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**DYNAMIC CHARACTERISTICS OF BRIDGESTONE LOW SHEAR
MODULUS-HIGH DAMPING SEISMIC ISOLATION BEARINGS**

by

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DYNAMIC CHARACTERISTICS OF BRIDGESTONE LOW SHEAR MODULUS-HIGH DAMPING SEISMIC ISOLATION BEARINGS

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Y. W. Chang and R. W. Seidensticker

I. INTRODUCTION

Argonne National Laboratory (ANL) has been deeply involved in the development of seismic isolation for use in nuclear facilities for the past decade. Under the funding and direction of the U.S. Department of Energy (USDOE), ANL has been developing methodology needed to evaluate the usefulness and effectiveness of seismic isolation for advanced reactors. Seismic isolation is also growing rapidly worldwide as a cost-effective and reliable design strategy for a wide range of critical and important facilities, such as hospitals, computer facilities, data centers and emergency preparedness centers.

In the early stages, the seismic isolation elastomeric bearings were manufactured with low damping natural rubber compound and were used with supplementary dampers. As the technology evolved, the supplementary dampers have been eliminated and the damping has been incorporated in the bearings themselves by appropriate compounding. High damping rubber bearings have been used in many base isolated buildings. These bearings carry the vertical load, provide low horizontal stiffness and generate significant damping, thus obviating the need for additional mechanical energy dissipating mechanisms.

To ensure that the seismic isolation elastomeric bearings manufactured for the critical and important facilities meet the stringent design and functional requirements, ANL has tested several types of bearings manufactured by various bearing manufacturers. The first type of seismic bearings tested was a high shape factor-high shear modulus-high damping rubber bearing manufactured by Fluorocarbon (now FURON) of Texas, U.S.A. The bearings were made from a highly damped rubber compound designated by the elastomer compounder, LTV Energy Products as 243-62. The shape factor value for those bearings is 24, the same as those used in the General Electric (GE) Company's design of the Power Reactor Inherently Safe Module Reactor (PRISM). ANL purchased 16 bearings from Fluorocarbon: eight bearings were shipped

to Japan for installation at Sendai test facility [1] and for laboratory testing at Shimizu Corporation; four bearings were sent to the Earthquake Engineering Research Center (EERC), University of California, Berkeley for additional laboratory tests; two bearings were shipped to the Energy Technology and Engineering Center (ETEC) for dynamic testing; and two were retained at ANL as archival samples. The results of laboratory tests are given in ANL/Shimizu Report ANL-002 [2].

The second type of seismic isolation bearings tested was a medium shape factor-high shear modulus-high damping rubber bearing manufactured by LTV Energy Products Company of Texas, U.S.A. ANL purchased 28 bearings: 14 bearings have a shape factor of 9 and the other 14 bearings have a shape factor of 18. These bearings were made of two different elastomer compounds. One has a shear modulus of 120 psi at 100% shear strain and the other has a shear modulus of 150 psi at 100% shear strain. They are all high damping and high shear modulus elastomeric compounds. The two compounds were designated as 259-62 and 257-71 by the elastomer compounder. The laboratory tests were performed at the Earthquake Simulator Laboratory, EERC. The mechanical characteristics and failure mechanisms of these four different types of elastomeric bearings are described in detail in EERC Laboratory Report No. 91-04 [3].

The third type of bearings tested was medium shape factor-high damping-low shear modulus rubber bearings. It used a new compound developed by the Malaysian Rubber Producers Research Association (MRPRA) which has a shear modulus that is about half that of the shear modulus of the high damping rubber developed by LTV. Also, the value of the shear modulus is less dependent on the shear strain, thus improving the response of the isolated building under small earthquakes. ANL purchased ten bearings from Rubber Consultants of the United Kingdom using the newly developed compound of MRPRA. Six bearings made by Rubber Consultants were installed in the Sendai test building for earthquake observation and four bearings were used for laboratory testing. The mechanical characteristics of these low shear modulus-high damping bearings are described in ANL/Shimizu Report ANL-004 [4].

Bridgestone Company of Japan is one of the leading seismic bearing manufacturers in the world. Their bearings have very good performance records. It appears that Bridgestone's high damping bearings are made of a blend of filled natural and synthetic rubbers with fillers and plastizers whereas in the United States, the high damping compound is a carbon filled natural

rubber. To compare the properties of the two different kinds of high damping compounds, ANL purchased eight bearings from Bridgestone: four of which were made of high shear modulus-high damping rubber compound KL401; the other four were made of low shear modulus-high damping rubber compounds: two with KL301 elastomer and two with KL302 elastomer.

Tests of the Bridgestone bearings were performed at EERC. The dynamic characteristics of the high shear modulus Bridgestone bearings, KL401, are described in ANL/Shimizu Report ANL-003 [5]. This report describes the dynamic and failure characteristics of the low shear modulus Bridgestone bearings, KL301 and KL302.

II. TEST BEARINGS

The dimensions of the test bearings provided by the Bridgestone Corporation are shown in Fig. 1. The bearings have 22 thin layers of 2 mm (0.079 in.) thick rubber and 21 steel shims which are 0.8 mm (0.031 in.) thick. The shim diameter is 240 mm (9.45 in.) and there is 2.5 mm (0.098 in.) of cover outside the perimeter of the shim plate. Thus, the diameter of the rubber layers is 245 mm (9.65 in.). The bearings have two oversize end plates which permit them to be bolted to the test machine.

The compound used in the bearings is designated by Bridgestone as KL301 or KL302. They are both low shear modulus, high damping rubber. KL301 is the earlier version of low stiffness high damping elastomer material developed by the Bridgestone Corporation, whereas KL302 is the improved version of the low stiffness high damping elastomer material with less temperature dependency than KL301. They are a blend of natural and synthetic rubber with around 30% carbon filler. The shear modulus and viscous damping of KL301 and KL302 are shown as a function of shear strain in Figs. 2 and 3, respectively. For the purpose of comparison, the properties of KL401 and KL501 are also shown. It should be mentioned that KL501 is a new high modulus rubber compound developed by Bridgestone to permit manufacturing of bearings with a wide range of stiffnesses.

The identification numbers of the test bearings are given below.

EERC ID	Bridgestone ID	Rubber Compound ID
1	68F041Z-HR030-2	KL301
2	68F041Z-HR030-3	KL301
3	68F041Z-HR030-5	KL302
4	68F041Z-HR030-6	KL302

The nominal vertical load of the bearings is 30 metric tons (tonnes) which corresponds to 66.2 kips of load and 6.52 MPa (945 psi) of vertical pressure. For this load, these bearings have a horizontal frequency of 0.85 Hz at 100% shear strain and a vertical frequency of 29.5 Hz. This very high vertical frequency is due to the use of extremely thin rubber layers. The shape factor of these bearings is 30 which is also considered to be very high.

III. TEST FACILITIES

The test program was carried out on a single bearing test machine as shown in Fig. 4 at the Earthquake Simulator Laboratory of EERC.

A. Test Setup

The mechanical characteristic tests for the elastomeric bearings were performed in a test machine which can produce horizontal and vertical dynamic loadings simultaneously on a single bearing. The details of the test machine are described below.

The test machine consists of two rigid reaction frames supporting one horizontal actuator and two vertical actuators. The test bearing is mounted on a force transducer which measures shear force, axial force and bending moment. The force transducer is located on a braced pedestal which is attached to a base block. The base block consists of a concrete block and a wide flange steel beam to provide anchorage to the test floor. Loads are applied to the test bearing by a beam; vertical loads by two vertical actuators to simulate gravity loads on the

bearings, and the horizontal loads by a horizontal actuator which acts along the longitudinal axis of the load beam.

The rigid pedestal is placed between the transducer and the test floor to maximize the length of the vertical actuators so that the change in the vertical load component due to horizontal displacements during testing is not significant. Two lateral struts are connected to opposite ends of the load beam to stabilize the setup in the transverse direction. For constant axial loads applied to the test bearing the vertical actuators are under force control, which means that the vertical load is maintained constant and is independent of the horizontal displacements of the load beam. In addition, the differential displacement between the two vertical actuators is maintained at zero, ensuring that the load beam is kept horizontal.

Control of the hydraulic system is performed by an MTS 443 Controller. The hydraulic actuator can develop a maximum dynamic load of 339 kN (76.2 kips) at a hydraulic pressure of 20.7 MN/m² (3000 psi). The maximum travel of the horizontal actuator is 152.4 mm (± 6 in.) (i.e., 304.8 mm or 12 in. stroke). Maximum piston velocity is 770 mm/sec (30.3 in./sec) and the servo-valve on the actuator has a flow capacity of 200 gpm. If displacements in excess of the 152.4 mm (± 6 in.) limit are required, the setup can be modified to obtain a maximum displacement of 254 mm (10 in.) for loading in one horizontal direction only. A maximum load of 1334.4 kN (300 kips) can be applied by the two vertical actuators, each with a servo-valve capacity of 25 gpm.

Signal control is performed by an IBM-AT 286 personal computer. Control signals for both components of loading can be completely general in nature.

B. Instrumentation

A total of 19 channels of data were recorded for the tests of the elastomeric bearings in the single bearing test machine. The following is a brief description of the components that were measured.

