Proceedings of the Institute of Acoustics

ELASTOMERIC ISOLATION MOUNTS FOR BUILDINGS AND STRUCTURES: FROM DESIGN TO INSTALLATION

A J Alder Andre-Silvertown UK Ltd., Burton-on-Trent
K N G Fuller Rubber Consultants, Brickendonbury, Hertford

1. INTRODUCTION

The use of elastomers as structural bearing materials dates back to the nineteenth century. An example from the 1880s is the natural rubber pads supporting the Flanders Street railway viaduct in Melbourne. In the 1950s laminated bearings made up of alternate rubber and steel layers were introduced as bridge supports. They were able to take up the thermal changes in the length of the bridge deck without the maintenance problems associated with roller bearings. The Pelham Bridge in Lincoln, constructed in 1957, was the first application of this technology in Great Britain. The capability of laminated rubber bearings to act as anti-vibration mounts for structures was first exploited in 1966. Albany Court is a block of flats constructed over St. James's Park underground station in London [1]. It is supported on 13 rubber bearings carrying loads from 60t to 200t (Figure 1). The main disturbing frequency in the ground is about 22Hz though the spectrum is fairly broad. The vertical natural frequency of 7Hz achieved by the bearings reduces the vibration levels in the building to about ±0.3mm/s which is below perception thresholds. The success of the Albany Court project opened up the possibility of developing valuable, inner-city sites for both residential and commercial uses in locations near railways and roads previously only thought suitable for industrial or warehouse use. The same technology can be used to isolate accommodation blocks on off-shore platforms, or residential parts of mixed developments.

This paper describes a recent project involving the construction of a new hotel on elastomeric anti-vibration mounts; it covers design, testing and installation. First some background on elastomeric mounts is given. The final sections cover some general issues concerning the use of this technology.

2. BACKGROUND

2.1 Laminated Elastomeric Bearings

The incorporation of internal reinforcing plates into elastomeric bearings (Figure 1) increases the load that can be supported for a given plan area without placing the elastomer under excessive strains. The steel plates, which are bonded to the elastomer, restrain the tendency for the sides of the elastomer to bulge out under load. Appropriate choice of the three geometrical parameters:-

- elastomer layer thickness
- number of elastomer layers
- plan area

and the elastomer modulus enables a bearing giving the desired natural frequency for the mounted structure to be designed whilst satisfying the requirements of:-

- stability of bearing under applied load
- elastomer strain below maximum permitted level.

The natural frequency, f_n, is related to the vertical stiffness of the bearing, K, and the mass, M, it supports:-

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (1)$$

Although other systems such as steel coil springs can be designed to give the required stiffness, elastomeric bearings offer the advantage of a small amount of intrinsic damping. Though damping slightly reduces the degree of isolation at frequencies above f_n some is needed to control the amplitude at primary resonance; the broad range of the exciting vibrations generally means they extend down to f_n. The damping in laminated elastomeric bearings also reduces the peaks in transmissibility at the higher frequencies ($\pi f_n \sqrt{M/m}$, where m is the active mass of the spring) corresponding to the excitation of standing waves in the spring. The intrinsic damping in the elastomer can be more effective than the noise-stop pad commonly inserted between coil springs and the structure. Moreover the generally lower value of m for elastomeric springs gives a broader frequency range of good isolation [2]. With steel springs there is an ongoing maintenance commitment as unprotected carbon steel components are susceptible to corrosion, particularly in damp basement environments. The elastomeric bearing steel components are hermetically sealed when encased in rubber during the manufacturing process, and therefore require little or no maintenance beyond occasional inspection.

2.2 Longevity and Creep

Their use as structural mounts requires that the elastomeric bearings perform satisfactorily over several decades. The elastomer - natural rubber - generally used in Britain for mounts can be extremely durable. Indeed, as already mentioned, atmospheric attack of the steel plates is usually avoided by having outer cover layers of rubber to encase the plates and protect the bondline between the plates and the rubber. The large volume to surface ratio of the rubber in the bearings protects the bulk from oxidative degradation; the addition of antioxidants gives further protection. Ozone cracking, to which natural rubber is susceptible, can also be prevented by chemical additives.

