The Current Status of Seismic Isolation Technology in the United States

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Abstract

Seismic isolation is at the present time in a very active state of development. Many new types of isolation systems are being explored and elastomeric isolators, the system which has been employed on almost all isolation systems completed to date, continue to undergo improvements. At least one dozen large projects, either new or the retrofit of existing buildings, have been completed and design studies are underway for at least another one dozen large projects.

A large experimental research project for isolators with nuclear reactor application has been carried out over the past few years at EERC. This program has involved shake table testing and the testing of full-scale and model isolators. A wide variety of isolators have been tested including low-shape factor, moderate-shape factor, and very high-shape factor elastomer bearings. The range of elastomers that have been tested include low-damping, high-damping, and very low-modulus compounds. Full-size and model isolators have been tested to failure in several failure modes and the safety margins for isolation systems have been established. The test results have shown that properly designed and manufactured isolators for nuclear reactor applications can sustain levels of loading beyond any possible seismic input and demonstrate that failure of an isolation system cannot occur before failure of the isolated structure. Thus, the use of isolation can only have beneficial contributions to the protection of nuclear facilities, internal piping, and equipment.

The presentation will review the latest developments in the implementation of base isolation and describe the results of the test program for its application to nuclear facilities.

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Introduction

At the present time, the concept of seismic isolation is in a very active state of development. Ten years ago the use of base isolation to reduce the response of structures to seismic activity was not regarded as a realistic approach and was met with great skepticism by the engineering community. After a slow start, the concept is gaining widespread acceptance. The extent of this acceptance can be gauged by the large number of journal articles, technical reports, workshops, and symposia devoted to the topic. At least one dozen large projects, either new or the retrofit of existing buildings, have been completed and design studies are underway for at least another one dozen large projects.

It is now generally accepted that a base-isolated building will perform better than a conventional building in moderate and strong earthquakes. A number of buildings so designed has experienced such earthquakes and their response has confirmed these expectations. The major benefit of isolation in such cases is to reduce damage to contents and sensitive internal equipment and in many buildings, such as computer manufacturing facilities, emergency preparedness centers, and hospitals, the reduction of damage to equipment is of sufficient importance to justify the increased initial cost of isolated construction.

Nuclear power plants are another class of building in which the reduction of response of internal equipment is of primary concern. The analysis of equipment and piping systems in nuclear plants for seismic loading is one of the most expensive parts of the design process. The analysis is complicated by the fact that with conventional construction, the higher levels of the plant have amplified accelerations and the time histories at each level can be very different. Generally, it is necessary to analyze piping and equipment using multiple support response spectrum analyses. Base isolation reduces drastically the amplification of acceleration at the higher levels of the plant and would permit the use of simpler design methods for piping and equipment as well as eliminating the need for seismic restraints such as snubbers.

As the popularity of base isolation has grown, so too has the volume of research devoted to developing new types of isolation systems. The system which has been employed on almost all isolation systems to date involves the use of elastomeric isolators; current research continues to improve the performance of these isolators. A large experimental research project for isolators with nuclear reactor application was carried out over the past few years at Earthquake Engineering Research Center (EERC). This program involved shake table testing and the testing of full-scale and model isolators. A wide variety of isolators were tested including low-shape factor, moderate-shape factor, and very high-shape factor elastomer bearings. The range of elastomers that were tested included low-damping, high-damping, and very low-modulus compounds. Full-size and model isolators were tested to failure in several failure modes and the safety margins for isolation systems were established. The test results show that properly designed and manufactured isolators for nuclear reactor applications can sustain levels of loading beyond any possible seismic input and demonstrate that failure of an isolation system cannot occur before failure of the isolated structure. Thus, the use of isolation can only have beneficial effects in the protection of nuclear facilities, internal piping, and equipment. This paper will review the latest developments in the implementation of base isolation and describe the results of the test program for its application to nuclear facilities.

Base Isolation in 1992

New types of isolation systems have been proposed that are based in some way or another on sliding systems. Sliding elements and sliding isolation systems have been tested in the bearing testing machines at EERC and in model systems used in shake table testing. As compared to elastomeric systems, sliding systems have both a number of advantages as well as some drawbacks. The major advantage is cost. Sliders are widely used for both bridges and to reduce shrinkage and thermal stresses in large reinforced-concrete structures; thus, the manufacturing base for sliding elements is very wide. Many companies make sliding bearings and the industry is highly competitive. Thus, the cost of a sliding bearing is low compared to that of an elastomeric bearing. The cost factor between the two depends on detailing and size, but might be of the order of 1/2 to 1/3. The other advantage the sliding bearing has is its low height as compared to an elastomeric bearing. With one notable exception, the Kroeberg Nuclear Facility in South Africa isolated on sliders of a lead-bronze alloy in contact with stainless steel plates, sliding bearings are usually made of teflon pads filled with fiberglass bearings on stainless steel plates.

