DYNAMIC TESTS ON LAMINATED RUBBER BEARINGS

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ABSTRACT

Simulated dynamic tests in shear on laminated rubber bearings are described. The purpose of the tests was to check the performance of the bearings when used as mounts for base isolating buildings against earthquake attack.

Over 1,000 cycles were applied to the bearings, mostly at 50% shear strain at a frequency in the range 0.2 to 0.9 Hz. Values of damping were checked by carrying out separate torsional oscillation tests.

It is concluded that the bearings are suitable for use in the dynamic mode for the purpose of achieving base isolation in earthquake resistant buildings. Damping is likely to be 2 to 3% of critical. Possibly greater values occur at faster speeds and under cold conditions. The use of separate lead or steel damping elements to prevent the build-up of damaging horizontal oscillations is considered necessary.

1. INTRODUCTION

Buildings have already been mounted on laminated rubber bearings successfully for the purpose of insulating them from base transmitted noise effects(1,2). In that application insulation is required at comparatively high frequencies, usually above 10 Hz, and examples include insulation from the noise of underground trains, an organ in an adjacent church, and heavy machinery in a nearby factory. It has been proposed to mount buildings on rubber bearings to reduce the effects of earthquakes and, in one such system, specially designed rubber bearings become progressively stiffer with increasing deflection(3).

In the proposals put forward by the Physics and Engineering Laboratory, D.S.I.R., for the isolation of buildings against earthquake attack, flexibility is introduced in the horizontal direction to lessen the effects on damaging horizontal forces which may be applied at comparatively low frequencies in the range 0.5 to 10 Hz(4). This flexibility is provided by conventional laminated rubber bearings as used for bridge structures which at the same time carry the weight of the building. Separate damping elements, which may be of lead or steel(5-8), prevent the damaging build-up of oscillations which would otherwise occur despite the additional flexibility.

While laminated rubber bearings have been used in bridge structures over about two decades to allow for comparatively slow movements such as those arising from temperature, creep and shrinkage, they have not so far been employed in a structural dynamic mode where large horizontal deflections of the order of 100 mm may be induced, at cyclic frequencies of 0.5 to 1.0 Hz. Tests involving bearing strains and strain rates comparable to those which will occur in base isolated buildings during severe earthquakes are herein referred to as dynamic tests. The purpose of the tests described in this paper was to check the performance of standard laminated bearings in dynamic shear and establish the level of natural damping that would be achieved.

2. DETAILS OF RUBBER BEARINGS

The bearings tested were of the moulded type as used in bridges, manufactured in a softer rubber than that normally employed in order to lessen shear resistance. They were chosen as the largest size which would conveniently fit into the available test machine, which was a bulldozer adapted for linear dynamic testing by means of an eccentric through its rear drive. They were square in plan since the effect of an earthquake would be to cause movements in any direction horizontally and the square shape offered a degree of symmetry. Since the tests were carried out circular bearings have become available and would probably be preferred if competitive in price. The bearings were manufactured to a durometer hardness of 45 as opposed to the value of 50 normally employed. Other details, obtained by letter from the bearing manufacturer, were as follows :

Size : 356 x 356 x 140 mm.
Rated load : 580 kN.
Thickness of upper and lower rubber layers : 11.1 mm.
Number of layers between steel plates : 6, each 15.9 mm thick.
Total rubber thickness : 118 mm.
Number of steel plates : 7, each 343 x 343 x 3.2 mm thick.
Horizontal deflection at 50% strain = 58.8 mm.
Shear stiffness = 0.542 kN/mm.
Vertical stiffness at zero shear strain = 87.5 kN/mm.

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Vertical stiffness at 50% shear strain = 52.5 kN/mm.

3. DETAILS OF TEST RIG

The rig shown schematically in Fig. 1 was devised to enable static vertical loads to be applied to a sandwich of two rubber bearings, while at the same time applying dynamic horizontal loads to the centre plate by means of the bulldozer drive to give a balanced shearing action on the pair of bearings. The link system shown was attached to the top plate to ensure that this remained horizontal when shear deflections caused the jack loading to become eccentric to the centre of the bearings. In this way instability in the jack was avoided and the generally horizontal movement of the base of a building resting on a number of rubber bearings simulated.