As well as remaining free from obvious signs of degradation, elastomeric mounts need to maintain their stiffness within acceptable limits. In 1995, bearings were removed from the Pelham Bridge for testing and detailed examination in Britain and Japan [3]. The shear stiffness of the two bearings tested in Britain and the original prototype are given in Table 1. The change after 38 years service is small, being comparable with the variability between bearings. The tests confirm that the anaerobic stiffening expected in the bulk of a structural bearing will be small over a service life comparable with that of many buildings. Tests from sections cut from Bearing 1 showed that significant oxidative effects and reactions involving the antidegradants extended only 10-20mm below the surface, results confirming the expectation that the large size of structural bearings protects the bulk.

Table 1: Shear stiffness of Pelham Bridge Bearings

	Shear stiffness, kN/mm
Prototype	3.7
After 38 years: Bearing 1	3.7
After 38 years: Bearing 4	4.2

Elastomeric bearings will creep under the dead load applied. Albany Court provided a test bed to measure the amount of creep over several years and compare the observations with predictions based on laboratory data from rubber testpieces [1]. The observations and predictions are seen to agree well (Figure 2); the former have to be corrected for changes in ambient temperature. The creep predicted over 100 years is 5.5mm, an amount easily accommodated when designing the foundation.

2.3 Bearing Stiffness

2.3.1 Static

The deflection of the bearing under the design vertical load is determined by the static stiffness, normally taken as the secant stiffness ie. change in load/change in deflection. For an engineering elastomer, the stiffness depends slightly on loading history and loading rate so these have to be specified in a test schedule. Slight misalignment of the ends of a bearing normally result in a lead-in to the force-deflection curve. Thus the static stiffness has to be measured between the working load and a significant fraction (eg. 0.3) of the working load to avoid the initial part of the curve. The design formulae enable the static stiffness to be estimated from the bearing geometry and the elastomer shear modulus. As engineering elastomers contain filler to increase the stiffness, their stress-strain behaviour is non-linear; thus the value of the shear modulus appropriate to the equivalent shear strain experienced by the rubber has to be used in the formulae [4].

2.3.2 Dynamic

The isolation frequency given by the bearing is determined by its dynamic vertical stiffness, K, about the working dead load according to equation (1). The dynamic stiffness is greater than the static stiffness because of the following:

- small strain dynamic stiffness of filled rubber >> large strain static stiffness
- geometrical non-linearity
- frequency effects

For natural rubber the last is quite small for the relevant range of frequencies. The non-linearity arising purely from the geometry of the bearing is more significant, though much of the stiffening typically seen in static force-deflection plots arises from the lead-in associated with slight misalignment of the bearing faces. The most important factor is generally the non-linearity of the properties of filled rubbers: the stiffness at small strain amplitudes is much higher than that at large strains. This phenomenon reflects through to the dynamic properties of the bearing, and is present whether or not a static load is applied.

The ratio between the dynamic and static stiffnesses is termed the "dynamic/static ratio". There is no standard definition of static stiffness in this context. Because of the existence of lead-in it can be confusing simply to use the secant stiffness between zero load and the working load. This problem is overcome by taking the static stiffness to be the tangent to the static force-deflection curve at the working load. Such a definition of dynamic/static ratio ignores the influence of geometrical non-linearity, however. With this definition values would generally be less than 2.

3. PERFORMANCE REQUIREMENTS AND DESIGN

3.1 Background

The Stakis Metropole Hotel is located in central London next to the Marylebone Flyover, a site adjacent to the London Underground Bakerloo Line running tunnels. The current construction works are the second phase of the development, which will ultimately become Europe's largest conference facility. Both phases of the project are constructed on elastomeric bearings, phase one being successfully completed in 1992.

3.2 Overall Isolation Performance

The design requires that elastic deformation under the working load shall achieve a dynamic natural frequency for the entire isolation system in the range of 12-15Hz. Somewhat high figures were specified because the structure is relatively "lightweight" with long internal spans, which according to finite element modelling are predicted to have a natural frequency of 6-7Hz. Therefore the structural isolation needs to be at the upper end of the normal range of isolation frequencies to avoid the possibility of exciting internal harmonics. The ground-borne vibrations to be attenuated peak at frequencies of 60 to 65Hz. Another factor leading to a relatively high isolation frequency (and thus bearing stiffness) is that, because the completed building will only be partially isolated (the existing link block is not isolated), the bearing deformation under the working load has to be limited to <10mm to avoid potential differential settlement problems.