The coefficient for the rate of movement that results from thermal expansion or shrinkage of concrete is around 5%. However, this coefficient is very sensitive to velocity at pressures below around 2000 psi, and increases to around 20% at the velocities of seismic loading. The velocity sensitivity makes such a system extremely difficult to analyze and there have been attempts to eliminate, or at least reduce, the velocity sensitivity by increasing the pressure on the teflon pad. At pressures around 10,000 psi, the coefficient of friction remains of the order of 5% at seismic velocities and is not very velocity sensitive. The difficulty in such a strategy is that the bearing plate must be designed to sustain this pressure with large displacements and not a lot of data is available on the long-term behavior of the teflon-stainless steel surface under these high pressures. Such an approach is unlikely to be acceptable, or to pass code requirements, until these questions are answered.

Another problem in using sliders, and only sliders, in an isolation system is that there is no effective restoring force, and thus the design factor for the displacement will become extremely large. Since this displacement can be in any horizontal direction, the diameter of the stainless steel bearing plates and its support system must be made very large; in addition, the superstructure components bearings on this must be designed for large moments caused by these large displacements.

It is possible to introduce a restoring force capability in several ways. The sliding bearings can be combined with elastomeric bearings. The combination of sliders and elastomers was originally proposed by the author in 1978 [1] as a way to make use of the best features of both types of isolator. The use of sliders gives a system with a long period without running the risk of instability in the elastomeric bearings. The rubber bearings control the displacement by providing a centering section; additionally, they control torsion and if the displacements exceed the design level they produce stiffening action. This type of system was studied experimentally on the shake table and its performance was excellent. The results are published in a number of articles [2] [3]. A system of this type was used in the seismic rehabilitation of a University of Nevada building, the Mackay School of Mines in Reno, Nevada [4]. The retrofit of this building is due to be completed in 1992.

At the present time, retrofits projects constitute a large proportion of the base isolation projects that are under design or are being proposed, and sliding systems have been proposed for several. The use of base isolation for retrofit generally involves a brittle and weak structure, i.e., an unreinforced masonry building or a reinforced-concrete building of an early design that does not include the type of detailing of the reinforcement that will ensure ductile performance. Base isolation will lower the force demand on the structural system and impart a certain degree of energy absorption to the structure. However, if a sliding system is used for retrofit it is absolutely essential that the force which causes the slider to break be predictable. If the break-away force increases over the years of quiescence, the possibility exists that the structure could be damaged before the isolation system begins to move. If a weak, brittle structural system begins to deteriorate above the isolation system, it may never be able to produce the necessary force to cause the isolation system to start to slide and the building will act as if it were unisolated; the mitigating effects of the isolation system will not be achieved, thus negating the whole point of the retrofit.

There are, as of 1992, at least 3 retrofit projects that have been completed or under construction; two using lead-rubber bearings, and as mentioned above, one using the combined high-damping rubber and slider system. Several other large retrofit projects in the northern California area are in the design phase, including Oakland City Hall, Hayward City Hall, and San Francisco City Hall. The United States Government buildings in San Francisco are to be retrofitted with base isolation (and at least one state building).

Recent Experimental Studies of Elastomeric Isolator Performance

As a result of an interest to use base isolation for nuclear power plant facilities, a large program of bearing testing has been carried out at EERC over the past five years. The funding of this testing program came from several companies involved in the developing of liquid-metal fast-breeder nuclear systems and from the U.S. Department of Energy through the Argonne National Laboratories. A large number of different types of bearings were designed and procured from several bearing manufacturers in the United States, United Kingdom, and Japan. These were tested at EERC to determine their mechanical behavior and to study their failure mechanisms. The results of this test program have been published in a series of EERC technical reports.

As an example of the type of results obtained during this program, it is useful to review the tests of four bearings obtained from Bridgestone Corporation in Japan. These bearings were models of the Bridgestone high-damping rubber bearings used in several large isolation projects in Japan, including the Tohoku Power Co. Office Building. The results of the test program are given in detail in Ref. [5].

The rubber compound used in the bearings is designated KL401, which is a high-stiffness, high-damping rubber with around 31% carbon filler. The rubber has a shear modulus of around 0.86 MPa (125 psi) at 100% shear strain and an equivalent viscous-damping factor of around 15%. The dimensions of the bearings are shown in Fig. 1. The bearings are very flat with a width that is about four times the height between the end plates. The shape factor is 30, which for these bearings is very high. Four bearings were tested under horizontal shear in displacement controlled cycles from ±5% up to a maximum of ±350%. The test program was identical for all bearings with one variation, the vertical pressure was different for each bearing and ranged from zero pressure through 3.45 MPa (500 psi), 6.90 MPa (1000 psi), to 10.34 MPa (1500 psi). After the cyclic tests, each bearing was loaded monotonically to failure at the same level of vertical load.

The effective stiffness and the equivalent viscous damping are the characteristics of most interest to be determined from the dynamic tests. The effective stiffness is computed from the secant measured from peak to peak in each hysteresis loop. The equivalent viscous damping is computed from the area of the hysteresis loop. At each level of maximum strain there is a certain amount of softening between the first cycle and subsequent cycles. The effective stiffness and damping for the first and fifth cycles are given in Table 1.