There was a drop-off in jack loading with increasing shear deflection (See Table 1) so the constant vertical load condition which would generally apply for a building was not realised. It was shown, however (see para 5.2 and Table 1), that the dynamic performance in shear was not sensitive to the vertical reaction. It is worth pointing out that the link system as devised allowed freedom to the top plate to follow the vertical movements of the rubber bearings as the dynamic shear loads were applied, which would simulate quite well any vertical movement of a structure resting on rubber bearings when subjected to horizontal earthquake loading. Where acceptance tests are carried out on rubber bearings which involve shear forces carried by guides on the testing machine there is a strong possibility that friction in the guides will upset the vertical load/deflection relationship. This friction was insignificant for the rig employed in this test.

The maximum total stroke available from the bulldozer drive was about 150 mm and a 100 ton load cell was incorporated in the drive. A transducer having a stroke of 250 mm was used to record travel and its output, together with that of the load cell, was fed into a XY plotter in order to obtain the load/deflection relationship.

For the hot and cold tests a chart recorder was used in conjunction with thermocouples, five of which were placed on the top of the centre plate below the top bearing in positions centre front nearest the bulldozer drive, centre back, centre, mid-side edge and at the quarter point between mid-side and centre.

4. TEST PROCEDURE

4.1 Tests at 50% Strain in Dynamic Shear

As the allowable shear strain for design purposes is usually taken as 50% from the point of view of long-term temperature movements in bridges, most of the testing was carried out for a cycle of 0 to 50% strain, which for the rubber thickness of 118 mm gave a deflection range of 0 to 59 mm. No attempt was made to obtain a travel of ± 59 mm as it was desired to keep the link system in tension to avoid instability, but later it was tried successfully, presumably because of effective restraint offered by the 50 ton jack acting vertically.

The first tests were carried out at room temperature, which was about 15°C, initially slowly at about 0.2 Hz and later faster at about 0.9 Hz; hysteresis loops were obtained for both speeds. The vertical jack load was set to about 240 kN, corresponding to a dead load in the bearings, as opposed to the rated load of 580 kN which would be accounted for by dead load plus live load. The effect of varying the vertical load on the hysteresis loops was small (para 5.2, Table 1) and some of the later tests were carried out at a jack load of 360 kN.

About a fortnight after the tests at room temperature were completed the bearings were heated up for about 6 hours using electric heaters and the tests repeated. The temperatures recorded by the thermocouples were in the range 43-45°C, the lowest temperature being at the rear of the bearings, i.e. farthest away from the bulldozer drive, where there was no adjacent heater.

On completion of the 'hot' tests, the bearings were allowed to cool down for a few hours and 'semi-hot' tests carried out. For these tests four thermocouples gave readings in the range 37-38°C while the fifth, at the front of the bearings where cooling was greatest showed 33°C.

On the day following, when the bearings had cooled down, more tests were carried out at room temperature. Dry ice was then packed around the bearings overnight and the 'cold' tests carried out the following afternoon. By then the recorded temperature range was 2-4°C, the lowest temperature being at the front of the bearings and the highest at the back. The temperatures were in near equilibrium by the time of the tests, having fallen an average of only 1°C during the previous 3 hours.

About 6 weeks later a further test was carried out at room temperature to determine whether the characteristics of the rubber bearings had changed. The effect of varying the normal pressure was also determined.

4.2 Tests at 130% Strain in Dynamic Shear

On completion of the tests at 50% strain, the bulldozer drive was reset to give a stroke of 150 mm, to give a shear deflection of the same amount in one direction on the rubber bearings. A few cycles were carried out but the tendency to slip became greater, which would appear to indicate a dependence on the surface condition of the rubber.

4.3 Effect of Variation of Vertical Load on Dynamic Performance in Shear

In the last set of dynamic tests carried out the vertical jack pressure was reduced in 7 steps from 365 kN until slipping occurred between the centre plate and the rubber bearings at 54 kN. Hysteresis loops were obtained for each step.