3.3 Resilient Bearings Specification

The bearing materials and design had to follow the guidelines set out in BS6177:1982 - Selection and use of elastomeric bearings for vibration isolation of buildings. Specific issues covered in the Design Specification included:

Types and Materials
Bearing pads shall be formed from high quality elastomeric materials based on natural or synthetic rubber, with reinforcement by means of encased steel plates (as was the case in phase 2 of the project) or fabric mesh (as was the instance in phase 1). The physical properties of natural rubber compounds, the elastomer used in the fabrication of the bearings, in particular have to conform to BS1194:1992 Specification for natural rubber compounds. BS6177 also gives particular requirements regarding ozone resistance, creep and low temperature stiffening (for applications involving service temperatures <0°C).

Dimensional Properties
The shape factor of bearings shall be arranged to ensure stability under all operating conditions and freedom from distortions, which may adversely effect the life expectancy of the bearing pad or its fixings. The shape factor is determined by the plan dimensions of the bearing and the thickness of individual elastomer layers.

Static Compression
The bearings shall be capable of being stressed axially up to at least 4x the normal operating stress without breakdown or permanent damage.

Dynamic Stiffness
The dynamic stiffness of the bearings shall be such that the ratio of measured dynamic natural frequency to the natural frequency estimated from static deflection under the intended operation conditions shall not exceed 3.5. The dynamic natural frequency shall be measured at the working load with an imposed dynamic load giving 0.1mm peak-to-peak displacement amplitude.

Creep
Changes in vertical deflection shall not exceed 20% of the initial deflection after 5 years, and the design shall be based on a target of <25% change after 25 years.

Shear Stiffness
Lateral restraint devices shall be provided. Test data and/or calculations shall show the effect of the proposed devices on the vertical stiffness of the isolation system.

Environmental Conditions
All bearings shall be designed to meet the operating requirements for at the least the minimum operating life within the following environmental conditions:

0-100%	humidity
0°C to + 30°C	for internal bearings
-20°C to + 40°C	for external bearings

Durability and Replacement
All bearings shall be durable, remain stable and retain the required performance characteristics over a minimum operating life of 50 years with a warranty of 25 years.

3.4 Other General Requirements

Because the bearings are located in a space not leading to fire risk, no fire resistance requirement was specified with the exception of bearings located adjacent to the lift shaft. (The standard to be satisfied was BS476:Part 1 Fire tests on Building Materials and Structures.) The number of different types of bearing shall be kept to a reasonable minimum.

3.5 Bearing Design and Loads

The building has 117 steel columns. The working loads (dead + 0.4 x live + effect of wind loading) to be exerted on the column supports range from 680 to 12,600kN. In order to accommodate this wide range with a small number of different types of bearing, the more heavily loaded columns rest on an array of similar bearings. With this strategy, only four types of bearing are needed. The columns, according to load, are supported by an individual bearing or arrays of 4 to 16 bearings. The range of working and ultimate loads for each bearing type and its plan area are listed in Table 2; the height in all cases is 50mm. The vertical deflection at the operating loads is predicted to be 3-4mm, well within the specified limit of 10mm. All four types are designed to operate at a working contact pressure up to approximately 9N/mm^2, a figure above the maximum working pressure demanded in the present project. Generally 6N/mm^2 has been regarded as the norm. Using improved component design and manufacturing technology developed for seismic applications, elastomeric antivibration mounts have been successfully installed at contact pressures in excess of 12N/mm^2. Operating at higher contact pressures has the benefit that the bearings are smaller and/or fewer in number; this has both commercial and environmental benefits as less material is consumed in manufacture.

Table 2: Bearing details

Bearing type	1	2	3	4
Plan dimensions, mm	200 x 200	250 x 250	300 x 300	279 x 406
Working load range, kN	250 - 300	350 - 525	550 - 725	750 - 930
Ultimate load (max), kN	500	1100	1400	1600

3.6 Column Support Layouts

In order to cater for the combinations of vertical and horizontal loads, up-lift conditions, and space limitations including local variations for lift car clearances and other architectural details, a total of 70 different column support layout patterns were necessary. The column load is transferred to the bearings through a single steel top-plate; the bearings rest on a steel bottom plate. The layouts incorporate orthogonally disposed lateral restraints and fail-safe supports.