The reduction in the damping ratios in the higher strain cycles is a consequence of the strong hardening of the material when the strain exceeds 200%. The damping factor quoted is based on modelling the bearing as an elastic and linear viscous element. This model predicts that the energy dissipation is quadratic in the displacement and the effective stiffness is independent of the displacements. In the actual component, the energy dissipation is not quadratic but varies roughly as displacement to the power 1.5, and the effective stiffness increases at the higher strains. Both factors act to reduce the damping factor. This reduction, however, is of very little significance to the response of a system using the isolators, since at these large strains it is futile to predict the dynamic response of the isolated structure by linear modelling. The important aspect of the bearing behavior is the energy dissipation which continues to increase while the strong hardening of the elastomer eliminates the possibility of resonant response.

The relationship between the hysteresis loops generated at the various strain levels indicate it might be useful to use one model to analyze the response at the design level; for example, for strains that do not exceed 200%, and a second model for extreme events at strains above that. It should be emphasized, however, that the dynamic tests were carried out within a time frame of a few hours and that the large strain cycles followed many cycles at lower levels. Thus, the results at the larger strains were obtained from bearings that underwent many tests in rapid succession. The response of a bearing might be somewhat different if it were to be tested to ± 350% strain initially.

Isolation bearings are generally used at pressure levels ranging from 5 to 7 MPa (700 to 1000 psi). Bearings with low shape factors and the range of height to width ratios that result from the selection of a low pressure tend to be somewhat sensitive to vertical load due to the fact that the vertical load is a significant fraction of the bearing buckling load. For bearings of the Bridgestone type, which have very large shape factors and a squat aspect ratio, the buckling load is so much larger than the design vertical load that the influence of vertical load on the horizontal characteristics through the stability of the bearing is negligible. However, the vertical pressure does play a role in the horizontal response and in these bearings the effect must be through an interaction between pressure and shear in the elastomer. This is a reasonable conjecture since for such large shape factors it has been shown [6] that the normal assumption of incompressible material behavior does not hold. Thus, the vertical load on the bearing produces a volume change in the material which could interact with the shear behavior to modify the horizontal response.

The dynamic tests were carried out at four levels of vertical pressure, 0, 3.45, 6.90, 10.34 MPa (0, 500, 1000 and 1500 psi). The bearing stiffness at the various peak strains were computed using peak-to-peak measurements in the resulting hysteresis loops. The stiffnesses are given in Table 1. At smaller strain levels ofless than 200%, there is no identifiable effect of pressure on stiffness; above 200% the stiffness is smaller at the higher pressure but the effect is small and can be ignored. The pressure, however, has a very definite effect on the damping. It is obvious from the hysteresis loops that their area for fixed strain increases with increasing pressure, leading to much larger damping factors.

The damping factors for each pressure level and each peak strain level are given in Table 1. The damping values over the range of strains up to 200% varies very little with strain and averages 12% for 0 MPa (0 psi), 12% for 3.45 MPa (500 psi), 13.6% for 6.90 MPa (1000 psi) and 15% for 10.34 MPa (1500 psi).

These are very high values for damping. This is especially when it is recalled that in the high-damping, natural-rubber compound bearings commonly used in the United States [7], the damping drops steadily with strain. The fact that the Bridgestone compound retains its high values of damping over such a wide range of strain is a significant advance in rubber technology. Furthermore, the fact that the higher pressure can generate higher damping factors with no detrimental effects would encourage the use of higher bearing pressures.

Since the horizontal natural frequency of an elastomeric isolation system is governed by the ratio of pressure to shear modulus, using a higher pressure could allow the use of a stiffer elastomer. Since it is generally easier to increase the damping in the rubber by increasing the stiffness, the result is an increase in damping both from the increased pressure and from the increased stiffness.

Each bearing was loaded monotonically to failure at a rate of 6.35 cm/min. (2.5 in/min.). The response of the bearings during this test is shown in Fig. 2 which gives the shear stress as a function of shear strain to failure for the four bearings. The stress-strain curve for the bearing with zero-vertical load lies below the others but continues to a displacement which is larger than the others. The failure of this bearing was also different from the others in that the force rose continuously to the point of failure; whereas for the loaded bearings, the curve near failure was more rounded, increasingly so with increasing pressure. In the heaviest loaded bearing, the curve reached a maximum and began dropping before the rubber failed. In the bearing with 6.90 MPa (1000 psi) pressure, the peak load in the bearing developed at 507% strain, and the rubber failed at 516% strain. For the bearing with 10.34 MPa (1500 psi), the peak load developed at 473% strain and the rubber failed at 513% strain. The failure was instantaneous in the bearing with zero pressure; in the bearings it was more gradual. It is interesting to note that the displacement at failure exceeded the diameter of the bearing in the case of the bearings with 0 and 3.45 MPa (0 and 500 psi) vertical pressure.