4.4 Static Tests for Vertical Stiffness

The vertical stiffness of the bearings was measured on 11.3.76 by loading the pair of bearings with the hydraulic jack in the bulldozer rig and again on 11.8.76 with the bearings detached from the bulldozer. Deflections were recorded by 4 dial test indicators at the corners. On 12.8.76 the bearings were put back in the bulldozer and a 50% static shear strain applied and the stiffness re-estimated for the vertical load range of 200-430 kN, lower vertical loads not being applied because of the danger of slipping of the centre plate.

5. RESULTS

5.1 Dynamic Shear Tests

Results of the tests are given in Table 1 and typical hysteresis loops are given in Fig. 2. The hysteresis loops obtained for 130% shear strain are not shown but were of the same general shape as those for 50% strain. In the table the vertical loads quoted are those indicated by the pressure gauge on the jack during the cyclic motion, while the stiffnesses quoted are for the mean slope through the centre of the loop. The energies represented by the loop areas are also given, expressed in terms of the percentage of critical damping, ζ, as given by:

$$\zeta = \frac{\text{Energy per cycle in loop}}{4\pi \times \text{Maximum potential or kinetric energy}}$$

$$= 0.637 \times \frac{\text{loop area}}{\text{area of circumscribing rectangle}}$$

This defines the effective damping of a single mass oscillator in which the centering force is given by the hysteresis loop.

The values of damping obtained in this way vary from 2.8% for a hot test at slow speed to 9.6% for a cold test at fast speed.

After the tests at 130% shear strain some fretting of the rubber surface was observed at the outer surface of the bearings at positions of the internal steel plates. The measured temperature rise at the centre plate between the two bearings at no time exceeded 1°C during any of the tests.

The tests to indicate the effect of varying the vertical pressure showed that, for practical purposes, the performance in dynamic shear was unaffected by dead load variations (see Table 1).

5.2 Static Tests for Vertical Stiffness

A truly linear load/deflection relationship was found during the vertical stiffness tests up to the full jack capacity. With zero shear strain a load of 428 kN gave a deflection of 4 mm for a single bearing - giving a vertical stiffness of 108 kN/mm, i.e. about 25% greater than the manufacturer's value (of Para 2). The same value for stiffness was obtained with 50% shear strain applied. This is contrary to the accepted belief that the bearings become less stiff with superimposed shear deflection (of Para 2) and may have been caused by a compensating action in the link system attached to the upper platen. It was noted earlier (para 3) that there was a drop-off in jack loading as the shear strain was increased, which appears to support the hypothesis of a reduced vertical stiffness. However, it could also have been caused by a reduction in height of the bearings as the shear strain was applied.

6. COMMENT

As would be expected, the shear/deflection characteristic is basically linear with a narrow hysteresis loop. Overall the results indicate a slight stiffening of the rubber over the period of the tests. A little increased flexibility is apparent during the hot tests and the greatest energy lost was recorded in the cold tests, although this was very nearly equalled by the energy lost in the tests at room temperature later, when the stiffnesses were about the same. The slight increase in stiffness of the bearings over the period of the tests is possibly due to ageing associated with fatigue of the rubber.

It is accepted that the hysteresis loop obtained is associated with the friction between the filler particles added to achieve the desired degree of hardness in the rubber(9,10). The size of the hysteresis loop increases with hardness as the friction between the filler particles is greater than that between the rubber chains. Lindley(10) reported that at high extensions, not normally used in practical applications, hysteresis is much greater. "Rapidly repeated deformations can cause considerable hysteresis energy to be created which must be dissipated as heat .... Natural rubber, with its low hysteresis is the preferred material for vibration applications where the hysteresis provides a small but desirable measure of damping without the danger of serious heat build-up".

It is possible, however, that, for the bulldozer tests, some of the energy indicated in the loops may have been dissipated in other parts of the rig, e.g. one possible energy loss may have been in the vertical jack. As already noted (para 3 and Table 1) there was a drop-off in jack loading with increasing shear deflection thus indicating a reduction in height of the bearings as the shear load was applied. Thus there was a small rise and fall of the jack ram during cyclic testing which could have given rise to some energy loss. Further energy may have been lost in the small motions of the link system and in frictional losses associated with slipping motions of the rubber on the steel plates at the front and rear edges of the bearings in the direction of the drive, which would not be incurred in the practical application because the bearings would be bonded to the steel plates.