The loads applied by the hydraulic actuators were measured by precalibrated load cells. The compression load on the bearing is calculated by summation of the measured forces in the two vertical actuators. Shear force, axial force and bending moment are measured by six force transducers located underneath the bearing. A linear variable differential transformer (LVDT)

built into the horizontal actuator measures the horizontal displacement of the load beam (this being the lateral displacement of the bearing). Linear potentiometers attached to both of the vertical actuators provide feedback signals for the control of the vertical load. Four direct current differential transformers (DCDTs) measure the vertical displacements of the load beam near the corners of the top of the bearing. A complete list of channels is given in Table I.

IV. TEST PROGRAM

A. Horizontal Tests

All bearings were subjected to the same horizontal tests which consist of three series of cyclic shear tests. They are:

Series I	$\gamma = \pm 5\%, \pm 10\%, \pm 25\%, \pm 50\%, \pm 75\%, \pm 100\%$
Series II	$\gamma = \pm 100\%, \pm 150\%, \pm 200\%, \pm 250\%$
Series III	$\gamma = \pm 200\%, \pm 250\%, \pm 300\%, \pm 350\%$

where the shear strain γ is defined as the ratio of the horizontal displacement of the bearing to the total rubber height. There were five displacement cycles for each level of strain.

Each series was repeated four times on each bearing, where the axial load was varied each time. The vertical pressures on the bearing for four axial loads were set at approximately 0, 3.45, 6.90 and 10.35 MPa (0, 500, 1000, 1500 psi).

The frequency of horizontal load in all tests was 0.5 Hz which is the design frequency of the isolated structures. Tests involving different load frequencies were not considered since it had already been shown in Ref. 6 that the frequency of the applying load does not have a significant effect on the dynamic properties of elastomeric bearings.

The tests were carried out in rapid succession for each bearing; between one test and the next there was a time interval of only a few minutes, which was necessary for verification of correct data acquisition and test execution.

B. Vertical Tests

Each bearing was subjected to five cycles of vertical loading centered around vertical pressures of 3.45, 6.90 and 10.35 MPa (500, 1000, 1500 psi). The variation in vertical load in each of these tests corresponded to about ± 0.69 MPa (± 100 psi).

Since the vertical displacements due to this variation in load are of the order of magnitude of 0.2 mm, measurement of displacement was carried out using four DCDT type transducers located between the end plates of the bearing; these transducers had an accuracy of the order of 0.025 mm.

The frequency of the vertical load was fixed at 0.33 Hz for all the tests, which is the upper limit permitted by the hydraulic actuator specifications.

C. Failure Tests

After the horizontal and vertical dynamic tests were completed, each bearing was subjected to a combined axial compression-shear failure test. The horizontal shear load had a velocity of 4.4 mm/s (strain velocity 10%/s). The axial compressive load was constant for each bearing. The vertical pressure of the axial compressive load in the tests was 3.45 MPa (500 psi) for bearing nos. 1 and 3 and 6.90 MPa (1000 psi) for bearing nos. 2 and 4.

The failure strain was the shear strain at which the bearing failed. The failure load was assumed to be the maximum shear load recorded in the failure test.

V. TEST RESULTS

The tests were performed at EERC by Francesco Di Martino, an Italian exchange student from Università degli Studi di Catania. The test results are given in Ref. 7. Although the text of the test report was written in Italian, the behavior of the bearings can be interpreted from the test data, the hysteresis loops, and the force displacement curves in the failure tests given in the report. Based upon these information and translation of selected sections on test results in Ref. 7, the dynamic characteristics of the bearings are described below. The conclusions given in this report are drawn by the authors. They may be different from those in Ref. 7.

A. Dynamic Properties Determined from the Tests

The most interesting properties that can be determined from the horizontal tests are effective stiffness and equivalent damping.

The effective horizontal stiffness is a function of the peak values of shear force and displacement and is defined as follows:

$$K_{eff} = \frac{F_{max} - F_{min}}{d_{max} - d_{min}} \quad (1)$$

where F_{max} , F_{min} , d_{max} and d_{min} are the maximum and minimum values of shear force and displacement, respectively, obtained during one specific load cycle. Actually, Eq. (1) is only an approximate expression for determination of the effective stiffness, but it was used since it is easy to calculate from the data and, as shown in Appendix A, any error involved is negligible for application purposes.

The equivalent damping can be evaluated by taking into account the linear viscous-elastic behavior of the bearing. In the linear viscous-elastic model, the energy dissipated in one cycle of loading and unloading is a quadratic function of displacement.

The equivalent viscous damping of the bearings is defined as follows [8]:

$$\beta = \frac{W_d}{4\pi W_e} \quad (2)$$

where W_d = energy dissipated in one cycle

$$W_e = \text{elastic energy stored in the load cycle} = \frac{1}{2} K_{eff} d_{max}^2.$$

It should be noted that the behavior of the bearings is not independent of the history of the bearing load. In fact, the rubber, particularly high-damping rubber, undergoes a reversible process under the action of a load, a process known as "scragging" occurs (degradation of stiffness). When standard horizontal tests are carried out at a fixed level of shear strain it is found that the stiffness is greater in the first cycle than in successive cycles. However, the material rapidly reaches a stable condition, and the cycles following the third can be considered

identical. Therefore the results obtained are a function of the specific load history for each bearing.

It has been found that degradation in stiffness is not permanent effect but is a phenomenon of short duration. W. Fletcher and A. Gent were the first to observe that the dynamic stiffness of natural vulcanized rubber decreases after several strain cycles [9,10]. They also observed that when natural vulcanized rubber is brought to rest after a load cycle its stiffness gradually increases over time, reaching its initial value after about 24 hours at ambient temperature. Subsequent research has shown that the recovery time could be less [11,12].

All of this indicates that the high-damping rubber may exhibit a deterioration in stiffness through repeated high-strain load cycles, but it will recover the original stiffness value after a short resting period. Thus, the scragging effect causes some difficulties for investigation of the dynamic characteristics of elastomeric bearings.

B. Dynamic Horizontal Properties of the Bearings

The values of K_{eff} and β were determined from the hysteresis loops using the relations described above, the energy dissipation per cycle, W_d , was calculated by numerically evaluating the area within the hysteresis loop, and the shear modulus G was calculated by inverting the equation normally used to determine the shear stiffness of the bearings:

$$K_{eff} = \frac{GA}{T_r} \quad (3)$$

where A = area of the cross section of the bearing

T_r = total height of the bearing rubber.

The effective stiffness K_{eff} , the equivalent viscous damping β , the energy dissipation per cycle W_d and the shear modulus G for the first and fifth cycles of each strain level are given in Table II, in which the average values for the same quantities in the second, third and fourth cycles are also shown.

The loads and the displacements for the cycles at 5% of shear strain are very small and are close to the transducer limit. Thus, the accuracy of the results at 5% shear strain is less than

the values obtained with larger strain. As a consequence, the results for cycles at 5% of shear strain are not included in the table, even though these cycles are shown in the figures.

The graphs showing the relationship between load and displacement of bearing no. 1 for Series I, II and III are shown in Figs. 5, 6 and 7 for zero vertical pressure, in Figs. 8, 9 and 10 for vertical pressure of 3.45 MPa (500 psi), in Figs. 11, 12 and 13 for vertical pressure of 6.90 MPa (1000 psi) and in Figs. 14, 15 and 16 for vertical pressure of 10.35 MPa (1500 psi). Since numerous tests were carried out, the results for other bearings are not presented.

These figures indicate clearly the change in the shape of the hysteresis loops with an increase in strain amplitude. The shape of the loops is initially elliptical, in good approximation, whereas the increase in the strain amplitude causes the loops to become elongated and to exhibit two parallel sides and significant sharpening at ends.

One also notes the reduction in equivalent damping with the increase of strain amplitude, which is a function of the hardening of the material when strain exceeds 200%. Furthermore, for these types of elastomers the energy dissipation is not a quadratic function of the displacement amplitude but varies approximately with an exponent equal to about 3/2.

An important aspect related to bearing behavior is the fact that the energy dissipation increases with an increase in strain and that the considerable hardening of the elastomer eliminates the possibility of the premature failure of the bearing due to resonance response to low frequency earthquake components.

The bearing hysteresis loops of bearing no. 4, obtained at different levels of strain, are shown in Figs. 17, 18, 19 and 20, where only the first loop for each strain level is shown. These diagrams indicate that it is convenient to use two equivalent viscous models: an initial model for analyzing the response of the system for design earthquakes, where the strains do not exceed 200%, and a second model for extreme events where the strains exceed 200%.

C. The Effect of Vertical Pressure on the Horizontal Dynamic Properties

The bearings used for seismic isolation are generally designed for a vertical pressure of 5 to 7 MPa (700-1000 psi). However, a much lower pressure level of 1.72 MPa (250 psi) has also been proposed for very conservative designs.

The bearings having a low shape factor are considerably affected by the vertical pressure since the vertical load for these bearings constitutes a significant fraction of the critical bearing

load. For bearings of the type manufactured by Bridgestone, which have a high shape factor, the critical load is much greater than the vertical design load and therefore the effect of vertical load is negligible compared with the equilibrium stability.