The results show that the stress-strain relation of the elastomer is trilinear. An initial stiffness of around 2.276 Mn/m (13 kips/in.) applies for a strain of up to around 15%, the bearing has a stiffness of 350 kN/m (2 kips/in.) up to a strain of around 250%, and the third segment of the force-displacement curve has a stiffness of 2.276 Mn/m (13 kips/in.) from 250% to failure.

The implications of these results for the analysis of buildings using this type of isolation system are several. The initial stiffness is significant for estimating the response of the isolated building to wind load and ground borne vibrations from traffic and other sources of low-level vibration. For seismic loading at design levels the initial stiffness can be ignored and the system analyzed as a linear system with viscous damping. For an estimate of the response under earthquake loading beyond the design level, the system can be analyzed using a bilinear model with the second stiffness much larger than the first. The analysis will be nonlinear and a realistic modeling of the energy dissipation can be made by combining viscous damping and hysteretic damping.

The strongly-stiffening character of the force-displacement curves also has implications for design. For example, for the bearing with 6.90 MPa (1000 psi) pressure the force level at 200% strain which could safely be considered as the design level is around 44.5 kN (10 kips) and at the maximum of the force-displacement curve it is 275.7 kN (62 kips). Thus, if a superstructure is designed just to be at yield level at the design strain of the isolators, the superstructure would have to be able to sustain a base shear of six times the yield level in order that the isolation system would fail before the superstructure would collapse. Although this is possible, it is highly unlikely. By using this kind of approach to isolation design, the bearing designer can be fairly confident that the isolation system will not be the weakest link.

The failure mechanism of the bearings at all levels of pressure was tearing of the rubber. No evidence of bond failure was observed.

Design Process for Elastomeric Bearings

The critical factor in the design of a bearing is the bond between the rubber and the steel shims. In the ideal case, the bonding compound should be sufficiently strong and the workmanship of the molding process reliable enough to insure that failure is always by tearing of the rubber and not delamination by bond failure. In the United States, concern about the quality of the bonding has meant that the maximum design shear strain has been 100% and this has led to bearing designs that are rather tall, and consequently somewhat unstable and prone to roll-out. Experience with Japanese designs of isolators such as those manufactured by Bridgestone Corporation which tend to use design shear strains of 200% and even in some cases 300%, suggests that a better proportioned isolator will result. It will be more squat and less subject to instability and roll-out, and in a sense, makes more efficient use of the highly intrinsic strength of the elastomer by making material failure the mechanism of failure rather than buckling or roll-out which are overall rather than local modes of failure. If the bond strength can be guaranteed, then the elastomer can be relied on to sustain shear strains of 450%-500%. The computation for roll-out suggests that roll-out of dowelled bearings or severe tension in bolted bearings will not develop if the displacement is less than 90% of the plan dimension. Accordingly, the diameter of the circular bearing should be about five times the rubber thickness. If the maximum shear strain is 200%, then the rubber thickness should be half the design displacement. The design process for a bearing with this configuration can be made fairly automatic in the following way.

The design process for elastomeric bridge bearings is governed by a number of code specifications that reflect the fact that the loads to which the bearings are subjected are well-defined and happen on a regular basis. If these provisions were to be applied to elastomeric bearings for isolation, they would result in unnecessarily conservative designs. In the design of seismic isolation bearings for buildings, it has to be recognized that codes such as the Uniform Building Code (UBC) 1991 impose very severe seismic loading on the isolation system and that this loading may be interpreted as ultimate state loading and that the isolators should be designed reflecting this. The point is that the conservatism is already incorporated in the specified seismicity of the site and need not be further increased by over conservative design of the isolators, and further, that the extreme loads to which the isolator may be subjected will occur, if at all, no more than once or twice over the lifetime of the structure.

The preliminary design of a bearing in an isolation system begins with the determination of the load to be carried by the bearing. In most buildings, the design load at each column (based on dead load plus fixed partitions, equipment, furniture, etc.) can vary quite widely. It will generally be necessary to minimize the number of different types of isolators, and thus, the first decision to be made will be how many different bearing types to design. Once this decision is made, the design load for each bearing type can be selected to minimize the variation of load on that type.

After the design load is selected, the design specifications will fix the following quantities:

f_H = horizontal frequency or T = horizontal period
f_V = vertical frequency
γ_{max} = maximum permissible shear strain
D = design displacement (from response spectrum or SEAOC formula)
W = isolation load

Two safety factors will also be needed. The first is the safety factor against buckling: this should be based on dead load plus live load on the bearing. The second is the safety factor against roll-out which should be based on the minimum load on the bearing.