Because of the possibility of indicated energies being greater than the energies actually dissipated in the rubber bearings, separate torsional oscillation tests were carried out to indicate the degree of damping. Details are given in Appendix 1. Steel plates were bonded to the upper and lower surfaces of a single bearing Fig. A1.1 and the bearing was bolted and grouted to the floor. A steel channel was bolted to the upper plate and rotated in plan to give a shear strain in the rubber at the corners of the bearing of approximately 50%. The channel was then released and the decay recorded; the period was about 1 second. The experiment was repeated with a greater moment of inertia to give a period of about

2 seconds.

The measured damping of about 2% for the moulded bearing cannot be matched with any bulldozer test since all of these were conducted without bonding of the upper and lower plates and with a substantial normal load. A comparison indicates that the dampings deduced from the bulldozer rig are probably inflated and should not be adopted. However the general effect of cyclic period on damping is confirmed and doubtless the trend with changing temperature is correct.

The levels of damping associated with a moulded bearing mounted under a building may be somewhat higher than the 2% of the torsional test owing to:

(a) The effect of the vertical load.
(b) The use of spigots rather than glue to provide shear connections.

On the other hand a torsional test on a completely undamaged moulded bearing may give a damping of less than 2%.

The general conclusion from the tests must be that the level of damping in plain rubber bearings is too low for them to be used on their own without separate dampers. This damping can be provided by lead or steel devices$^{(4-7)}$.

The torsional tests on a different type of rubber bearing, viz. a type manufactured from alternate layers of rubber and steel glued with an epoxy resin, which were also reported in Appendix 1, showed a higher level of damping at 3%. This was to be expected as the rubber was harder and therefore would contain more filler. The period of oscillation, however, was longer, which would not be expected in view of the stiffer rubber. The longer period, and possibly part of the additional damping, probably arose from the lamination of the bearing by means of an epoxy resin.

In all, during the bulldozer tests, the moulded bearings performed over 1,000 cycles at 50% strain mostly at the faster speed, and in addition a few cycles at 130% strain, with little distress, and must therefore be considered suitable for use as mounts for the base isolation of buildings and bridges against earthquake attack.

7. CONCLUSIONS

7.1 The moulded bearings of natural rubber were subjected to over 1,000 cycles at 50% shear strain at representative frequencies of earthquake loading with little distress and must therefore be considered suitable for use as mounts for the purpose of isolating bridges and buildings from earthquake attack.

7.2 Damping in the bearings is likely to be 2 or 3% of critical, but may have greater values under cold conditions and at faster speeds. In view of the comparatively low level of damping, the use of separate lead or steel dampers is considered necessary.

7.3 The level of damping is affected by the construction of the bearings. A bearing of the same size but manufactured by laminating rubber and steel using an epoxy resin showed slightly greater values of damping.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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APPENDIX 1

SEPARATE TORSIONAL OSCILLATION TESTS TO CHECK THE DAMPING OF BEARINGS IN SHEAR

Because the values obtained for damping in the bulldozer tests appeared to be rather high, a separate experiment was set up to determine damping by means of a torsional oscillation test, which effectively eliminated all non-bearing contributions to the measured damping.

A1.1 Test Procedure

One of the moulded rubber bearings which had undergone over 1000 cycles at 50% strain was taken from the bulldozer rig and 12 mm thick steel plates glued to its upper and lower surfaces by means of a special epoxy resin. The bearing was bolted and grouted to a concrete floor by the lower plate and a steel channel mounted centrally on the upper plate. (Fig. A1.1) The size of the channel was adjusted to give the bearing a torsional period of oscillation of about one second. An accelerometer was mounted on the channel and a horizontal deflection of about 0.5 m applied to each end of the beam by pulling to give a shear strain at the corners of the rubber of about 50%. The beam was released and the decay in the oscillation recorded.

The test was then repeated with I beams bolted to either end of the channel to effectively double the period of oscillation.

The two tests were repeated using a rubber bearing of a different type. The bearing was identical in size but was laminated from layers of rubber and steel using an epoxy resin and had not been subjected to prior cyclic deformation. The object of the tests was to show up any differences in performance of this type of bearing compared with the moulded type tested previously. The rubber used in manufacture had a hardness between Z12 and Z13 to BS.1154:1970, i.e. a durometer value of about 50.