The horizontal dynamic tests were carried out at four different levels of vertical pressure: 0, 3.45, 6.90 and 10.35 MPa (0, 500, 1000 and 1500 psi). The effective stiffness and equivalent damping as a function of strain and vertical load are shown in Figs. 21 and 22, respectively. As can be seen from Fig. 21, the effective stiffness is virtually independent of the magnitude of the vertical load. But the magnitude of the vertical load has a considerable effect on damping. The diagram given in Fig. 22 shows clearly the effect of pressure on the damping factor. It should be mentioned that the data relating to low strain values (less than 5%) are not very accurate and should be ignored. The average values of equivalent damping for bearing no. 2 are 13.2% at 0 MPa (0 psi), 15% at 3.45 MPa (500 psi), 16.3% at 6.90 MPa (1000 psi) and 21.9% at 10.35 MPa (1500 psi). The values for the other bearings do not differ much from these of bearing no. 2 given above.

The equivalent damping value of the Bridgestone bearings proves to be very large, especially when compared with the high-damping bearings made by other manufacturers. For those bearings the damping factor, among other things, was also found to be dependent on strain, namely, it decreases with an increase in strain. The fact that the Bridgestone elastomers KL301 and KL302 have a very high damping factor value over a considerable range of strains represents a significant development in the technology of rubber production for seismic bearings.

As a consequence of these results, the use of higher pressures for the bearings should be encouraged in the future, since by increasing the pressure one increases the damping value without introducing any collateral negative effects of any significance (at least for the bearings with a high shape factor).

The damping factor was calculated, as already stated, on the basis of the linear viscous-elastic model, which predicts a quadratic dependence of energy dissipation on displacement and an independence of the elastic energy from equivalent stiffness. But it has already been shown in Fig. 21 that the effective stiffness is a function of the displacement, and moreover, as shown in Fig. 23, the energy dissipation is not a quadratic function of displacement.

To determine the relationship between energy dissipation per cycle and strain amplitude, the following procedure is proposed.

Assuming that

$$\frac{W_d}{d_{max}^\alpha} = \text{constant} \quad (4)$$

that is, that the energy dissipation is a function of displacement raised to an unknown power α .

By means of a simple transformation of Eq. (4) one obtains:

$$\ln(W_d) = \alpha \ln(d_{max}) + \text{constant}$$

which represents the equation for a line having the slope α . It is possible to find the empirical value for α .

Figures 24, 25, 26 and 27 show the relationship between the natural logarithm of energy dissipation and the natural logarithm of displacement for different values of vertical pressure acting on the four tested bearings.

The average values for α , as determined from the slope of the lines, are as follows: 1.54 for the bearings made of the elastomer KL301 and 1.56 for the bearings made of the elastomer KL302. From these results one can see that the mechanical behavior of the bearings tested cannot be represented analytically by viscous or hysteretic models, but rather it is necessary to use a nonlinear model.

D. Vertical Load Tests

Each bearing was subjected to five cycles of vertical loading corresponding to ± 0.70 MPa (± 100 psi) centered on 3.45 MPa (500 psi), 6.90 MPa (1000 psi) and 10.35 MPa (1500 psi). The frequency of vertical loading was fixed at .33 Hz. The resulting hysteresis loops for bearing no. 2 are shown in Figs. 28, 29 and 30. The area of the loops was measured and the equivalent damping is around 9% at 3.5 MPa (500 psi), 14% at 6.90 MPa (1000 psi) and 18% at 10.35 MPa (1500 psi). The effective vertical stiffnesses determined from these tests for all four bearings are summarized in Table III. The measured stiffnesses are sensitive to the average vertical pressure.

The stiffness increases with pressure over the range of vertical pressures tested. The vertical frequency as a function of the axial load is shown in Fig. 31.

E. Shear Failure Tests

Each bearing was subjected to a monotonic shear load at a velocity of 4.4 mm/s (strain velocity $10\% \text{ s}^{-1}$) until it failed. The configurations of the bearing at 0, 200%, 350% and 600% of shear strains during the test are shown in Figs. 32, 33, 34 and 35. Figure 36 shows the force-displacement curves for these tests.

Since there are two bearings which were made of the same material, the shear failure tests can be performed at two different vertical loading conditions to study the effects of vertical pressure on the shear failure. Thus, one bearing was tested at a vertical pressure of 3.45 MPa (500 psi) and the other was tested at a vertical pressure of 6.90 MPa (1000 psi).

For bearings no. 1 and no. 2, which were made of the type KL301 elastomer, failure was instantaneous and occurred at a shear strain of about 700%. It is possible that for this type of elastomer the failure mode is not influenced by the vertical pressure, although a greater number of tests would be required to confirm this conjecture.

Bearings nos. 3 and 4, made of the type KL302 elastomer, were also tested at vertical pressures of 3.45 MPa (500 psi) and 6.90 MPa (1000 psi). For bearing no. 3 failure occurred instantaneously at a shear strain of about 600%, while for bearing no. 4 the maximum value of shear force, which was reached at a strain of about 500%, does not coincide with the failure shear strain. The failure of bearing no. 4 occurred at a shear strain of 600%, slightly less than bearing no. 3. It seems that for this type of elastomer the failure mode can be influenced by the vertical pressure. Of course, a large number of tests would be required to confirm this conjecture.

It one examines the force-displacement curves shown in Fig. 36, one also sees that the axial load on the bearing influences the shear stiffness, and in fact the slope of the four curves increases with an increase in vertical pressure. The failure mechanism for all bearings involved tearing of the rubber in the stressed zone; separations in the bond between elastomer and steel shim plate were never detected. It is interesting to note that for these bearings the displacement at failure exceeds the diameter of the bearing itself.

The behavior of the bearing in terms of stress and strain is shown in Fig. 37, which indicates that for the bearings tested the stress-strain relation can be effectively approximated by a trilinear curve. The first segment of the trilinear curve extends from zero to about 10% of the shear strain, the second segment includes strains from 10% to 250% (approximately), and the third and last segment extends from about 250% to failure.

The higher initial stiffness is important so that the building will not experience large displacement and excessive vibrations under the action of the wind load. For analysis of the design basis earthquake, the initial stiffness can be disregarded and the system can be analyzed as an viscous-elastic system with a stiffness value equal to that of the second segment of the trilinear curve and a damping value obtained from the area of the hysteresis loop relative to the strain considered. In the case of beyond the design basis earthquakes, the system response can be analyzed by means of a nonlinear analytical procedure, using a bilinear model both for the elastic forces and the viscous forces.

VI. CONCLUSIONS

The experimental tests have confirmed the high quality of the Bridgestone bearings. These bearings have been proved to be capable of withstanding large shear strains while under high axial loads.

The failure mechanism and the shear stiffness are only slightly affected by the vertical pressure acting on the bearing. The equivalent damping of the bearing, although increasing with vertical pressure on the bearing, is virtually independent of the shear strain amplitude. This is in contrast to findings of other commercial bearings where equivalent damping value decreases with an increase in strain amplitude.

It should be noted that the effect of seismic isolation using elastomeric bearings is due essentially to the difference of the fundamental frequencies of the structures that are conventionally founded and seismically isolated. When the ratio of these two frequencies is great, the participation factors of the higher modes are small. This means that the displacements due to an earthquake are almost entirely associated with the fundamental mode of the isolation system. But the participation factor of higher modes increases with increasing damping value of bearing. Thus, damping in the isolation bearings will increase the stress of the isolated

structure. However, damping is necessary in order to limit displacements of the isolated structure in the event of a resonant response.

In the bearing tests it was found that the shear stiffness of the bearing increases considerably beyond the 250% strain. Therefore, if the 200% strain is taken as the design basis strain for bearings and the base shear corresponding to 200% of bearing shear strain is taken as the design basis lateral force for the structure, then the elastomeric bearings will have a considerable reserve of strength compared with the structure. This implies that the structural collapse will precede the failure of the bearings.

The most important result of the failure test of these bearings is the fact that the bearing was able to sustain horizontal (shear) displacements, while under design vertical load, that exceeded the diameter of the bearing. The maximum shear strain developed at the failure of bearing is 600% for bearings made of KL302 compound and 700% for bearings made of KL301 compound, which has far exceeded the design limit of 200% shear strain currently used in the bearing design.