4. Prototype testing

The dynamic stiffness of an agreed representative samples of each of the four types of bearing was measured at a laboratory (Rubber Consultants) independent of the manufacturer.

Prior to the dynamic test each bearing was cycled at a constant rate between zero and a specified maximum load (related to the maximum working load) for 2 cycles, each cycle taking 60 seconds to complete. A plot for the Type 3 bearing is shown in Figure 3.

Dynamic tests were performed at specified static preloads covering the expected working load range. For each preload, dynamic amplitudes of ±0.05mm and ±0.1mm were applied at frequencies between 5 and 30Hz. Dynamic stiffnesses and phase angles were calculated from the observed load amplitudes. The frequency sweep (in 5Hz steps) was carried out at the low amplitude first. Two bearings of each type were tested for each preload. Converting the static load applied into an equivalent gravitational load, a natural frequency can be calculated (equation 1) from the observed stiffness. For all applied preloads and both displacement amplitudes the range of natural frequencies calculated using the stiffness determined from the 15Hz test is 12.0 to 14.5Hz, figures within the isolation frequency range specified.

The effect of the frequency of test on the dynamic stiffness was confirmed to be relatively small (Table 3). The phase angle is seen to be more sensitive; the values in Table 3 are typical and indicate the percentage of critical damping to range from 3 to 6%. Doubling the applied displacement amplitude reduced the dynamic stiffness by less than 1%. Increasing the preload raised the dynamic stiffness (Table 4). The effect is seen to be beneficial as the increased stiffness results in a smaller change of the natural frequency with change in static loading: only 5% increase for a 50% increase in mass supported. The results for the two samples of a given type of bearing indicated very good reproducibility (within <3%).

Table 3: Bearing tests. Effect of frequency						
Frequency Hz	5	10	15	20	25	30
Dynamic stiffness kN/mm	446	458	467	472	476	479
Phase angle deg.	3.8	4.6	5.2	5.8	6.4	7.1

Bearing Type 3. Amplitude ±0.05mm. Preload 725kN

Table 4: Dynamic bearing tests. Effect of preload			
Preload, kN	350	450	525
Dynamic stiffness, kN/mm	259	368	433
Natural frequency, Hz	13.6	14.3	14.3

Bearing Type 2. Amplitude ±0.1mm. Test frequency 15Hz

5. GENERAL MANUFACTURE AND INSTALLATION ISSUES

5.1 Quality Control, Assurance Requirements

All major projects will operate some form of Quality Assurance Programme. Most creditable manufacturers will also have either a nationally or internationally accredited system such as BS 5750 or ISO 9001. Each project will then have in-turn its own Quality Plan specific to the Elastomeric Bearing design and manufacture developed by the manufacturer and covering: Prototype sampling and testing, Design approval, Contract procedures, Design and Documentation reviews, Operative briefing, Procurement control, Equipment calibration, Project Specifications and Standards, Manufacturing controls, QC production testing, Certification and Documentation. This plan is submitted and approved by the clients' engineer prior to commencement of manufacture.

5.2 Standard Bearing Sizes

Manufacturers generally have a range of standard bearing designs which are known to satisfy the standard type tests for the bearings and elastomer compounds. Typical square bearings range from 150 to 600mm in plan. Rectangular plan bearings are also available and manufacturers generally have several mould tools each covering a range of sizes. The height of the bearings is typically between 50 and 150mm, the value depending upon stiffness and stability considerations.

5.3 Site Installation

In steel framed buildings isolation break-lines are normally either at basement level or, when the property is of mixed uses ie. retail at ground floor and residential/commercial office on the upper levels, at ground-floor level in the ceiling void. In concrete framed buildings isolation break-lines are normally either at basement level between the foundation ground beams and superstructure or in the foundations, the bearings being seated on a pile cap with the ground beams above. In the latter case, great care must be taken not to compromise the isolation by bridging either with services or construction rubble. The following are critical installation factors:

- maintenance of the air gaps to avoid bridging
- accurate setting-out

- good site construction practice
- detail designing of service connections

Installation will be covered by a separate quality assurance document developed in co-operation with the installation contractor. Issues such as sequence of installation, safe-handling techniques, bearing locations and alignments, any pre-loading requirements, witness and hold points and post-installation inspections, should be detailed in the document.