The design quantities to be selected are a or Φ, t_r, t, n, G, and h, where

a = plan dimension of a square bearing
Φ = diameter of a round bearing
t_r = total rubber thickness in the bearing
t = thickness of individual layer
n = number of layers
G = shear modulus of elastomer
h = total height of the bearing br
$p = W/A$ = vertical pressure on bearing

In almost every case, a design spectrum will be a constant velocity spectrum and thus, at least for preliminary design, the design displacement D will vary linearly with the period T. We can begin then from the formula

$$D = kT \tag{1}$$

where k with units of length per second will depend on the site, the soil, and the damping in the system. Next, the average load to be carried by each type of isolator can also be assumed to be specified. The maximum shear strain, γ, in the isolator may be specified by code but it is possible that its choice may be left to the designer. With W, k, and γ known, the choices available to the isolator designer are aspect ratio and the shear modulus of the elastomer. A compact design for the isolator will mandate that the diameter of Φ will be related to the total elastomer thickness, t, through $\Phi = \lambda t_r$, with λ being at least 4 and preferably around 5. The shear capacity of high-strength natural rubber compounds is at 500% and with an aspect ratio of 5, this can be developed while some overlap of the top and bottom still exists to carry the vertical load.

The other design parameter of interest is the vertical pressure p. This is related to the other quantities through the fact that the period T is given by

$$T^2 = \left(\frac{2\pi}{\omega}\right)^2 = (2\pi)^2 \cdot \frac{p}{g} \cdot \frac{t_r}{G}$$

Now

$$t_r = \frac{D}{\gamma}$$

so that with Eq. (1) we have

$$T^2 = (2\pi)^2 \cdot \frac{p}{g} \cdot \frac{D}{\gamma g} = (2\pi)^2 \cdot \frac{p}{g} \cdot \frac{kT}{\gamma g}$$

which can be written in the form

$$p = \frac{g}{(2\pi)^2} \cdot \frac{\gamma G T}{k} \tag{2}$$

The area A of the isolator is $\frac{\pi}{4}\Phi^2$ and thus

$$\frac{\pi}{4}\lambda^2 t_r^2 = \frac{W}{p} = \frac{W(2\pi)^2 k}{g \cdot \gamma \cdot G \cdot T} \tag{3}$$

Since $t_r = \frac{D}{\gamma} = \frac{kT}{\gamma}$ we have

$$\frac{\pi}{4}\frac{\lambda^2 k^2 T^2}{\gamma^2} = \frac{(2\pi)^2}{\gamma} \cdot \frac{Wk}{\gamma G T} \tag{4}$$

This can be solved for T if the other quantities are specified. However, since Φ is related to T through

$$\Phi = \lambda t_r = \frac{\lambda D}{\gamma} = \frac{\lambda k T}{\gamma} \tag{6}$$

we can solve directly for the isolator diameter in the form

$$\Phi = \left\{\frac{\lambda^3 k^3}{\gamma^3} \cdot \frac{(2\pi)^2}{g} \cdot \frac{Wk}{\gamma G} \cdot \frac{4}{\pi} \cdot \frac{\gamma^2}{k^2 \lambda^2}\right\}^{1/3}$$

$$= \left\{\frac{16\pi}{g} \cdot \frac{\lambda}{\gamma^2} \cdot \frac{k^2 W}{G}\right\}^{1/3} \tag{7}$$

When Φ has been computed we can easily compute

$$t_r = \frac{\Phi}{\lambda}$$

$$D = \gamma t_r$$

$$T = \frac{D}{k}$$

and the base shear coefficient $C = \dfrac{\gamma G}{p}$ becomes by virtue of Eq. 2.

$$C = \frac{(2\pi)^2 k}{gT}$$

The range of the parameters that appears in this sequence of equations is quite wide. The aspect range should be around 4 or 5 and the maximum shear strain could vary between 1 and 2. The variation in the shear modulus will depend to some extent on the choice of maximum shear strain, but will vary over a factor of 3 from minimum to maximum. At a shear strain of 2, the range of shear modulus can be from .035 to 1.03 MPa (50 to 150 psi).

The solution of the design equation for isolator loads varying from 0.07 to 20.69 MPa (10 to 3000 kips) is shown in Fig. 3 with the corresponding pressures shown on the graph. It is clear that there is a wide range of possibilities for any value of W. If the pressure is too low, which would lead to high values of C, it is possible to increase G; and if too high, say above 13.79 MPa (2000 psi), it can be reduced by reducing G or increasing λ. In fact, the manipulation of Eqs. 3 and 4 gives p explicitly as

$$p = \frac{g^{2/3}}{2^{2/3}\pi^{5/3}} \cdot \frac{\lambda^{4/3}}{k^{4/3}} \cdot \frac{1}{\lambda^{2/3}} W^{1/3} \cdot G^{2/3}$$

In both this equation and that for Φ, the quantities k and γ come in as the ratio of one to the other. The value of k represents the seismicity of the site. A large value of k might represent a degree of conservatism in assessing the possible ground motion. On the other hand, the value of γ represents the degree of conservatism assumed for the strength of the elastomer. If a large value of k is used to represent a conservative approach to the seismicity, a large value of γ is appropriate to avoid compounding factors of safety.