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Table I. List of Channels Used in the Single Bearing Test Machine

Channel Number	Channel Name	Quantity Measured	Channel Units
0	horiz. load	horiz. actuator load	kips
1	horiz. disp.	horiz. actuator displ.	inches
2	vload 1	vert. actuator 1 load	kips
3	vload 2	vert. actuator 2 load	kips
4	vdisp 1	vert. actuator 1 displ.	inches
5	vdisp 2	vert. actuator 2 displ.	inches
6	dcdt NE	top plate displ. NE (corner)	inches
7	dcdt NW	top plate displ. NW (corner)	inches
8	dcdt SE	top plate displ. SE (corner)	inches
9	dcdt SW	top plate displ. SW (corner)	inches
10	vpm#8 moment2	force trasd. moment load	kip-inches
11	vpm#8 shear2	force trasd. shear load	kips
12	vpm#8 axial	force trasd. axial load	kips
13	vpm#7 moment 2	force trasd. moment load	kip-inches
14	vpm#7 shear2	force trasd. shear load	kips
15	vpm#7 axial	force trasd. axial load	kips
16	frame flex	horiz. bottom plate displ.	inches
17	back up horiz.	horiz. actuator displ.	inches
18	beam accel.	load beam acceleration	g

NB: SE = South East
 SW = South West
 NE = North East
 NW = North West

Table II. Horizontal Shear Test of Bridgestone Bearings

Bearing ID: HR030-2 EERC ID: No. 1 Vertical Pressure: 0 psi														
File No.	920302.04					920302.08				920302.12				
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
K_{cem} (1st cy)	5.31	4.51	3.69	3.10	2.77	2.36	2.03	1.82	1.85	1.82	1.70	1.69	1.80	
K_{cem} (aver.)	5.40	4.38	3.58	3.01	2.68	2.28	1.92	1.77	1.75	1.71	1.59	1.59	1.68	
K_{cem} (5th cy)	5.40	4.31	3.55	2.99	2.63	2.24	1.89	1.74	1.74	1.66	1.57	1.55	1.63	
β (1st cy)	13.4	13.4	12.6	12.3	12.1	13.1	12.5	12.0	11.1	13.2	12.1	11.2	10.3	
β (aver.)	14.8	13.5	12.7	12.2	12.2	13.2	12.7	12.3	11.6	12.9	12.3	11.5	10.7	
β (5th cy)	15.2	14.3	12.8	12.5	11.6	13.3	13.4	12.5	10.5	12.6	12.5	11.7	10.1	
W_D (1st cy)	0.1	0.7	2.1	3.9	6.1	5.5	10.1	15.5	22.1	16.6	22.1	28.8	37.9	
W_D (aver.)	0.1	0.6	2.1	3.8	6.0	5.3	9.7	15.3	22.0	15.3	21.1	27.8	36.4	
W_D (5th cy)	0.1	0.7	2.1	3.8	5.6	5.3	10.1	15.2	19.7	14.6	20.9	27.5	33.7	
G (1st cy)	135	115	94	79	70	60	51	46	47	46	43	43	46	
G (aver.)	137	111	91	76	68	58	49	45	44	43	41	40	43	
G (5th cy)	137	110	90	76	67	57	48	44	44	42	40	39	41	

$\gamma(\pm)$: Shear Strain (%)
 K_{cem} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-2 EERC ID: No. 1 Vertical Pressure: 500 psi													
File No.	920302.01					920302.05				920302.09			
	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
γ ($\pm$)													
$K_{(em)}$ (1st cy)	6.99	5.45	4.19	3.48	3.01	2.89	2.49	2.29	2.24	1.92	1.86	2.03	2.17
$K_{(em)}$ (aver.)	6.80	5.14	3.94	3.27	2.83	2.76	2.30	2.07	2.02	1.80	1.77	1.86	1.90
$K_{(em)}$ (5th cy)	6.79	5.18	3.82	3.20	2.77	2.69	2.21	2.01	1.94	1.75	1.73	1.79	1.78
β (1st cy)	14.3	14.0	13.7	13.5	13.6	14.3	13.4	12.9	12.3	14.1	12.2	10.9	10.1
β (aver.)	16.7	14.1	13.6	13.6	13.7	13.9	13.7	13.2	12.6	13.8	12.6	11.6	11.0
β (5th cy)	16.5	15.7	14.4	13.9	13.1	14.4	14.1	13.5	12.0	14.0	13.0	11.8	10.8
W_b (1st cy)	0.2	0.8	2.6	4.9	7.6	7.3	13.2	20.8	29.8	18.8	24.5	33.8	44.7
W_b (aver.)	0.2	0.8	2.5	4.6	7.1	6.8	12.6	19.2	27.5	17.3	24.1	32.9	42.4
W_b (5th cy)	0.2	0.9	2.5	4.6	6.7	6.9	12.4	18.9	25.1	17.1	24.3	32.4	39.3
G (1st cy)	178	139	107	88	76	73	63	58	57	49	47	51	55
G (aver.)	173	130	100	83	72	70	58	53	51	46	45	47	48
G (5th cy)	173	132	97	81	70	68	56	51	49	45	44	46	45

$\gamma(\pm)$: Shear Strain (%)
 K_{em} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-2 EERC ID: No. 1 Vertical Pressure: 1000 psi													
File No.	920302.02					920302.06				920302.10			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
K_{cem} (1st cy)	6.99	5.45	4.19	3.48	3.01	2.54	2.11	1.94	1.99	1.66	1.58	1.64	1.79
K_{cem} (aver.)	6.80	5.14	3.94	3.27	2.83	2.41	1.98	1.82	1.85	1.56	1.50	1.53	1.60
K_{cem} (5th cy)	6.79	5.18	3.82	3.20	2.77	2.36	1.94	1.78	1.80	1.51	1.46	1.51	1.58
β (1st cy)	14.3	14.0	13.7	13.5	13.6	18.1	17.5	16.3	14.6	18.0	15.7	14.7	13.1
β (aver.)	16.7	14.1	13.6	13.6	13.7	18.2	17.8	16.9	15.2	17.9	16.6	15.3	13.7
β (5th cy)	16.5	15.7	14.4	13.9	13.1	18.3	18.0	17.1	14.8	18.4	16.7	15.2	13.4
W_D (1st cy)	0.2	0.8	2.6	4.9	7.6	8.1	14.7	22.3	31.3	20.7	26.8	36.6	47.6
W_D (aver.)	0.2	0.8	2.5	4.6	7.1	7.7	14.0	21.6	30.4	19.5	26.8	35.8	45.9
W_D (5th cy)	0.2	0.9	2.5	4.6	6.7	7.6	13.9	21.4	28.8	19.3	26.2	34.9	43.3
G (1st cy)	178	139	107	88	76	65	54	49	51	42	40	42	45
G (aver.)	173	130	100	83	72	61	50	46	47	40	38	39	42
G (5th cy)	173	132	97	81	72	60	49	45	46	38	37	38	40

 γ ($\pm$): Shear Strain (%) K_{cem} : Effective Stiffness (kips/in.) β : Equivalent Viscous Damping (%) W_D : Energy Dissipation (kips-in.)

G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-2 EERC ID: No. 1 Vertical Pressure: 1500 psi														
File No.	920302.03					920302.07				920302.11				
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
$K_{(en)}$ (1st cy)	8.70	5.38	3.90	3.10	2.84	2.26	1.87	1.74	1.82	1.44	1.40	1.44	1.59	
$K_{(en)}$ (aver.)	7.82	5.05	3.72	3.03	2.63	2.16	1.76	1.64	1.69	1.35	1.31	1.36	1.43	
$K_{(en)}$ (5th cy)	7.44	5.22	3.63	2.96	2.56	2.10	1.72	1.60	1.64	1.26	1.28	1.31	1.35	
β (1st cy)	18.1	19.6	20.0	19.3	19.4	22.8	21.9	20.5	17.6	23.9	21.4	19.2	17.0	
β (aver.)	16.8	20.2	21.1	20.5	19.9	23.3	22.9	21.1	18.7	24.6	22.7	19.9	18.7	
β (5th cy)	19.9	19.7	21.0	20.4	19.2	23.3	23.7	21.5	18.2	25.0	22.4	22.0	18.9	
W_D (1st cy)	0.2	1.2	3.6	6.2	10.1	9.1	16.3	25.1	34.6	24.1	32.2	42	54.9	
W_D (aver.)	0.2	1.1	3.6	6.5	9.7	8.9	16.1	24.3	34.2	23.2	31.9	41.2	54.6	
W_D (5th cy)	0.2	1.1	3.5	6.3	9.1	8.7	16.3	24.2	32.1	22.2	30.8	43.8	51.9	
G (1st cy)	221	137	99	79	72	57	48	44	46	37	35	37	40	
G (aver.)	199	128	94	77	67	55	45	42	43	34	33	34	36	
G (5th cy)	189	133	92	75	65	53	44	41	42	32	32	33	34	

$\gamma(\pm)$: Shear Strain (%)
 $K_{(en)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-3 EERC ID: No. 2 Vertical Pressure: 0 psi																
File No.	920303.08						920303.12						920303.16			
γ ($\pm$)	10%	25%	50%	75%	100%		100%	150%	200%	250%			200%	250%	300%	350%
$K_{(em)}$ (1st cy)	5.89	4.67	3.86	3.26	2.90		2.47	2.08	1.88	1.86			1.66	1.54	1.56	1.69
$K_{(em)}$ (aver.)	5.62	4.75	3.72	3.12	2.70		2.37	1.96	1.77	1.73			1.57	1.47	1.48	1.58
$K_{(em)}$ (5th cy)	5.60	4.75	3.68	3.06	2.72		2.32	1.91	1.74	1.68			1.53	1.45	1.45	1.53
β (1st cy)	14.2	13.2	13.1	13.0	12.7		13.8	13.7	13.3	12.5			15.2	14.1	13.2	11.8
β (aver.)	16.0	13.2	12.6	12.7	12.5		13.7	13.7	13.4	12.7			14.7	14.0	13.4	12.1
β (5th cy)	15.7	13.9	13.1	12.8	11.7		14.3	14.1	13.7	11.6			14.7	14.5	13.4	10.8
W_D (1st cy)	0.1	0.7	2.3	4.4	6.8		6.0	11.4	17.5	25.2			17.7	23.2	31.4	40.6
W_D (aver.)	0.1	0.7	2.1	4.1	6.4		5.7	10.7	16.6	23.9			16.1	22.1	30.2	38.7
W_D (5th cy)	0.1	0.7	2.2	4.1	6.0		5.8	10.8	16.7	21.1			15.8	22.5	29.5	33.8
G (1st cy)	150	119	98	83	74		63	53	48	47			42	39	40	43
G (aver.)	143	121	95	79	71		60	50	45	44			40	37	38	40
G (5th cy)	142	121	94	78	69		59	49	44	43			39	37	37	39

