TEST RESULTS FOR LEAD-RUBBER BEARINGS FOR WM. CLAYTON BUILDING, TOE TOE BRIDGE AND WAIOTUKUPUNA BRIDGE

W.H. Robinson* and A.G. Tucker*

ABSTRACT:

Four lead-rubber bearings designed to base isolate structures from earthquake attack were tested for the Ministry of Works and Development on PEL's dynamic test rig. The lead-rubber bearings ranging in size up to 600 mm square, consisted of elastomeric bearings containing lead plugs. In the case of the Wm Clayton Building two bearings were selected at random from 82, of which 80 have been installed under the building, and were tested at 0.3 Hz with strokes of + 20, + 45 and + 110 mm, and vertical loads of 1.05, 2.10 and 3.15 MN. For the two bridges one bearing from each was tested at 0.9 Hz with vertical loads of 160 to 350 kN, and strokes of + 30 to 93 mm. In all cases the bearings performed satisfactorily over 9 to 35 cycles and the hysteresis loops could be described reasonably well by assuming that the lead behaved as a plastic solid with a yield stress of 10 MPa.

INTRODUCTION:

The damage to a structure during an earthquake can be reduced if the structure sits on some form of base-isolation (1,2) which increases the structure's resonant period to a value far greater than one second, out of the range of the earthquake's strong excitation. Further improvement in the reduction of forces and moments occurs if the base isolation includes some damping such as provided by the plastic deformation of steel (3) or the extrusion of lead (4,5). However, these hysteretic dampers require the structure to be mounted on separate PTFE or rubber bearings. A review of the research completed on these dampers is contained in (6).

In the case of the lead-rubber bearing (7), a laminated elastomeric bridge bearing is modified by placing a lead plug down its centre (Figs. 1 and 2). The bearing carries the weight of the structure and supplies a horizontal restoring force while the plastic deformation of the lead produces hysteretic damping. Thus one component provides both the base isolation and the damping giving a relatively cheap solution to the problem of base isolation.

Initially, a 356 x 356 x 140 mm lead-rubber bearing, containing seven 3 mm thick steel plates, six 16 mm rubber plates and a lead plug of 100 mm diameter was tested at 0.9 Hz with vertical loads and strokes of up to 450 kN and +68 mm respectively (8). This bearing completed a total of 340 cycles and operated satisfactorily at temperatures of $-35 \pm 5^{\circ}\text{C}$ and $45 \pm 5^{\circ}\text{C}$. More recently a 650 mm diameter x 197 mm lead-rubber bearing has been tested with a range of lead inserts of 50 to 170 mm diameter with vertical loads and strokes of up to 3 MN and +90 mm.

The results of these tests together with results for the lead-rubber bearings for the Scamperdown, Toe Toe and Waiotukupuna Bridges (9) and the Wm Clayton Building (10) (all MWD), are being used to prepare a design procedure for lead-rubber bearings (11).

The good performance of the lead-rubber bearing is due to the fact that at ambient temperatures the lead is being "hot worked" so that during plastic deformation the lead is continually recovering its mechanical properties by the process of recovery (annealing of dislocations), recrystallization (formation of new undeformed grains) and grain growth (growth of new grains). Also, the efficient use of the lead in providing the hysteresis loop is ensued by the lead being tightly confined by the steel and rubber so that all of the lead is forced to deform plastically in approximately pure shear. An example of the ability of the lead to withstand many cycles of plastic deformation is shown by its behaviour in lead extrusion dampers (4,5) where the lead is forced to extrude back and forth through an orifice. These dampers have been found to perform well for 3400 cycles at 1 Hz, and twelve extrusion dampers operating at 150 kN with a maximum stroke of + 250 mm have been installed in Wellington in two bridges mounted on PTFE sliding bearings (6).

DESCRIPTION OF TEST AND BEARINGS:

The lead-rubber bearings were mounted horizontally, one at a time, in the PEL dynamic test rig (Fig. 3). Underneath the rubber bearing was a horizontally located pressure plate which transmitted the vertical force from four hydraulic jacks to the bearing. On top of the bearing was a moving plate which was attached via a linkage to the drive of a modified Caterpillar D8. The upper face of the moving plate was greased and rubbed against fifty-

* Physics and Engineering Laboratory,
DSIR, Lower Hutt.

