dependence following the equation

$$p = av^b \qquad (1)$$

where p is the extrusion pressure, v the speed of extrusion (or strain rate) and a and b are contants (Ref. 2). For extrusion speeds of less than 10^{-2} mm/s $b = 0.12$, while at higher speeds b has the value of 0.03. Thus at speeds which would occur during an earthquake each factor of 10 increase in extrusion speed would cause the extrusion force to increase by only 7%.

To date our recent experiments have confirmed all of our earlier conclusions (Refs 1,2) though we have found with the manufactured lead extrusion dampers that the hysteresis loop is far more rectangular than for the early laboratory-made prototypes. At present we are manufacturing the extrusion dampers (250 kN ± 400 mm) to be used in a new Police Headquarters in Wellington, a 10-storey building which is supported by flexible columns (Ref. 3).

LEAD RUBBER BEARINGS

Initially in an attempt to reduce the cost of hysteretic dampers a cylindrical lead shear damper was developed with its ends soldered to steel plates. To overcome the problem of soldering lead cylinders of the order of 100 mm diameter to steel plates a lead plug was placed in an elastomeric bridge bearing. Elastomeric bearings are commonly used to enable bridge decks to expand and contract and they consist of a sandwich of steel and rubber layers vulcanised to form one unit (Fig. 4).

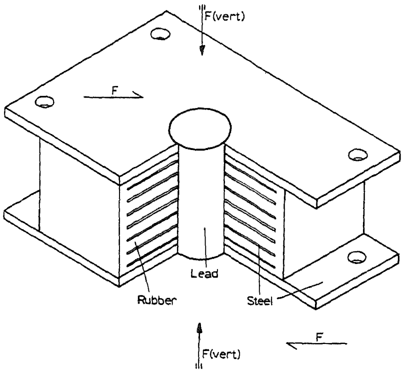

Fig. 4 Lead-rubber shear damper

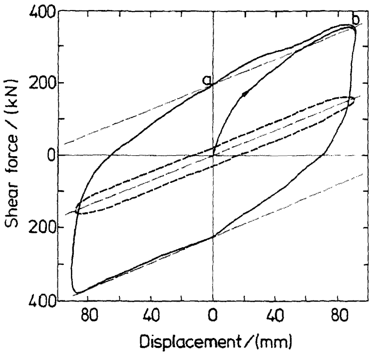

Fig. 5 Force-displacement curves for a lead-rubber bearing (solid line) and a rubber bearing (dashed line).

As is the case for the lead extrusion devices, the lead in the lead rubber bearings 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 10.5MPa (Fig. 5). During the testing of the lead rubber bearing a vertical load of appropriate value is applied to the bearing. The maximum engineering shear strain at which the bearings have been tested is ± 200% at 0.9 Hz (Ref. 4).

The shear of the lead satisfies an equation of the form given in Eq. 1 with b = 0.15 below a strain rate of 3 x 10^{-1} s^{-1} and b = 0.035 for higher rates. Our recent tests have confirmed the results given in an earlier paper on the lead rubber bearing (Ref. 5) with two additions. These additions concern the vertical load dependence of the shear force required to operate the lead rubber bearing (Fig. 6) and the effect of decreasing the diameter of the lead plugs to very low diameter to height ratios.

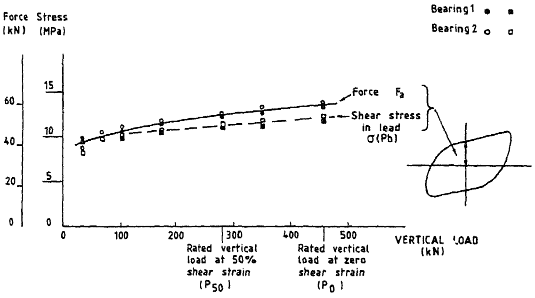

Fig. 6 Shear force in bearing F_a, and shear stress in lead σ (Pb), at zero strain on hysteresis loop for 2 cycle tests.

As can be seen by the results in Fig. 6, for a well-designed lead rubber bearing, that is one with rubber layers of the order of 10 mm in thickness, the effect of vertical load on the hysteresis loop is small. However if the bearing has inner layers of rubber with thickness greater than say 20 mm then the dependence of the hysteresis loop on vertical load becomes more important (Refs 4,6).

The influence of the ratio of the diameter of the lead plug to its height on the shear stress required to deform the lead has been investigated with diameter to height ratios of 0.2 to 0.8. Contrary to the opinion of some authors (Ref. 7) small diameter to height ratios are effective for producing a reasonable hysteresis loop (Ref. 6).

A base isolated bridge, Te Teko, on lead-rubber bearings was located within the zone of strongest shaking during the Edgecumbe, New Zealand, earthquake of 2 March 1987. An accelerograph 11 km from the bridge and outside the zone of strongest shaking recorded a peak ground acceleration of 0.33 g (Ref. 8). The bridge was mostly undamaged by the earthquake, losing approximately 0.1 m^2 of surface concrete from a pier; but one of the lead-rubber bearings moved out of its proper position. This reinforces the need to carefully consider and solve the problem of the attachment and the positioning of the lead rubber bearing in the structure. Robinson (Ref. 5) recommended that a lead-rubber bearing should be restrained by a vertical wall at least 20 mm high, followed by a further 75 mm of sloping wall at an angle of 45° (Fig. 7). Furthermore, he also recommended that the lead rubber bearing should either have to climb out of a well or at least have its surroundings outside its containing ring at the same level as under the bearing. In the case of the Te Teko Bridge neither of these recommendations were followed. The retaining rings were intended to be 20 mm high, were installed 5 to 20 mm high, there were no sloping walls, and the bearings were placed on 75 mm high pedestals.

Another satisfactory method of attachment is to pin the bearing to the structure and foundation with dowels located near the lead plug and of sufficient length to lock into the outermost steel plates (Ref. 4).

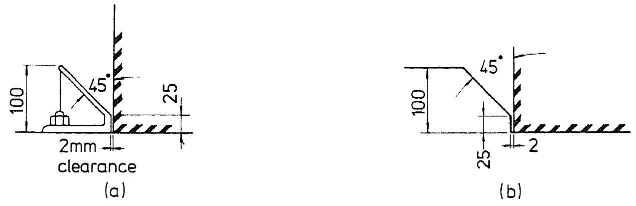

Fig. 7 Methods of restraining lead-rubber bearing, (a) on flat foundation and (b) in recess in foundation.

CONCLUSIONS

From our recent investigations of lead dampers for base isolation we have concluded that most of the information needed for the application of these bearings is contained in the two references (Refs 2, 5). In the case of the lead extrusion damper, that is, the damper which operates in one direction and can be designed for particularly large strokes, we have found that the manufactured devices have extremely rectangular hysteresis loops. The lead rubber bearing is possibly the more economic of the two in that it provides both base isolation and damping in the one compact device. It supports the structure vertically, permits lateral movement, provides both the elastic restoring force and the damping force in a horizontal plane and also gives resistance to wind loads. For well-designed rubber bearings we find that there is very little dependence of the hysteresis loop on either the vertical load or the height to diameter ratio of the lead plug.

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