$\gamma(\pm)$: Shear Strain (%)
 $K_{(em)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-3 EERC ID: No. 2 Vertical Pressure: 500 psi													
File No.	920303.09					920303.13				920303.17			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
K_{em} (1st cy)	6.34	4.94	3.86	3.23	2.83	2.35	1.97	1.76	1.75	1.52	1.40	1.40	1.51
K_{em} (aver.)	6.31	4.73	3.65	3.08	2.72	2.24	1.83	1.65	1.64	1.43	1.33	1.33	1.41
K_{em} (5th cy)	6.14	4.71	3.55	3.06	2.60	2.15	1.80	1.62	1.61	1.39	1.29	1.29	1.37
β (1st cy)	17.3	15.5	14.7	14.3	14.1	15.8	15.8	15.0	13.5	16.8	16.0	15.1	13.4
β (aver.)	16.7	16.2	14.8	14.3	14.1	15.9	15.9	15.3	14.1	17.0	16.1	15.2	13.8
β (5th cy)	17.3	16.4	15.4	14.9	13.3	16.0	15.7	15.3	13.0	17.5	16.8	15.6	12.5
W_D (1st cy)	0.2	0.9	2.6	4.8	7.4	6.6	12.4	18.6	25.7	17.8	24.1	32.2	41.2
W_D (aver.)	0.2	0.8	2.5	4.6	7.1	6.3	11.6	17.7	25.0	17.0	23.0	30.6	39.5
W_D (5th cy)	0.2	0.8	2.5	4.7	6.6	6.2	11.2	17.3	22.6	16.9	23.2	30.6	34.6
G (1st cy)	161	126	98	82	72	60	50	45	45	39	36	36	38
G (aver.)	160	120	93	78	69	57	46	42	42	36	34	34	36
G (5th cy)	156	120	90	78	68	55	46	41	41	35	33	33	35

$\gamma(\pm)$: Shear Strain (%)
 K_{em} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-3 EERC ID: No. 2 Vertical Pressure: 1000 psi														
File No.	920303.06					920303.10					920303.14			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
$K_{(cm)}$ (1st cy)	6.34	4.94	3.86	3.23	2.83	2.82	2.54	2.32	2.21	1.65	1.64	1.82	1.91	
$K_{(cm)}$ (aver.)	6.31	4.73	3.65	3.08	2.72	2.71	2.26	2.01	1.89	1.53	1.54	1.62	1.60	
$K_{(cm)}$ (5th cy)	6.14	4.71	3.55	3.06	2.68	2.65	2.20	1.91	1.79	1.49	1.49	1.54	1.48	
β (1st cy)	17.3	15.5	14.7	14.3	14.1	17.8	16.3	15.8	14.9	19.4	16.9	14.7	13.7	
β (aver.)	16.7	16.2	14.8	14.3	14.1	17.3	17.0	16.8	16.2	19.7	17.6	15.7	15.5	
β (5th cy)	17.3	16.4	15.4	14.9	13.3	18.0	17.5	17.3	15.5	20.1	18.2	16.7	15.1	
W_D (1st cy)	0.2	0.9	2.6	4.8	7.4	9.0	16.6	25.7	35.6	22.3	29.8	40.5	52.7	
W_D (aver.)	0.2	0.8	2.5	4.6	7.1	8.4	15.3	23.7	33.1	21.0	29.0	38.4	49.9	
W_D (5th cy)	0.2	0.8	2.5	4.7	6.6	8.5	15.2	23.3	30.0	20.9	28.9	39.0	45.0	
G (1st cy)	161	126	98	82	72	72	65	59	56	42	42	46	49	
G (aver.)	160	120	93	78	69	69	57	51	48	39	39	41	41	
G (5th cy)	156	120	90	78	68	67	56	49	45	38	38	39	38	

$\gamma(\pm)$: Shear Strain (%)
 $K_{(cm)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-3 EERC ID: No. 2 Vertical Pressure: 1500 psi																
File No.	920303.07						920303.11				920303.15					
γ ($\pm$)	10%	25%	50%	75%	100%		100%	150%	200%	250%	200%	250%	300%	350%		
$K_{(em)}$ (1st cy)	9.53	6.53	4.66	3.69	3.1		2.31	1.90	1.72	1.79	1.74	1.60	1.64	1.75		
$K_{(em)}$ (aver.)	9.12	6.02	4.23	3.4	2.88		2.20	1.73	1.58	1.62	1.52	1.42	1.45	1.51		
$K_{(em)}$ (5th cy)	8.74	5.88	4.13	3.3	2.82		2.11	1.68	1.53	1.55	1.42	1.35	1.36	1.40		
β (1st cy)	15.3	16.9	16.9	16.5	16.6		24.2	23.4	22.3	19.5	23.5	21.9	20.2	18.2		
β (aver.)	15.5	17.0	16.7	16.7	16.8		24.5	24.8	23.3	20.6	25.1	23.9	21.6	20.2		
β (5th cy)	16.6	17.7	16.9	17.1	17.5		25.4	25.3	23.7	20.1	26.3	24.5	22.8	20.1		
W_D (1st cy)	0.2	1.2	3.6	6.4	9.5		9.9	17.9	27	37.7	28.5	37.4	50.1	63.9		
W_D (aver.)	0.2	1.1	3.2	5.9	9.0		9.5	17.1	25.9	36	26.4	36.3	47.3	61.0		
W_D (5th cy)	0.2	1.2	3.2	5.9	9.1		9.6	17	25.5	33.9	26.1	35.3	47.1	56.7		
G (1st cy)	242	166	118	94	79		59	48	44	46	44	41	42	45		
G (aver.)	232	153	107	86	73		56	44	40	41	39	36	37	38		
G (5th cy)	222	149	105	84	72		54	43	39	39	36	34	35	36		

$\gamma(\pm)$: Shear Strain (%)
 $K_{(em)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-5 EERC ID: No. 3 Vertical Pressure: 0 psi														
File No.	920304.05					920304.09				920304.13				
	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
γ ($\pm$)														
K_{cem} (1st cy)	7.62	5.95	4.83	3.98	3.56	2.98	2.46	2.24	2.34	1.78	1.70	1.83	2.06	
K_{cem} (aver.)	7.33	5.73	4.56	3.87	3.40	2.86	2.31	2.11	2.17	1.71	1.65	1.71	1.93	
K_{cem} (5th cy)	7.28	5.80	4.52	3.76	3.31	2.79	2.27	2.06	2.11	1.69	1.64	1.69	1.88	
β (1st cy)	14.9	13.8	14.3	14.7	15.0	16.5	16.6	15.4	13.7	16.3	14.9	13.3	11.1	
β (aver.)	14.8	14.5	14.3	14.9	15.2	16.2	16.5	15.9	14.1	16.1	14.9	13.5	11.4	
β (5th cy)	16.3	14.2	14.2	15.2	14.9	16.3	16.8	16.1	13.1	16.3	15.1	13.5	10.9	
W_D (1st cy)	0.2	0.9	3.1	6.1	9.8	8.8	16.5	24.7	35.4	20.5	27.9	36.9	47.4	
W_D (aver.)	0.2	0.9	3.0	5.9	9.5	8.3	15.5	23.9	33.9	19.6	26.7	35.8	45.7	
W_D (5th cy)	0.2	0.9	2.9	5.9	9.1	8.1	15.3	23.8	30.8	19.4	26.7	35.5	41.6	
G (1st cy)	194	151	123	101	90	76	63	57	59	46	43	46	52	
G (aver.)	186	146	116	98	86	73	59	54	55	44	42	44	49	
G (5th cy)	185	147	115	96	84	71	58	52	54	43	42	43	48	

$\gamma(\pm)$: Shear Strain (%)
 K_{cem} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-5 EERC ID: No. 3 Vertical Pressure: 500 psi														
File No.	920304.02					920304.06					920304.10			
	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
γ ($\pm$)														
K_{cem} (1st cy)	10.98	7.68	5.64	4.64	3.81	3.52	3.13	2.89	2.8	2.12	2.20	2.57	2.76	
K_{cem} (aver.)	10.24	7.37	5.36	4.29	3.68	3.39	2.8	2.52	2.40	2.01	2.08	2.28	2.30	
K_{cem} (5th cy)	11.52	7.15	5.35	4.36	3.54	3.33	2.7	2.41	2.29	1.96	2.04	2.17	2.12	
β (1st cy)	13.0	15.2	15.5	15.2	16.3	16.6	16.2	15.3	14.2	17.6	14.7	12.5	11.3	
β (aver.)	13.7	14.8	14.9	15.3	15.9	16.3	16.8	16.2	15.2	17.5	15.2	13.0	12.5	
β (5th cy)	15.3	15.1	14.8	15.2	16.8	16.3	16.4	16.7	14.3	18.0	15.3	13.6	12.1	
W_b (1st cy)	0.2	1.3	4.0	7.2	11.4	10.5	20.5	31.6	44.0	26.2	35.2	49.5	64.1	
W_b (aver.)	0.2	1.2	3.6	6.8	10.7	9.9	19.2	29.2	40.6	24.8	34.5	45.8	59.0	
W_b (5th cy)	0.3	1.2	3.5	6.7	10.8	9.7	17.9	29.0	36.4	24.8	33.8	45.4	52.7	
G (1st cy)	279	195	143	118	97	89	80	73	71	54	56	65	70	
G (aver.)	260	187	136	109	94	86	71	64	61	51	53	58	58	
G (5th cy)	293	182	136	111	90	85	69	61	58	50	52	55	54	