Bearings with a large aspect ratio λ will be very stable. The critical buckling stress σ_{crit} is given [8] approximately by

$$\sigma_{crit} = \frac{1}{A}\sqrt{P_S P_E}$$

where

$$P_S = GA \cdot \frac{h}{t_r}$$

and

$$P_E = \frac{\pi^2 (EI)_{eff}}{h^2}$$

For moderate values of shape factor $S = \frac{\Phi}{4} t$, say between 4 and 16, the bending stiffness $(EI)_{eff}$ of a single pad is given by

$$(EI)_{eff} = \frac{1}{3} \cdot E_C \cdot \frac{\pi \Phi^4}{64} \cdot \frac{h}{t_r}$$

and

$$E_C \approx 6GS^2$$

Taken together these give

$$\sigma_{crit} = \frac{\sqrt{2}\pi}{4} \cdot \frac{GS\Phi}{t_r}$$

with

$$p = \frac{g}{(2\pi)^2} \cdot \frac{\gamma GT}{k}$$

$$= \frac{g}{(2\pi)^2} \cdot \frac{\gamma GD}{k^2} = \frac{g}{(2\pi)^2} \cdot \frac{\gamma G \gamma t_r}{k^2} = \frac{g}{(2\pi)^2} \cdot \frac{\gamma^2}{k^2} \cdot \frac{G\Phi}{\lambda}$$

We have the safety factor against buckling, *S.F.*, given by

$$S.F. = \frac{\sigma_{crit}}{p} = \frac{\sqrt{2}\pi}{4} \cdot \frac{S}{t_r} \cdot \frac{(2\pi)^2}{g} \cdot \frac{k^2}{\gamma^2} \lambda$$

$$= \frac{\sqrt{2}\pi^3}{g} \cdot \frac{Sk^2}{t_r \gamma^2} \lambda$$

$$= \frac{\sqrt{2}\pi^3}{g} \cdot \frac{\Phi}{4t} \frac{k^2 \lambda}{\gamma^2 t_r} = \frac{\sqrt{2}\pi^3}{4g} \cdot \frac{\lambda^2 k^2}{\gamma^2} \cdot \frac{1}{t}$$

This leads to the useful result that once the design criteria λ, k, γ are specified, the only design quantity that appears in the formula for the safety factor is t, the thickness of an individual layer. The safety factor will be greater than 1 for values of t less than a certain thickness given by

$$S.F. \geq 1$$

if

$$t \leq \frac{\sqrt{2}\pi^3}{4g} \frac{\lambda^2 k^2}{\gamma^2}$$

For $\lambda = 5$, $k = 4$, $\gamma = 2$, this gives $t \leq 72.9$ mm (2.83 in.). Since t is the thickness of an individual layer, which will be at most around 12.7 mm (0.5 in.), this indicates that the safety factor will be at least 6 and possibly more.

This result verifies that the bearings designed by this approach will be very stable against buckling. The advantage of using this type of design method is that overall behavior of the bearing will not be the critical factor in defining the bearing capacity. The bearing capacity will be controlled solely by the strength of the elastomer and by the shear capacity of the steel-rubber bond. Both of these quantities can be verified and controlled using small test specimens, thus reducing the cost of verifying the bearing capacity.

Conclusions

The results of the test program on the mechanical and failure characteristics of elastomer bearings has confirmed the extremely high quality that can be achieved for such isolators. They have been shown to be capable of extremely large shear strains before failure even under high levels of vertical pressure. Additionally, because a) the failure mechanism is only slightly affected by pressure, and b) the stiffness is unaffected by pressure while the damping is increased by pressure, these unique characteristics can be used in the design process, leading to the implementation of smaller isolators than those currently in use.

The damping in the bearings was found to be in the range of 15% of critical damping. However, damping is a secondary issue in isolation. It is not generally realized that the effect of an isolation system of the elastomeric type is the result of the difference between the fixed-base frequency of the superstructure and the overall frequency of the isolated building. When the ratio between these is large the participation factor of the higher modes that involve structural deformation is low. This means that the displacement that results from the earthquake input is almost entirely in the isolation system. Also, if there is large energy in the earthquake input at these higher frequencies, this energy is not transmitted into the structure as it is in conventionally based structures. This effect is achieved even in the absence of damping. Damping is only needed to counteract the possibility of resonance at the isolation frequency. In fact, damping can be viewed as a contaminant of the isolation process The more damping there is in the isolation system - and especially if this damping is produced by nonlinear mechanisms such as mechanical dampers - the more energy leaks into the higher modes thus counteracting the beneficial effects of the isolation system.

The search to find damping mechanisms to accompany isolation systems has been a misplaced effort. Much more important in designing practical isolation systems is the consideration that the elastomer hardens very strongly after a level of shear strain has been exceeded. In these tests, the stiffness increased by a factor of six beyond 250% shear strain. Thus, if 200% shear strain were taken as the nominal design level, at which level of base shear the superstructure is just at the yield point, then the base shear must be increased by at least a factor of six before the isolation system were to fail. This means that the failure mechanism for the entire structure will occur in the superstructure and not in the isolators. Conceptually, the collapse of an isolated structure is no different from that of a conventional structure with, however, the proviso that the level of earthquake impact that produces the failure must be much greater for the isolated structure owing to the large displacement capacity of the isolation system. The strong-hardening response of the system beyond the design level dictates that if the system exceeds this level, the period shortens significantly and the system becomes non-resonant.