Figure 1 – Lead-rubber bearing.

Figure 2 – Lead-rubber bearing for Wm, Clayton Building (1–78).

Figure 3 — Dynamic test rig with vertical loading system in the reaction frame.

Figure 4 — Dimensions of lead-rubber bearing for Wm. Clayton Building.

two 20 x 20 x 2 mm squares of PTFE bonded to a steel reaction plate. The area of PTFE required was determined from tests carried out previously at PEL on PTFE sliding bearings (12). In the design the friction force on the lubricated PTFE was estimated to be ~1% of the normal reaction with a design vertical pressure up to 30 MPa. The rig was designed for a maximum power of 100 kW, maximum horizontal force of 500 kN, a maximum stroke of 250 mm (+125 mm) and maximum frequency of 0.9 Hz, though in fact for these tests at high loads the maximum power was approximately 30 kW.

In the case of the Wm Clayton Building (13), two lead-rubber bearings manufactured by Empire Rubber Mills Ltd, Christchurch, New Zealand, were tested. These bearings were selected at random from the total of 82 manufactured bearings, of which 80 have been installed under the building. The outside dimensions of the bearings were 600 x 600 x 207 mm and they contained 8 steel plates 5 mm thick (Figs. 2,4,5). The lead plug was a tight fit in the bearing and was 105 mm in diameter. Without the lead plug, the static shear stiffness, $\alpha(r)$, of these bearings was 1.7 ± 0.1 kN/mm (14).

For the Toe Toe Bridge the outside dimensions of the bearing were 280 x 230 x 127 mm (Figs. 6 and 7). Without the lead plug its static shear stiffness was 0.55 kN/mm and its compressive stiffness 204 kN/mm (15).

The Waiotukupuna bearing was 406 x 356 x 177 mm and without the lead plug had a shear stiffness of 0.50 kN/mm and compressive stiffness of 190 kN/mm (16). For both bridge bearings the lead plug diameter was 75 mm.

RESULTS:

After the Wm Clayton lead-rubber bearing had been fitted in the dynamic test rig a measure of its compressive stiffness was made by loading the bearing with the hydraulic jacks in steps to 3.15 MN and noting the vertical displacement. The compressive stiffness was found to be 600 ± 50 kN/mm.

The dynamic results were carried out at 0.3 Hz with vertical loads of 1.05, 2.10, and 3.15 MN and strokes of +45 mm (Fig. 8) and +110 mm (Fig. 9). In the figures of the horizontal shear force, F , versus the stroke, x , the value $F(a)$ is the shear force at $x = 0$ while $F(b)$ is the shear force at maximum displacement. $F(b)$ was found to always be the peak shear force. The shear force due to the sliding PTFE was determined by testing a 650 mm diameter elastomeric bearing without a lead plug in the dynamic test rig. For this rubber bearing there occurred on reversal of stroke a sudden change in force which was dependent on the vertical load. The sudden change in force on reversal of the direction of shear velocity was taken to be twice the shear force due to the PTFE, and was found to be in good agreement with previous work carried out at PEL (12). As can be seen by the results

summarised in Table I, the values for $F(a)$ and $F(b)$ (see Fig. 9) for the tests on bearings 1-78 (test 1) and 1-70 (test 6) at a vertical load of 3.15 MN and +110 mm stroke are at 138 kN, 288 kN and 136 kN, 285 kN respectively, a variation well within the estimated experimental error of +5%. For comparison with $F(a)$ and $F(b)$ the static shear force $F(r)$ calculated from

$$F(r) = \alpha(r) \times x \quad (1)$$

where x is the maximum shear displacement, is included in Table I. With a value of 1.3 to 1.55 kN/mm the shear stiffness $\alpha(ab)$ defined by

$$\alpha(ab) = (F(b) - F(a))/x$$

is 25 to 10% less than $\alpha(r)$ at 1.7 kN/mm.

At the end of the dynamic tests the lead-rubber bearings were in good condition. The chemical analysis of the lead plug (Table II) shows that the lead used is of a high enough purity so that any impurities present will not cause large changes in the mechanical properties of the lead.