$\gamma(\pm)$: Shear Strain (%)
 K_{cem} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-5 EERC ID: No. 3 Vertical Pressure: 1000 psi														
File No.	920304.03					920304.07					920304.11			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
K_{cm} (1st cy)	9.07	6.72	5.13	4.22	3.61	3.05	2.51	2.27	2.38	1.82	1.73	1.86	2.17	
K_{cm} (aver.)	9.58	6.60	4.96	4.02	3.47	2.96	2.32	2.12	2.19	1.71	1.65	1.74	1.98	
K_{cm} (5th cy)	8.61	6.62	4.83	4.03	3.40	2.83	2.29	2.08	2.11	1.65	1.62	1.72	1.90	
β (1st cy)	14.3	17.6	17.5	17.6	16.9	21.0	20.6	18.6	16.4	22.5	19.8	17.0	14.1	
β (aver.)	14.8	19.0	17.7	17.3	18.1	20.0	20.9	19.5	17.1	22.1	19.9	17.7	14.8	
β (5th cy)	21.4	18.1	18.4	17.0	18.1	21.0	21.1	19.9	16.5	22.3	20.2	17.3	14.0	
W_D (1st cy)	0.2	1.3	4.0	7.7	11.2	11.5	20.9	30.4	43.3	28.7	37.1	48.6	62.6	
W_D (aver.)	0.2	1.4	3.9	7.1	11.5	10.6	19.7	29.7	41.6	26.6	35.8	47.6	60.1	
W_D (5th cy)	0.3	1.3	4.0	7.0	11.3	10.7	19.5	29.7	38.8	25.9	35.3	45.8	54.7	
G (1st cy)	230	171	130	107	92	78	64	58	60	46	44	47	55	
G (aver.)	244	168	126	102	88	75	59	54	56	44	42	44	50	
G (5th cy)	219	168	123	102	86	72	58	53	54	42	41	44	48	

$\gamma(\pm)$: Shear Strain (%)
 K_{cm} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-5 EERC ID: No. 3 Vertical Pressure: 1500 psi														
File No.	920304.04					920304.08					920304.12			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
$K_{(en)}$ (1st cy)	10.25	6.75	5.06	4.12	3.62	2.81	2.34	2.10	2.28	1.57	1.50	1.64	1.89	
$K_{(en)}$ (aver.)	9.33	6.62	4.87	3.91	3.38	2.75	2.20	1.97	2.06	1.48	1.45	1.54	1.74	
$K_{(en)}$ (5th cy)	9.68	6.55	4.82	3.87	3.32	2.59	2.12	1.90	1.96	1.46	1.43	1.50	1.64	
β (1st cy)	14.9	19.5	20.3	20.3	20.3	24.1	23.1	21.7	18.4	27.7	24.4	20.9	17.3	
β (aver.)	15.7	19.6	20.4	21.0	21.2	24.3	23.9	22.8	19.9	27.4	25.4	21.8	18.6	
β (5th cy)	17.3	19.4	20.6	21.0	20.0	27.0	24.4	23.9	19.7	28.9	25.3	22.4	18.2	
W_b (1st cy)	0.2	1.5	4.7	8.6	13.6	12.1	21.8	32.7	46.3	30.5	39.9	52.8	67.0	
W_b (aver.)	0.2	1.4	4.4	8.5	13.2	11.9	21.2	32.2	45.3	28.5	39.8	51.6	66.1	
W_b (5th cy)	0.3	1.4	4.4	8.4	12.2	12.5	21.1	32.7	42.5	29.5	39.3	51.9	61.5	
G (1st cy)	260	172	129	105	92	71	59	53	58	40	38	42	48	
G (aver.)	237	168	124	99	86	70	56	50	52	38	37	39	44	
G (5th cy)	246	167	123	98	84	66	54	48	50	37	36	38	42	

$\gamma(\pm)$: Shear Strain (%)
 $K_{(en)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-6 EERC ID: No. 4 Vertical Pressure: 0 psi													
File No.	920304.22					920304.26				920304.30			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(en)}$ (1st cy)	7.25	5.88	4.68	3.95	3.50	2.89	2.42	2.23	2.30	1.80	1.73	1.84	2.07
$K_{(en)}$ (aver.)	6.98	5.75	4.47	3.80	3.36	2.79	2.29	2.11	2.16	1.74	1.68	1.74	1.94
$K_{(en)}$ (5th cy)	6.70	5.68	4.37	3.75	3.28	2.74	2.23	2.06	2.11	1.71	1.65	1.71	1.89
β (1st cy)	13.9	14.7	14.1	14.4	14.6	16.5	16.1	15.3	13.5	16.3	14.8	13.2	11.2
β (aver.)	14.8	14.7	14.2	14.4	14.6	16.0	16.0	15.4	14.0	16.1	14.8	13.5	11.5
β (5th cy)	14.3	12.8	15.2	14.9	14.3	16.2	16.6	16.0	12.8	16.3	15.2	13.5	10.8
W_D (1st cy)	0.2	1.0	3.0	5.8	9.4	8.5	15.6	24.1	34.1	20.6	27.6	36.9	47.5
W_D (aver.)	0.2	0.9	2.9	5.6	9.0	8.0	14.8	23.1	33.1	19.6	26.8	35.8	45.6
W_D (5th cy)	0.2	0.8	3.1	5.7	8.6	7.9	15.0	23.4	29.5	19.5	26.9	35.5	41.6
G (1st cy)	184	149	119	100	89	73	61	57	59	46	44	47	53
G (aver.)	177	146	113	97	85	71	58	54	55	44	43	44	49
G (5th cy)	170	144	111	95	83	70	57	52	54	43	42	44	48

$\gamma(\pm)$: Shear Strain (%)
 $K_{(em)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-6 EERC ID: No. 4 Vertical Pressure: 500 psi														
File No.	920304.23					920304.27					920304.31			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%	
K_{cem} (1st cy)	7.83	5.79	4.65	3.87	3.43	2.79	2.30	2.10	2.21	1.80	1.70	1.76	2.00	
K_{cem} (aver.)	7.72	5.74	4.40	3.69	3.30	2.66	2.15	1.98	2.07	1.70	1.61	1.67	1.87	
K_{cem} (5th cy)	7.33	5.80	4.37	3.63	3.26	2.57	2.12	1.95	2.05	1.66	1.59	1.63	1.83	
β (1st cy)	14.0	15.4	16.0	15.5	15.8	17.8	17.6	16.8	14.6	18.0	16.5	14.4	12.6	
β (aver.)	16.0	15.7	15.6	16.1	16.0	17.8	18.0	17.2	15.0	18.0	17.0	15.0	12.8	
β (5th cy)	16.4	16.4	16.5	16.6	15.3	18.7	18.8	17.2	14.0	18.4	17.1	15.3	11.9	
W_D (1st cy)	0.2	1.0	3.3	6.0	9.9	8.9	16.3	25.1	35.3	22.5	30.2	38.8	51.5	
W_D (aver.)	0.2	1.0	3.1	6.1	9.6	8.5	15.6	24.2	33.9	21.4	29.6	38.2	49.0	
W_D (5th cy)	0.2	1.0	3.3	6.3	9.1	8.6	15.9	23.9	31.3	21.1	29.3	38.3	44.5	
G (1st cy)	199	147	118	98	87	71	58	53	56	46	43	45	51	
G (aver.)	196	146	112	94	84	68	55	50	53	43	41	42	47	
G (5th cy)	186	147	111	92	83	65	54	50	52	42	40	42	47	

$\gamma(\pm)$: Shear Strain (%)
 K_{cem} : Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G: Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-6 EERC ID: No. 4 Vertical Pressure: 1000 psi													
File No.	920304.20					920304.24				920304.28			
γ ($\pm$)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(em)}$ (1st cy)	8.79	6.67	5.10	4.15	3.68	3.48	3.16	2.88	2.78	2.00	2.11	2.48	2.59
$K_{(em)}$ (aver.)	8.46	6.42	4.83	3.97	3.40	3.33	2.83	2.51	2.38	1.90	1.99	2.17	2.15
$K_{(em)}$ (5th cy)	8.18	6.40	4.72	3.88	3.39	3.27	2.70	2.39	2.24	1.87	1.95	2.07	2.00
β (1st cy)	14.7	17.6	18.0	18.0	17.6	18.4	17.2	16.6	15.7	20.5	16.6	14.1	12.9
β (aver.)	15.0	17.6	17.4	18.0	18.2	18.4	17.9	17.8	17.0	20.1	17.3	15.0	14.4
β (5th cy)	15.1	18.3	18.0	18.2	17.5	18.7	18.9	18.5	16.5	20.5	17.4	15.5	14.2
W_D (1st cy)	0.2	1.3	4.1	7.8	11.9	11.5	22.0	33.7	47.4	28.8	37.5	52.7	67.6
W_D (aver.)	0.2	1.3	3.8	7.4	11.5	11.0	20.4	31.6	44.0	26.7	37.1	49.5	62.6
W_D (5th cy)	0.2	1.3	3.9	7.3	10.9	10.9	20.6	31.3	40.2	26.8	36.4	48.7	57.5
G (1st cy)	223	169	130	105	94	89	80	73	71	51	54	63	66
G (aver.)	215	163	123	101	88	85	72	64	60	48	51	55	55
G (5th cy)	208	163	120	98	86	83	69	61	57	48	50	52	51