6. SAFETY ISSUES

6.1 Resistance to Fire

Laminated elastomeric bearings have been shown to survive a standard fire test (BS476:Part 1) for at least 3 hours, the time depending upon the degree of protection provided to the bearing [5]. After tests lasting 4 hours (a time sufficient for high temperatures to penetrate the bulk of the bearing with the level of protection used in the tests) the bearings were still able safely to support the design working load, though the deflections under load were increased from 4mm to 6-11mm. Such a movement, even if differential between bearings, was not considered to lead to serious problems when compared with other damage resulting from a fire of such severity. It was also concluded that a thick (~70mm) rubber cover layer combined with fire resistant tape would ensure bearings pass a 4-hour test without significant heating of the interior. Other forms of protection may be safely adopted. In the Stakis Hotel project the bearings adjacent to the lift shaft, the only ones requiring fire resistance, have been protected by an intumescent seal.

6.2 Provision of Fail-Safes and Lateral Restraints

Where structurally critical, fail-safes are provided to support the structure in the unlikely event of catastrophic failure of the elastomeric mounts. The fail-safes are usually part of the column support assembly mounted between the corrosion protected steel top and base spreader plates. Alternatively, they can be provided in the concrete detailing as was the case at Albany Court. The air gap between the ground beams and the isolated superstructure must always be maintained at a minimum value of 20mm. Any bridging will compromise the performance of the isolation system.

The design of the isolation system should allow for removal and replacement of the elastomeric mounts, in the remote case that this ever becomes necessary, with minimal disruption to the structure. This normally means that fail-safes are positioned so as not to obstruct bearing extraction and that adjacent structural detailing makes provision for safe access.

The elastomeric mounts are quite soft in shear and thus lateral restraints to prevent undue horizontal displacements, for instance under wind loadings, may be required. Elastomeric pads mounted vertically can act as restraints; they will be relatively stiff in the horizontal direction, but soft in the vertical direction so that they do not significantly add to the overall vertical stiffness of the isolation system.

6.3 Service Life

BS6177 suggests a minimum working life of 50 years can be assumed for materials conforming with the standard. Coupled with the creep test results at Albany Court which predict that creep deflections should remain acceptable for over a hundred years, engineers and clients can be assured of the long-term performance of elastomeric mounts.

7. PROJECT ECONOMICS

Acoustic isolation using elastomer bearings has a reputation for being complex and expensive compared with conventional concrete or steel frame construction. In acoustic engineers' reports wordings such as 'this option is both complex and expensive' can often be found. The fact that the construction detailing is critical and that good site working practice is required is not necessarily a bad thing. As the application of the technology spreads, developers see the potential and clients become aware of the benefits, more contractors will become familiar with the techniques and construction prices will fall accordingly. The possible incorporation of acoustic isolation should be considered at an early stage of the structural design to avoid unnecessary expenses and delays. Acoustic isolation should have a negligible effect on construction times and its costs are insignificant against the value of prime location sites that are made viable for commercial or residential development. For example, a building in London W1 costs £20m to construct and sells as an apartment complex or commercial offices for £70m. A 1% addition to the construction costs - a figure including surveys, design, testing, supply and installation - allows the acoustic isolation of the building. Had the land been developed for industrial use the market value would probably be less than £10m.

8. CONCLUSION

Acoustic isolation using elastomeric mounts is now a technically and economically proven technique provides a vibration-free living or working environment at sites subjected to ground-borne noise.

REFERENCES

[1] C.J. Derham and R.A. Waller, *Luxury without rumble*, The Consulting Engineer (1975) **39**, 49-53

[2] A.H. Muhr, *A comparison of rubber and metal springs for vibration isolation*, Plastics Rubber Composites: Processing and Applications (1992) **18**, 3-7

[3] K.N.G. Fuller and A.D. Roberts, *Longevity of natural rubber structural bearings*, in Proc. International Rubber Conf. (1997), 777-87; RRIM, Kuala Lumpur

[4] A.H. Muhr, G.H. Tan and A.G. Thomas, *A Method of allowing for Non-linearity of Filled Rubber in Force-Deformation Calculations*, J. Nat. Rubb. Res. (1988) **3**, 261-76

[5] C.J. Derham, *Fire resistance of steel laminated natural rubber bearings*, NR Technol (1976) **7**, 29-37

ACKNOWLEDGEMENTS

Consent has kindly been granted by the following organisations, to whom the authors are indebted for their co-operation, in the use of the Stakis Metropole Hotel Project as an illustration.