In the case of the Toe Toe bearing the tests were at a vertical force of 160 to 210 kN, strokes of +30, +65 and +93 mm with a frequency of 0.9 Hz. The first test (Test TTI* Table III) on the Toe Toe bearing was as received, with a 5 mm thick steel plate added to fill a 7 mm deep hole at the top of the lead resulting in a 2 mm air gap. Thus the lead was not well confined and gave the hysteresis loop shown in figure 10 and summarised in Table III. For the second and subsequent tests (TT2-5) a disc 10 mm thick was pressed in at the top and one 5 mm thick at the bottom of the lead plug and each was ~1 mm proud before the vertical force was applied. The hysteresis loop for strokes of +30 and +65 mm are shown in figures 11 and 12. Once the lead had been confined this bearing behaved well for the 20 cycles it was subjected to over a three day period (see Table III).

The value of the shear force, $F(r)$, calculated from the static stiffness, $\alpha(r)$, of the elastomeric bearing without the lead plug is included in the table for comparison with $F(a)$ and $F(b)$. The estimated error on these forces is +10% and is mainly due to the uncertainty in the friction force of the PTFE bearing.

The Waiotukupuna bearing was supplied with the lead plug protruding ~5 mm top and bottom. The protrusion was pressed down before the bearing was tested at a vertical force of 350 kN and strokes of +50 and 83 mm at 0.9 Hz for a total of 12 cycles. The result for the larger stroke is shown in figure 13.

Both the Toe Toe and Waiotukupuna bearings were in good condition after the dynamic tests. The results of these two should be comparable since they have similar shear and compression stiffnesses.

TABLE I

SUMMARY OF RESULTS FOR Wm CLAYTON BUILDING BEARINGS

Bearing	Time	Test	Stroke/mm	Vertical Force/MN	F(a)/kN	F(b)/kN	α (ab)/(kN/mm)	No cycles	F(PTFE)/kN	F(r) /kN
1-70	1435 21/2/80	1	+45	1.05	90	160	1.56	4.7	10	77+5
	0915 22/2/80	2	"	2.10	94	162	1.51	5.0	14	"
	1530 22/2/80	3	"	3.15	109	165	1.24	4.7	16	"
	1400 25/2/80	4	+110	1.05	99	270	1.55	4.5	10	187+10
	1400 26/2/80	5	"	2.10	112	274	1.47	3.4	14	"
	1440 27/2/80	6 *	"	3.15	136	285	1.35	3.7	16	"
	1415 28/2/80	7	"	3.15	148	290	1.29	3.5	16	"
1-78	1420 10/3/80	1 *	+110	3.15	138	288	1.36	5.3	16	187+10
	1430 10/3/80	2	"	3.15	147	267	1.09	3.5	16	"

TABLE II
CHEMICAL ANALYSIS OF LEAD SAMPLES

Impurity	Sample A	Sample B
Sn	< 0.01%	< 0.01%
An	< 0.01	< 0.01
Bi	0.01	< 0.01
Sb	< 0.01	< 0.01
Zn	< 0.01	< 0.01
Fe	< 0.01	< 0.01
Cu	< 0.005	< 0.005

Figure 5 — Bearing 1—39 in Wm. Clayton Building

Figure 6 — Toe Toe Bridge, Mangaweka.

Figure 7 — Lead rubber bearing in the Toe Toe Bridge.

Figure 8 — Force displacement hysteresis loop for lead-rubber bearing No. 1-70 (Test 3).
Vertical force = 3.15 MN and horizontal stroke = ± 45 mm.

TABLE III

SUMMARY OF RESULTS FOR BRIDGE BEARINGS

Bearing	Time	Test	Stroke/mm	Vertical Force/kN	F(a)/kN	F(b)/kN	α (ab)/(kN/mm)	No cycles	F(PTFE)/kN	F(r)/kN
Toe Toe	0930 21/2/80	TT1*	+30	180	10	45		5	6	17
	1122 16/11/79	TT2	+30	180	41	62	0.70	5.4	6	17
	1437 16/11/79	TT3	+65	210	45	87	0.50	4.1	6	36
	1440 16/11/79	TT4	+65	210	32	80	0.74	5.3	6	36
	1320 19/11/79	TT5	+93	160	44	101	0.61	5.2	6	51
Wiotuk-upuna	1415 20/11/79	W1	+50	350	49	83	0.68	6.2	7	25
	1510 20/11/79	W2	+83	350	53	105	0.63	5.5	7	42
Toe Toe	Linear Interpolation		+50	200	43 (-12%)	75 (-10%)	0.68 (0%)			
			+83	200	45 (-15%)	95 (-10%)	0.60 (-5%)			

* 2 mm air gap above lead plug.