A1.2 Results

A typical decay curve for the moulded rubber bearing is shown in Fig. A1.2. The decay curves for the laminated bearing were similar except that the decay was more rapid. For the moulded bearing the amplitude dropped to one tenth of its value in 17 cycles while for the laminated bearing only 13 cycles were required. The moulded rubber bearing appeared to be much more 'bouncy' and small oscillations persisted for a much longer period of time.

The fraction of critical damping, D, is given by:

$$D = \frac{0.366}{n} \log_{10} \frac{x_o}{x_n} \text{ for small values of D}$$

where x_o = peak to peak amplitude of trace on release

x_n = ditto after n cycles

n = number of complete cycles

The graphs of $\log_{10}x$ against n were found to be straight lines for the moulded rubber bearing and near straight lines for the laminated one; in the latter instance damping was a little greater at the higher strains. A check for windage showed that wind affected the results by only about 0.1%.

Results are summarised in Table 2. The fraction of critical damping was found to be about 2% for the moulded bearing, i.e. less than the values indicated in the bulldozer tests which were roughly in the range 3-10%. For the laminated bearing, which was manufactured from a harder rubber, damping was greater at about 3%, which was to be expected as the rubber would contain more filler. The period of oscillation, however, was longer, which would not have been expected in view of the stiffer rubber. The longer period, and possibly part of the additional damping, probably arose from the lamination of the bearing by means of an epoxy resin.

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TABLE 1

BEARING STIFFNESSES AND DAMPING IN DYNAMIC SHEAR

DATE	TEST	TEMPERATURE °C	VERTICAL LOAD (kN) AT ZERO SHEAR	VERTICAL LOAD (kN) AT MAX. SHEAR	0.2 Hz SLOW SPEED STIFFNESS (kN/mm)	0.2 Hz SLOW SPEED APPARENT DAMPING ζ PERCENT	0.9 Hz FAST SPEED STIFFNESS (kN/mm)	0.9 Hz FAST SPEED APPARENT DAMPING ζ PERCENT	TOTAL CYCLES
	TESTS AT 50% STRAIN IN RUBBER								
18.12.75	Room Temperature	18	243	195	0.57	3.3	First few cycles		11
					0.59	3.3	0.57	5.6	229
6. 1.76	Hot test 1.	43-45	243	195	0.57	2.8	0.57	7.3	131
	2.	43-45	395	334	0.54	2.9	0.56	7.6	65
	Semi-hot	33-38	395	334	0.54	2.9	0.56	7.6	54
7. 1.76	Room Temperature	18	395	334	0.57	3.9	0.60	8.3	71
8. 1.76	Cold test	2-4	395	334	0.60	4.7	0.62	9.6	56
3. 3.76	Tests with taper damper	18	304	343		Composite loops			333
	TESTS AT 130% STRAIN IN RUBBER								
8. 3.76	Room temperature	18	395	250		Slipping			80
	TESTS AT 50% STRAIN IN RUBBER								
4. 3.76	Variation of normal jack pressure	15	365	310	0.59	4.5	0.61	7.1	28
			304	243	0.60	4.1	0.62	6.6	31
			243	195	0.61	4.0	0.62	6.2	26
			200	158	0.63	4.1	0.64	7.5	32
			122	91	0.63	4.1	0.64	7.6	32
			79	61	0.63	4.7	0.62	8.3	29
			54	42		Slipping			11
					Total cycles all tests to 4. 3.76				1208

TABLE 2

PERIOD OF OSCILLATION AND DAMPING FOR TORSIONAL TEST

Bearing type	Hardness (I.R.H.D.)	Mass	Period of oscillation (secs)	Fraction of critical damping (per cent)
Moulded bearing	45	Channel only	0.89	2.21
		Channel plus I beams	1.77	2.12
Bearing laminated with epoxy resin	50	Channel only	1.00*	3.37*
		Channel plus I beams	2.00*	2.93*

* Values given were for shear strain range 50-30% at bearing corners. The values were slightly less at lower strains.