The test results have shown that properly designed and manufactured isolators for nuclear reactor applications can sustain levels of loading beyond any possible seismic input and demonstrate that failure of an isolation system cannot occur before failure of the isolated structure. Thus, the use of isolation can only have beneficial contributions to the protection of nuclear facilities and their internal piping and equipment.

References

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Table 1

Bridgestone Bearing Test
Horizontal Shear Test

BEARING ID: HR030-4
EERC ID: No. 3
VERTICAL PRESSURE: 0 PSI

File No.	901023.22					901023.23				901023.24			
γ (±)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(eff)}$ (1st cy)	12.58	9.22	7.28	5.89	5.14	4.86	4.53	4.41	4.62	3.28	3.84	4.5	4.49
Kips in (5th cy)	11.21	8.75	6.54	5.45	4.67	4.61	3.94	3.80	3.74	3.13	3.48	3.52	3.62
β (1st cy)	12.25	12.24	12.01	11.95	12.09	13.18	12.17	11.39	9.97	13.64	10.02	8.74	7.89
(%) (5th cy)	13.39	13.14	12.06	12.09	13.86	12.01	12.70	11.61	10.61	13.22	10.47	9.4	8.4
W_D (1st cy)	0	1	4	6	10	11	21	35	50	31	43	62	70
Kips-in (5th cy)	0	1	3	6	11	10	19	30	43	29	39	52	60
G (1st cy)	311	228	180	145	127	120	112	109	114	81	95	111	111
Ksi (5th cy)	277	216	162	135	115	114	97	94	93	77	86	87	90

BEARING ID: HR030-3
EERC ID: No. 2
VERTICAL PRESSURE: 500 PSI

File No.	901023.16					901023.17				901023.18			
γ (±)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(eff)}$ (1st cy)	13.11	10.22	7.77	6.43	5.56	5.27	4.89	4.6	4.61	3.4	3.79	4.46	4.5
Kips in (5th cy)	12.7	9.41	7.08	5.79	4.98	4.94	4.15	3.78	3.71	3.18	3.49	3.6	3.62
β (1st cy)	10.22	12.91	12.6	12.15	12.8	13.39	12.85	12.11	10.59	14.2	10.68	9.06	8.42
(%) (5th cy)	11.21	11.65	11.87	12.77	14.03	13.56	13.55	12.89	11.88	14.49	11.3	9.98	9.06
W_D (1st cy)	0	1	4	7	11	12	24	38	53	33	44	63	77
Kips-in (5th cy)	0	1	3	7	11	11	22	34	48	31	42	56	67
G (1st cy)	324	253	192	159	137	130	121	114	114	84	94	110	111
Ksi (5th cy)	314	232	175	143	123	122	103	93	92	79	85	89	89

γ (±): Shear Strain (%)
$K_{(eff)}$: Effective Stiffness (kips in)
β: Equivalent Viscous Damping (%)
W_D: Energy Dissipation (kips-in)
G: Shear Modulus (psi)

Table 1 (Cont.)

BEARING ID: HR030-2
EERC ID: No. 1
VERTICAL PRESSURE: 1000 PSI

File No.	901023.04					901023.05				901023.06			
γ (±)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(eff)}$ (1st cy)	12.66	9.61	7.36	5.89	5.08	4.87	4.58	4.53	4.83	3.31	3.91	4.65	4.75
Kips in (5th cy)	12.71	8.6	6.32	5.41	4.72	4.55	3.9	3.77	3.84	3.13	3.54	3.7	3.71
β (1st cy)	13.71	12.99	12.48	13.24	14.01	15.45	13.86	12.24	10.57	15.68	10.99	9.11	8.29
(%) (5th cy)	13.73	11.08	14.07	15.1	14.91	15.03	14.66	13.02	11.31	15.25	11.74	10.18	9.46
W_D (1st cy)	0	1	4	7	11	13	24	38	55	50	45	64	78
Kips-in (5th cy)	0	1	3	7	11	12	22	34	48	31	43	57	70
G (1st cy)	313	237	182	145	125	120	113	112	119	82	97	115	117
Ksi (5th cy)	314	213	156	134	117	113	96	93	96	77	87	92	92

BEARING ID: HR030-5
EERC ID: No. 4
VERTICAL PRESSURE: 1500 PSI

File No.	901023.10					901023.11				901023.12			
γ (±)	10%	25%	50%	75%	100%	100%	150%	200%	250%	200%	250%	300%	350%
$K_{(eff)}$ (1st cy)	15.76	11.04	8.56	6.13	5.09	4.66	4.38	4.28	4.33	2.97	3.52	4.15	4.2
Kips in (5th cy)	11.31	8.45	6.32	5.08	4.48	4.36	3.74	3.46	3.44	2.77	3.14	3.23	3.19
β (1st cy)	12.71	14.52	14.34	14.84	16.39	17.13	15.77	14.06	12.81	18.58	13.24	10.85	9.92
(%) (5th cy)	14.64	14.75	14.52	15.97	16.52	16.16	16.96	15.46	13.67	17.61	14.11	12.4	11.59
W_D (1st cy)	0	1	4	8	13	13	26	41	60	37	50	70	85
Kips-in (5th cy)	0	1	4	7	12	12	24	36	50	33	48	62	75
G (1st cy)	389	273	211	151	126	115	108	106	107	73	87	103	104
Ksi (5th cy)	279	209	156	125	111	108	92	86	85	68	78	80	79