Figure 9 — Force displacement hysteresis loop for lead-rubber bearing No. 1-78 (Test 1).
Vertical force = 3.15 MN and horizontal stroke = ± 110 mm.

Figure 10. — Force displacement hysteresis loops for Toe Toe bearing with vertical force = 180 kN, stroke = ± 30 mm, and a 2 mm airgap (test TT1*).

A linear interpolation of the Toe Toe results to +50 and +83 mm indicates that the results for $F(a)$ and $F(b)$ for Toe Toe are 10 to 15% lower than for Waiotukupuna while the values for the shear stiffness, $\alpha(ab)$, are 0 and 5% low (see Table I). The higher figures for Waiotukupuna can be attributed to the extreme confinement of the lead which must have pushed into the rubber layers between the steel. The higher vertical force of 350 kN is expected to cause an increase in $F(a)$ and $F(b)$ of less than 5%. In all except test TT3 $\alpha(ab)$ is greater than $\alpha(r)$ by 10 to 30%.

DISCUSSION:

When the forces $F(a)$ and $F(b)$ for the first cycle are plotted against displacement, x , as shown in figures 14 and 15 it is found that to a good approximation

$$F(a) = \sigma(Pb)A(Pb) \quad (3)$$

$$\text{and } F(b) = \sigma(Pb)A(Pb) + \alpha(r)x \quad (4)$$

where $A(Pb)$ is the cross section area of the lead plug, and $\sigma(Pb)$ is the characteristic yield stress for the lead. It is possible to formulate a more complete and complex analysis, but since the shear stiffness of the rubber bearings is specified and supplied with tolerances of $\pm 20\%$ resulting in large uncertainties in shear force at large strokes, such an analysis is hard to justify at present. In Figures 14 and 15 the error bar shown on the line through the $F(b)$ results was calculated from $\pm 20\%$ of the shear force due to the rubber. The force due to the friction of the PTFE bearings is also included in these figures.

The value of $\sigma(Pb)$ is partly dependent on vertical load and displacement. At a shear strain

$$\gamma = x/h = 0.5 \quad (5)$$

where h is the height of the lead plug, and with a compressive stress on the total bearing area of 3 MPa, then $\sigma(Pb)$ is 10 $\pm$ 1 MPa. This 10% uncertainty shown as the error bar on $F(a)$ in Figures 14 and 15. The dashed lines in Figure 14 shows schematically the behaviour of $F(a)$ and $F(b)$ when the stroke is small ($\gamma < 0.2$).

In selecting the diameter of the lead plug it is suggested that

$$1.5 < h/d < 4 \quad (6)$$

where d is the lead plug diameter, and at $\gamma = 0.5$

$$F(r) > (3/4) \cdot (\sigma(Pb)A(Pb)), \quad (7)$$

that is, the force due to the rubber be greater than 3/4 of the force due to the lead. The restriction $h/d > 1.5$ enables the shear force at the ends of the lead to be transmitted to the volume of lead via the top and bottom circumferential area since the ends of the lead are free

and do not transmit a shear force except by friction. If $h/d = 1$ then there will be a tendency for the lead to become a ball as the high end forces deform the corners of the lead plug. The limit $h/d < 4$ is to ensure that on assembly the lead can be pushed tightly into the hole in the bearing. Furthermore, so that the lead plug fills the hole in the bearing completely, the volume of the lead plug should $\sim 1\%$ greater than the hole. This means that the lead plug must be tightly pressed into the bearing during assembly.

CONCLUSIONS:

These dynamic tests show that lead-rubber bearings manufactured with tight lead plugs perform as good base isolation components. For design purposes it is suggested that the lead plug be assumed to behave plastically at a yield stress of 10 MPa and that the post yield stiffness of the lead rubber bearing be taken as the stiffness of the rubber bearing alone.