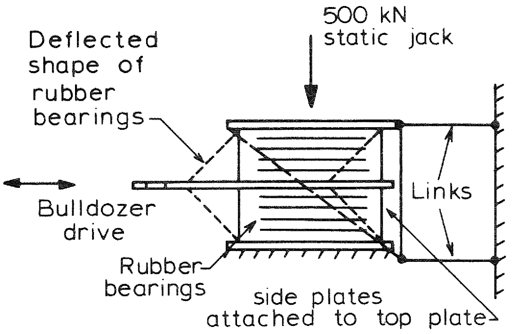


FIGURE 1: LOADING RIG FOR RUBBER BEARING

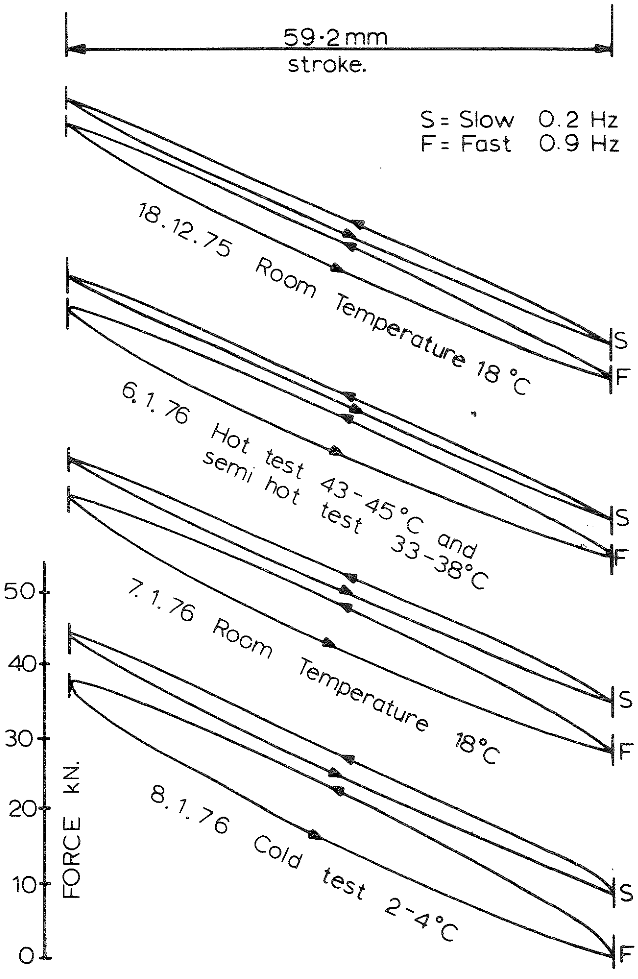
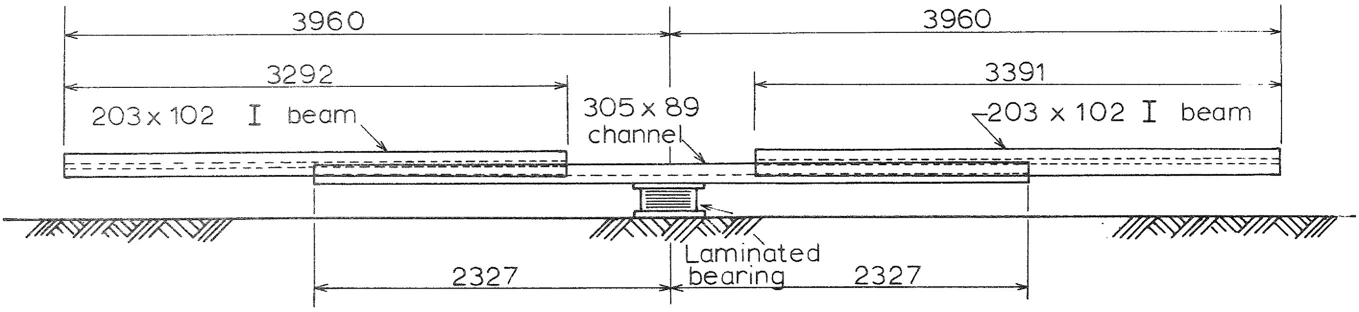


FIGURE 2 : FORCE SHEAR DEFLECTION RELATIONSHIP FOR RUBBER BEARINGS AT 50% STRAIN



NB The I beams were detached for the tests at the shorter period. The arrangement was set into oscillation in the horizontal plane.