Stakis Hotel Group:	Client
Laing Construction:	Design & Build Main Contractor
Clarke Nichols Marcel:	Structural Engineer
Helmuth, Obata & Kassabaum (HOK) Inc:	Architect
Arup Acoustics	Acoustic Consultant

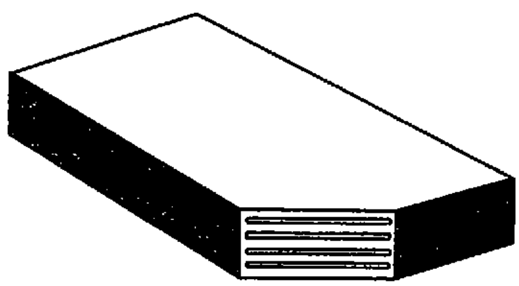

Figure 1: View of laminated bearing showing internal metal plates

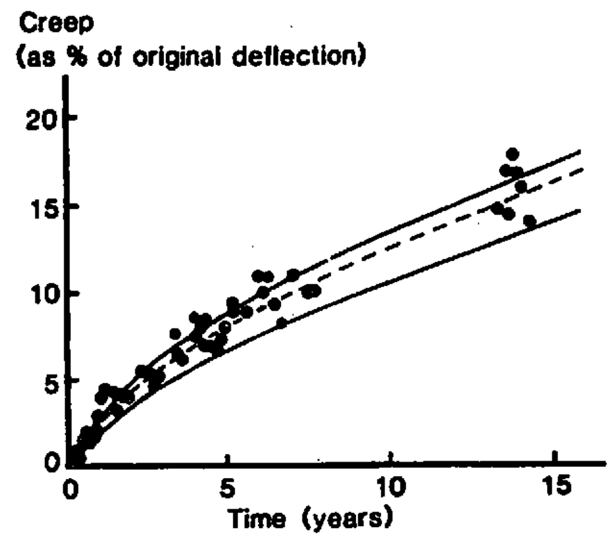

Figure 2: Long-term creep data for elastomeric mounts under Albany Court. The lines show the prediction (with upper and lower bounds) based on laboratory tests

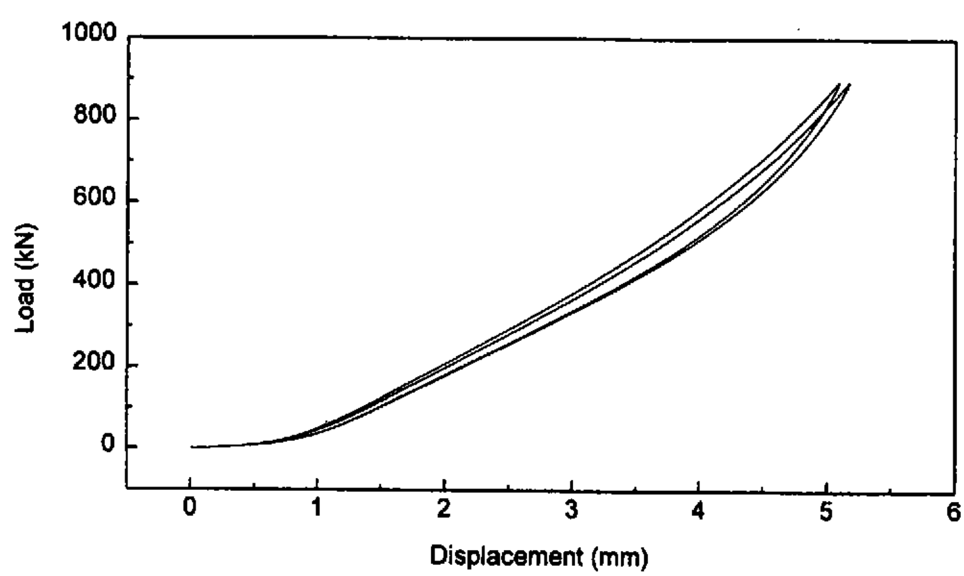

Figure 3: Quasi-static test of Type 3 bearing