Altogether for the Wm Clayton Building, bearing No. 1-78 was subject to nine cycles at ± 110 mm and bearing No. 1-70 ten cycles at ± 20 mm, fourteen cycles at ± 45 mm and fifteen cycles at ± 110 mm. The Toe Toe bridge bearing completed five cycles at ± 30 mm and fifteen at ± 65 mm while the Waiotukupuna bridge bearing underwent six at ± 50 mm and five at ± 83 mm. In all cases the bearings showed no signs of deterioration after the five cycles expected from an earthquake attack.

REFERENCES:

1. Skinner, R.I., Beck, J.L. and Bycroft, G.N., "A Practical System for Isolating Structures from Earthquake Attack", International Journal of Earthquake Engineering and Structural Dynamics, Vol. 3, 1975, pp.297-309.
2. Skinner, R.I. and McVerry, G.H. "Base Isolation for Increased Earthquake Resistance of Buildings", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 8, No. 2, June 1975, pp 93-101.
3. Skinner, R.I., Kelly, J.M. and Heine, A.J., "Hysteretic Dampers for Earthquake-Resistant Structures", International Journal of Earthquake Engineering and Structural Dynamics, Vol. 3, 1975.
4. Robinson, W.H. and Greenbank, L.R., "An Extrusion Energy Absorber Suitable for the Protection of Structures During an Earthquake", International Journal of Earthquake Engineering and Structural Dynamics, Vol. 4, 1976, pp. 251-259.
5. Robinson, W.H. and Greenbank, L.R., "Properties of An Extrusion Energy Absorber", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 8, No. 3, September 1975, pp. 287-191.
6. Skinner, R.I., Tyler, R.G., Heine, A.J. and Robinson, W.H. "Hysteretic Dampers

Figure 11. — Force displacement hysteresis loops for Toe Toe bearing with vertical force = 180 kN, stroke = ± 30 mm, and no airgap (test TT2).

Figure 12. — Force displacement hysteresis loops for Toe Toe bearing with vertical force = 210 kN and stroke = ± 65 mm (Test TT4).

Figure 13. — Force displacement hysteresis loop for Wiotukupuna bearing with a vertical force = 350 kN and stroke = ± 85 mm (Test W2).

Figure 14. — $F(a)$ and $F(b)$ versus displacement for Wm. Clayton Building bearing, filled points $F(a)$, open $F(b)$, lines from equations 3 and 4. Vertical force 1.05 MN— $\circ$, 2.10 MN— $\square$ and 3.15 MN— $\diamond$.

- for the Protection of Structures from Earthquakes", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 13, March 1980, pp.22-36.
7. Robinson, W.H. Patents - NZ 178949, US 4117637, Japan 49609/77.
 8. Robinson, W.H. and Tucker, A.G., "A Lead-Rubber Shear Damper", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 10, No. 3, September 1977, pp.151-153.
 9. Robinson, W.H. and Tucker, A.G. "Test of Lead-Rubber Bearings for the Toe Toe and Waiotukupuna Bridges", Physics and Engineering Laboratory Report 679, June 1980.
 10. Robinson, W.H. and Tucker, A.G. "Test of the Lead-Rubber Bearings for the Wm Clayton Building", Physics and Engineering Laboratory Report 678, June, 1980.
 11. Robinson, W.H. "Lead-Rubber Hysteretic Bearings suitable for Protecting Structures During Earthquakes" (in preparation).
 12. Tyler, R.G., "Dynamic Tests on PFTE Sliding Layers under Earthquake Conditions", Bulletin of the New Zealand National Society for Earthquake Engineering, Vol. 10, No. 3.
 13. Megget, L.M. "Analysis and Design of a Base-Isolated Reinforced Concrete Frame Building", Bulletin N.Z. National Society for Earthquake Engineering, Vol. 11, No. 4, December 1978, pp.245-254.
 14. Production tests by Stresscrete (NZ).
 15. Advanx (Sydney, Aust.) Test Report 692 (Nov. 1978).
 16. Silenthblock (Victoria, Aust.) Test Report 0036 (Aug. 1978).

Figure 15. — F(a) and F(b) versus displacement for Toe Toe and Waiotukupuna Bridge bearings, filled points F(a), open F(b), lines from equations 3 and 4.

- Toe Toe
- ◇ Waiotukupuna