$\gamma(\pm)$: Shear Strain (%)
 $K_{(em)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table II. Horizontal Shear Test of Bridgestone Bearings (Cont'd)

Bearing ID: HR030-6 EERC ID: No. 4 Vertical Pressure: 1500 psi													
File No.	920304.21					920304.25				920304.29			
	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
γ ($\pm$)													
$K_{(em)}$ (1st cy)	9.11	6.55	4.92	4.01	3.58	2.81	2.33	2.16	2.31	1.63	1.60	1.72	1.98
$K_{(em)}$ (aver.)	8.95	6.49	4.69	3.83	3.36	2.70	2.18	2.01	2.11	1.54	1.51	1.60	1.78
$K_{(em)}$ (5th cy)	8.93	6.40	4.59	3.80	3.31	2.68	2.11	1.96	2.03	1.51	1.48	1.57	1.70
β (1st cy)	22.1	17.3	20.4	20.5	20.1	24.6	23.8	21.9	18.6	27.1	23.8	20.2	16.9
β (aver.)	14.0	19.6	20.4	21.2	20.6	24.7	24.6	23.0	19.8	27.4	24.5	21.5	18.5
β (5th cy)	13.7	19.0	20.9	21.1	20.1	25.2	25.3	23.1	19.3	28.1	25.6	22.1	18.2
W_D (1st cy)	0.3	1.3	4.5	8.4	13.2	12.4	22.3	33.4	46.8	30.9	40.9	52.9	67.9
W_D (aver.)	0.2	1.4	4.3	8.4	12.8	11.9	21.6	32.7	45.6	29.5	39.8	52.3	66.8
W_D (5th cy)	0.2	1.4	4.4	8.3	12.2	11.9	21.5	32.1	42.8	29.4	40.7	52.8	62.7
G (1st cy)	232	166	125	102	91	71	59	55	59	42	41	44	50
G (aver.)	227	165	119	97	85	69	55	51	54	39	38	41	45
G (5th cy)	227	163	117	97	84	68	54	50	52	38	38	40	43

$\gamma(\pm)$: Shear Strain (%)
 $K_{(em)}$: Effective Stiffness (kips/in.)
 β : Equivalent Viscous Damping (%)
 W_D : Energy Dissipation (kips-in.)
 G : Shear Modulus (psi)

Table III. Vertical Load Test of Bridgestone Bearings

Pressure psi	Bearing ID: HR030-2 EERC ID: No. 1		Bearing ID: HI.030-3 EERC ID: No. 2	
	Filename	K_{eff} Kips-in.	Filename	K_{eff} Kips-in.
500	920225.05	5387	920303.02	6926
1000	920225.03	7860	920303.03	9223
1500	920225.04	9075	920303.14	10643

Pressure psi	Bearing ID: HR030-5 EERC ID: No. 3		Bearing ID: HR030-6 EERC ID: No. 4	
	Filename	K_{eff} Kips-in.	Filename	K_{eff} Kips-in.
500	920303.20	6889	920304.16	5589
1000	920303.21	8854	920304.17	7440
1500	920303.22	9769	920304.18	8721

- 1 - elastomer
- 2 - steel shim
- 3 - cover plate

Fig. 1. The Dimensions of the Test Bearings

Shear Modulus - BS Rubber Compounds

Fig. 2. Shear Modulus as a Function of Shear Strain of Bridgestone Elastomer Compounds

Fig. 3. Viscous Damping as a Function of Shear Strain of Bridgestone Elastomer Compounds

Fig. 4. Details of the Single Bearing Test Machine

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 50 - 100% SHEAR STRAIN**

	Strain	Stiffness	Shear Modulus	Damping
FILENAME : 920302.04				
BEARING No. : 1	49 %	3.58 Kips/in	91 psi	12.7 %
VERT PRESSURE : 6 PSI	74 %	3.01 Kips/in	76 psi	12.2 %
FREQUENCY : 0.5 Hz.	98 %	2.68 Kips/in	68 psi	12.2 %

Fig. 5. Force Displacement Plots for Sequence I Tests - Zero Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 100% - 250% SHEAR STRAIN**

FILENAME	:	920302.00	Strain		Stiffness		Shear Modulus		Damping
BEARING No.	:	1		96 %	2.28 Kips/in		50 psi		13.2 %
VERT PRESSURE	:	31 PSI		144 %	1.92 Kips/in		49 psi		12.7 %
FREQUENCY	:	0.5 Hz.		192 %	1.77 Kips/in		45 psi		12.3 %
				239 %	1.75 Kips/in		44 psi		11.6 %

Fig. 6. Force Displacement Plots for Sequence II Tests - Zero Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 200% - 350% SHEAR STRAIN**

FILENAME	: 920302.12	Strain	192 %	Stiffness	1.71 Kips/in	Shear Modulus	43 psi	Damping	12.9 %
BEARING NO.	: 1		238 %		1.59 Kips/in		41 psi		12.3 %
VERT PRESSURE	: 16 PSI		284 %		1.59 Kips/in		40 psi		11.5 %
FREQUENCY	: 0.5 Hz.		327 %		1.68 Kips/in		43 psi		10.7 %

Fig. 7. Force Displacement Plots for Sequence III Tests - Zero Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 5% - 100% SHEAR STRAIN**

FILENAME	:	920302.01	Strain	Stiffness	Shear Modulus	Damping
BEARING No.	:	1				
VERT PRESSURE	:	517 PSI	49 %	3.94 Kips/in	100 psi	13.6 %
FREQUENCY	:	0.5 Hz.	74 %	3.27 Kips/in	83 psi	13.6 %
			98 %	2.83 Kips/in	72 psi	13.7 %

Fig. 8. Force Displacement Plots for Sequence I Tests - 3.45 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 100% - 250% SHEAR STRAIN

FILENAME : 920302.05
 BEARING NO. : 1
 VERT PRESSURE : 520 PSI
 FREQUENCY : 0.5 Hz.

Strain	Stiffness	Shear Modulus	Damping
97 %	2.76 Kips/in	70 psi	13.9 %
145 %	2.3 Kips/in	58 psi	13.7 %
192 %	2.07 Kips/in	53 psi	13.2 %
239 %	2.02 Kips/in	51 psi	12.6 %

Fig. 9. Force Displacement Plots for Sequence II Tests - 3.45 MPa Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 2000 - 350% SHEAR STRAIN**

FILENAME	:	920302.09	Strain	:	193 %	Stiffness	:	1.8 Kips/in	Shear Modulus	:	46 psi	Damping	:	13.8 %
BEARING No.	:	1			240 %			1.77 Kips/in			45 psi			12.6 %
VERT PRESSURE	:	521 PSI			284 %			1.86 Kips/in			47 psi			11.6 %
FREQUENCY	:	0.5 Hz.			320 %			1.9 Kips/in			48 psi			11 %

Fig. 10. Force Displacement Plots for Sequence III Tests - 3.45 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 50 - 100% SHEAR STRAIN

FILENAME	:	920302.02	Strain		Stiffness		Shear Modulus		Damping
BEARING No.	:	1	48 %		3.79 Kips/in		96 psi		17.2 %
VERT PRESSURE	:	1061 PSI	73 %		3.14 Kips/in		80 psi		16.7 %
FREQUENCY	:	0.5 Hz.	98 %		2.73 Kips/in		69 psi		16.3 %

Fig. 11. Force Displacement Plots for Sequence I Tests - 6.90 MPa Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 100% - 250% SHEAR STRAIN**

FILENAME	:	920302.06	Strain		Stiffness		Shear Modulus		Damping
BEARING No.	:	1	96 %		2.41 Kips/in		61 psi		18.2 %
VERT PRESSURE	:	1062 PSI	145 %		1.98 Kips/in		50 psi		17.8 %
FREQUENCY	:	0.5 Hz.	192 %		1.82 Kips/in		46 psi		16.9 %
			239 %		1.85 Kips/in		47 psi		15.2 %

Fig. 12. Force Displacement Plots for Sequence II Tests - 6.90 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 200% - 350% SHEAR STRAIN

FILENAME	: 920302.10	Strain	177 %	Stiffness	1.56 Kips/in	Shear Modulus	40 psi	Damping	17.9 %
BEARING No.	: 1		223 %		1.5 Kips/in		38 psi		16.6 %
VERT PRESSURE	: 1021 PSI		260 %		1.53 Kips/in		39 psi		15.3 %
FREQUENCY	: 0.5 Hz.		311 %		1.65 Kips/in		42 psi		13.7 %

Fig. 13. Force Displacement Plots for Sequence III Tests - 6.90 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 5% - 100% SHEAR STRAIN