FIGURE A1.1: ARRANGEMENT FOR TORSIONAL OSCILLATION TEST

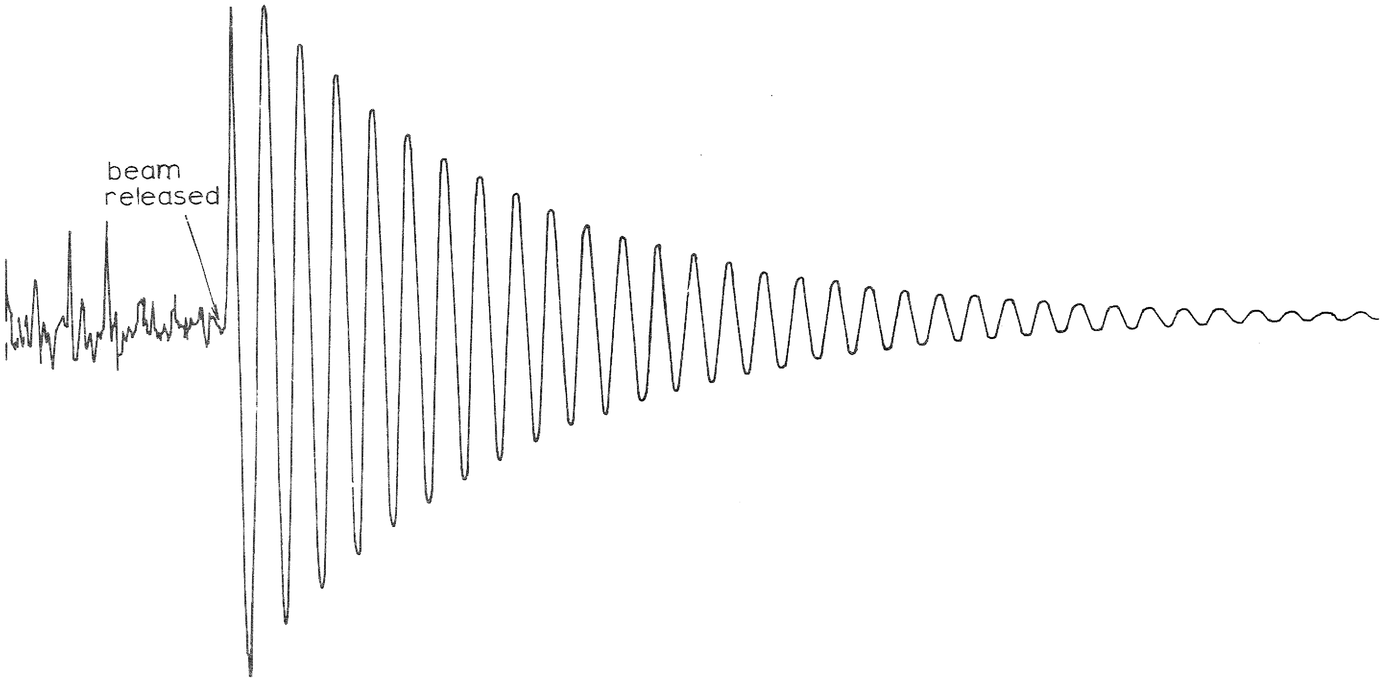


FIGURE A1.2: ACCELEROMETER DECAY CURVE FOR MOULDED BEARING : PERIOD 1.77 secs.

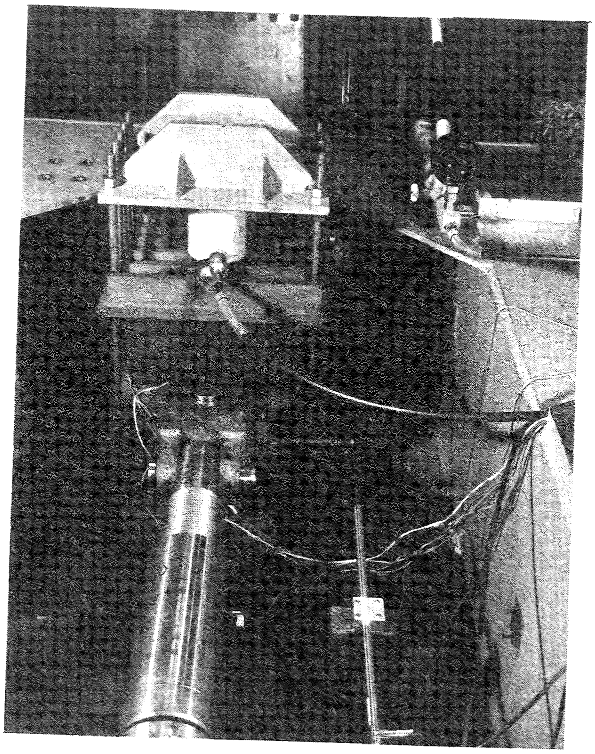


PLATE 1: RUBBER BEARING RIG IN BULLDOZER

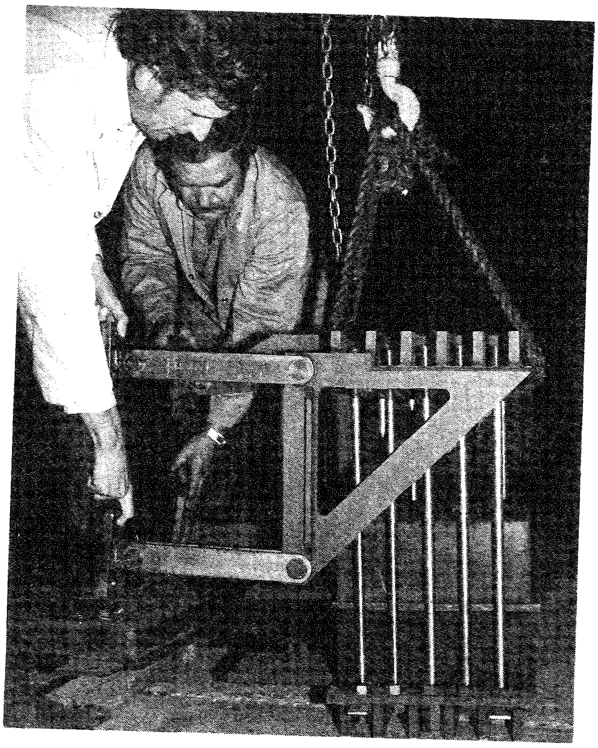


PLATE 2: THE RIG LINK SYSTEM. BEARINGS AND LOADING RODS

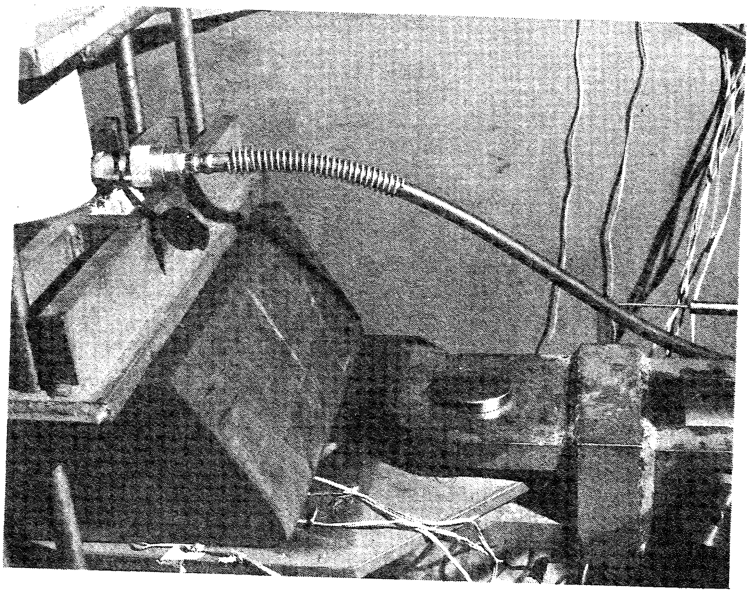


PLATE 3: SLIPPING OF BEARINGS FROM 130% SHEAR