FILENAME	Strain	Stiffness	Shear Modulus	Damping
: 920302.03				
BEARING No. : 1	49 %	3.72 Kips/in	94 psi	21.1 %
VERT PRESSURE : 1540 PSI	74 %	3.03 Kips/in	77 psi	20.5 %
FREQUENCY : 0.5 Hz.	98 %	2.63 Kips/in	67 psi	19.9 %

Fig. 14. Force Displacement Plots for Sequence I Tests - 10.35 MPa Vertical Pressure

**BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 100% - 250% SHEAR STRAIN**

FILENAME	:	920302.07	Strain		Stiffness		Shear Modulus		Damping
BEARING No.	:	1	96 %		2.16 Kips/in		55 psi		23.3 %
VERT PRESSURE	:	1554 PSI	145 %		1.76 Kips/in		45 psi		22.9 %
FREQUENCY	:	0.5 Hz.	193 %		1.64 Kips/in		42 psi		21.1 %
			240 %		1.69 Kips/in		43 psi		18.7 %

Fig. 15. Force Displacement Plots for Sequence II Tests - 10.35 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
DIAGNOSTIC TEST 2000 - 3500 SHEAR STRAIN

FILENAME	: 920302.11	Strain		Stiffness		Shear Modulus		Damping	
BEARING NO.	: 1	192 %		1.35 Kips/in		34 psi		24.6 %	
VERT PRESSURE	: 1552 PSI	238 %		1.31 Kips/in		33 psi		22.7 %	
FREQUENCY	: 0.5 Hz.	284 %		1.36 Kips/in		34 psi		19.9 %	
		327 %		1.43 Kips/in		36 psi		18.7 %

Fig. 16. Force Displacement Plots for Sequence III Tests - 10.35 MPa Vertical Pressure

Fig. 17. First Cycle Force Displacement Plots at Different Strain Levels Under Zero Vertical Pressure

Fig. 18. First Cycle Force Displacement Plots at Different Strain Levels Under 3.45 MPa Vertical Pressure

Fig. 19. First Cycle Force Displacement Plots at Different Strain Levels Under 6.90 MPa Vertical Pressure

Fig. 20. First Cycle Force Displacement Plots at Different Strain Levels Under 10.35 MPa Vertical Pressure

Fig. 21. Effects of Vertical Pressure on the Stiffness - Strain Curves

Fig. 22. Effects of Vertical Pressure on the Damping - Strain Curves

Fig. 23. Effects of Vertical Pressure on the Energy Dissipation - Displacement Curves

Fig. 24. Log (Energy Dissipation) - Log (Displacement) Curves of Bearing No. 1 Under Vertical Pressures = 3.45, 6.90, 10.35 MPa

BRIDGESTONE BEARING TEST

LOG ENERGY DISSIPATION - LOG DISPLACEMENT AT DIFFERENT PRESSURE LEVELS
BEARING No.2

□ pressure p=0	psi: $\log(Wd) = 1.622 + \log(Disp) + 0.835$	
○ pressure p=500	psi: $\log(Wd) = 1.478 + \log(Disp) + 1.054$	
△ pressure p=1000	psi: $\log(Wd) = 1.520 + \log(Disp) + 1.268$	
◇ pressure p=1500	psi: $\log(Wd) = 1.556 + \log(Disp) + 1.366$

Fig. 25. Log (Energy Dissipation) - Log (Displacement) Curves of Bearing No. 2 Under Vertical Pressures = 3.45, 6.90, 10.35 MPa

Fig. 26. Log (Energy Dissipation) - Log (Displacement) Curves of Bearing No. 3 Under Vertical Pressures = 3.45, 6.90, 10.35 MPa

Fig. 27. Log (Energy Dissipation) - Log (Displacement) Curves of Bearing No. 4 Under Vertical Pressures = 3.45, 6.90, 10.35 MPa

Fig. 28. Hysteresis Loops of Bearing No. 2 Under 3.45 MPa Vertical Pressure

BRIDGESTONE - BEARING TEST
 VERTICAL TEST - MEAN VERT. PRESSURE: 1000 psi

Filename: 920303.03
 Bearing No.: 2
 Average Pressure: 992 psi
 Frequency: 0.33 Hz

Vertical Stiffness 1st Cycle: 9898 kips/in
 Vertical Stiffness 5th Cycle: 9378 kips/in

Fig. 29. Hysteresis Loops of Bearing No. 2 Under 6.90 MPa Vertical Pressure

BRIDGESTONE - BEARING TEST
VERTICAL TEST - MEAN VERT. PRESSURE: 1500 psi

Filename: 920303.04 Bearing No.: 2 Average Pressure: 1474 psi Frequency: 0.33 Hz.	Vertical Stiffness 1st Cycle: 11220 kips/in Vertical Stiffness 5th Cycle: 10780 kips/in
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Fig. 30. Hysteresis Loops of Bearing No. 2 Under 10.35 MPa Vertical Pressure

BRIDGESTONE BEARING TEST
VERTICAL FREQUENCY - AXIAL LOAD CURVES FOR DIFFERENT BEARINGS

Fig. 31. Vertical Frequency as a Function of Axial Load

Fig. 32. Configuration of the Bearing at 0% Deformation

Fig. 33. Configuration of the Bearing at 200% Deformation

Fig. 34. Configuration of the Bearing at 350% Deformation

Fig. 35. Configuration of the Bearing at 600% Deformation

BRIDGESTONE BEARING TESTS

SHEAR FORCE - DISPLACEMENT CURVES FOR FAILURE TESTS

FILENAME	BANG No	PRESSURE	MAX DISPL	MAX LOAD
920302.13	1	557 PSI	12.31 in	86.3 Kips
920303.18	2	1085 PSI	11.72 in	105.1 Kips
920304.14	3	543 PSI	10.54 in	52.3 Kips
920304.32	4	1056 PSI	8.69 in	45.8 Kips

Fig. 36. Force-Displacement Curves for Bearings in Failure Tests

BRIDGESTONE BEARING TESTS
SHEAR STRESS - SHEAR STRAIN CURVES FOR FAILURE TESTS

FILENAME	BRNG No	PRESSURE	MAX STRAIN	MAX STRESS
920302.13	1	557 PSI	711 %	1.27 Ksi
920303.10	2	1085 PSI	677 %	1.54 Ksi
920304.14	3	543 PSI	608 %	0.77 Ksi
920304.32	4	1056 PSI	502 %	0.67 Ksi

Fig. 37. Stress-Strain Curves for Bearings in Failure Tests

APPENDIX A

Experimental Determination of the Effective Stiffness
and the Equivalent Damping Constant

As indicated, the relation between force and displacement parameters for a linear viscous-elastic model is of the following type:

$$f = k\delta + c\dot{\delta}$$

where k = stiffness constant

c = damping constant

δ = displacement

$\dot{\delta}$ = displacement velocity.

If a sinusoidal displacement is imposed on such a model, i.e.

$$\delta(t) = \delta_0 \sin \omega t$$

then the corresponding force is

$$f = \delta_0(k \sin \omega t + c \omega \cos \omega t)$$

The maximum value of force is given by the value of ωt for which $\dot{f} = 0$, namely,

$$\tan \omega t = \frac{k}{c \omega}$$

and is

$$f_{\max} = k\delta_0 \sqrt{1 + \left(\frac{c \omega}{k}\right)^2} \quad (\text{A.1})$$

Since $f_{\max}$ is a quantity easily determined by the data collected during the test and δ_0 is constant, the effective stiffness $K_{\text{eff}} = \frac{F_{\max}}{\delta_0}$ can then be determined.

From Eq. (A.1) it follows that the effective stiffness is

$$K_{eff} = \frac{F_{max}}{\delta_0} = k \sqrt{1 + \left(\frac{c\omega}{k}\right)^2}$$

If we solve this equation for k we obtain:

$$k = \sqrt{K_{eff}^2 - (c\omega)^2} \quad (A.2)$$

On the other hand, the energy dissipated in one complete cycle is

$$W_d = \int_0^{2\pi/\omega} F(t)\dot{\delta}(t)dt = \pi c\omega\delta_0^2 \quad (A.3)$$

Since W_d (area of the hysteresis loop) and K_{eff} are easily measurable in an experimental test, as already indicated, it is possible using Eqs. (A.2) and (A.3) to determine the values of the stiffness constant k and the damping constant c of the viscous-elastic model equivalent to the real model.

It is interesting to note that the equivalent viscous-elastic model, as defined above, dissipates the same energy per cycle as the real model and provides the exact estimate of the maximum force exerted.

Furthermore, it is easy to verify from Eq. (A.2) that for low damping values the stiffness constant k is not very far apart from K_{eff} .

In fact, when the error is defined as follows:

$$\epsilon = \frac{K_{eff} - k}{k}$$

it follows that

$$\epsilon = -1 + \sqrt{1 + \left(2\beta \frac{\omega}{\omega_0}\right)^2}$$

A-3

where ω_0 = fundamental frequency

$$\beta = \frac{c}{2m\omega_0} \text{ (damping ratio).}$$

If the experimental test is carried out under resonance conditions ($\omega = \omega_0$), it follows that

$$\epsilon = -1 + \sqrt{1 + (2\beta)^2}$$

It is obvious that there is no error if damping is zero, whereas for damping of 20% the error is less than 8%.

It also seems clear that for typical damping values for the isolation device under investigation the error that is made using the approximate relation is within the uncertainty limits of experimental data and therefore negligible.

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