γ (±): Shear Strain (%)
$K_{(eff)}$: Effective Stiffness (kips in)
β : Equivalent Viscous Damping (%)
W_D : Energy Dissipation (kips-in)
G : Shear Modulus (psi)

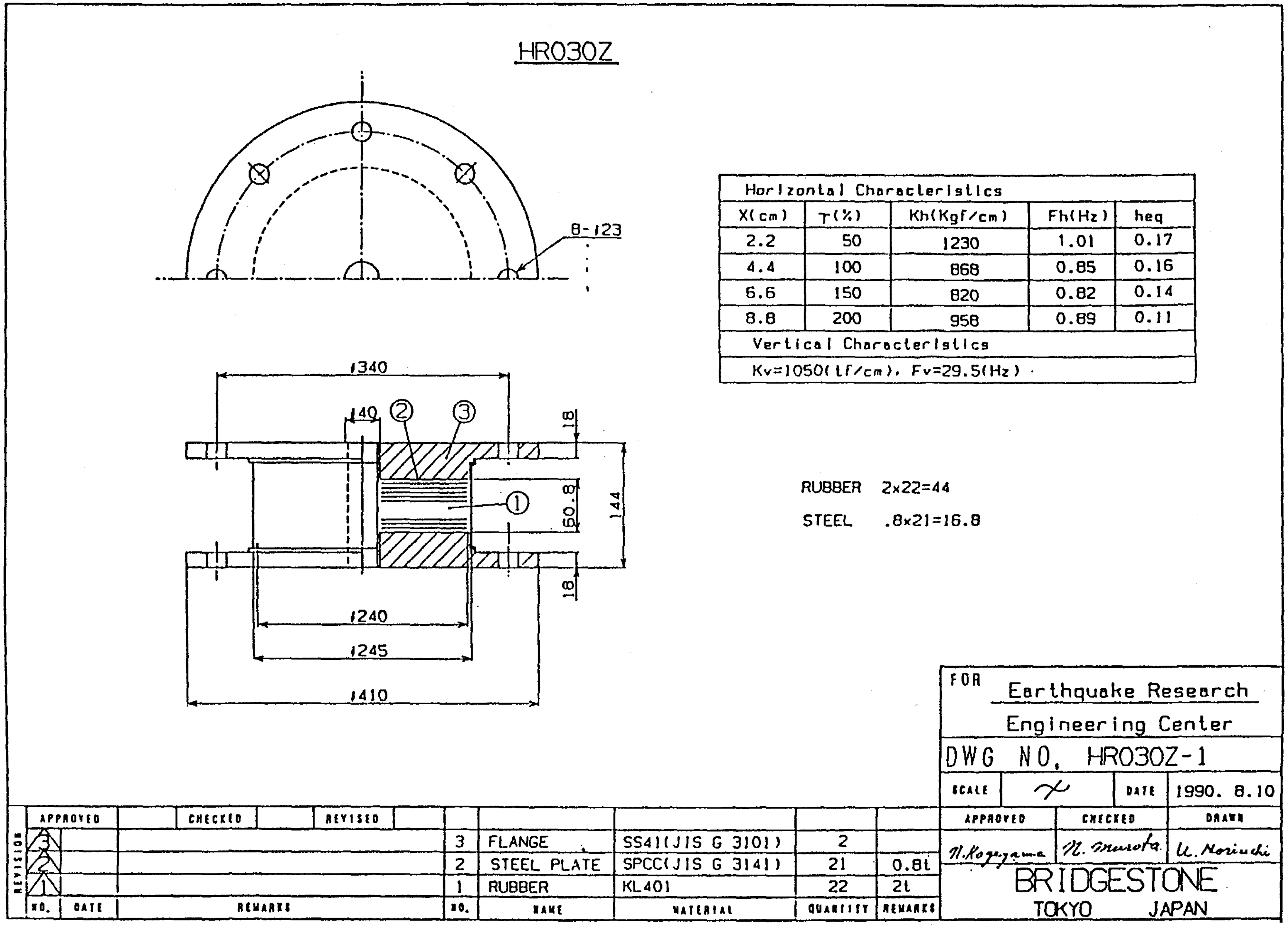

Fig. 1: Design Details for Test Bearings

BRIDGESTONE-BEARING TEST
SHEAR STRESS-STRAIN DIAGRAMS

BEARING ID:	HR030-4	HR030-3	HR030-2	HR030-5
VERT PRESSURE:	0 psi	500 psi	1000 psi	1500 psi
STRAIN RANGE :	561 %	550 %	507 %	473 %

Shear Stress/Shear Strain

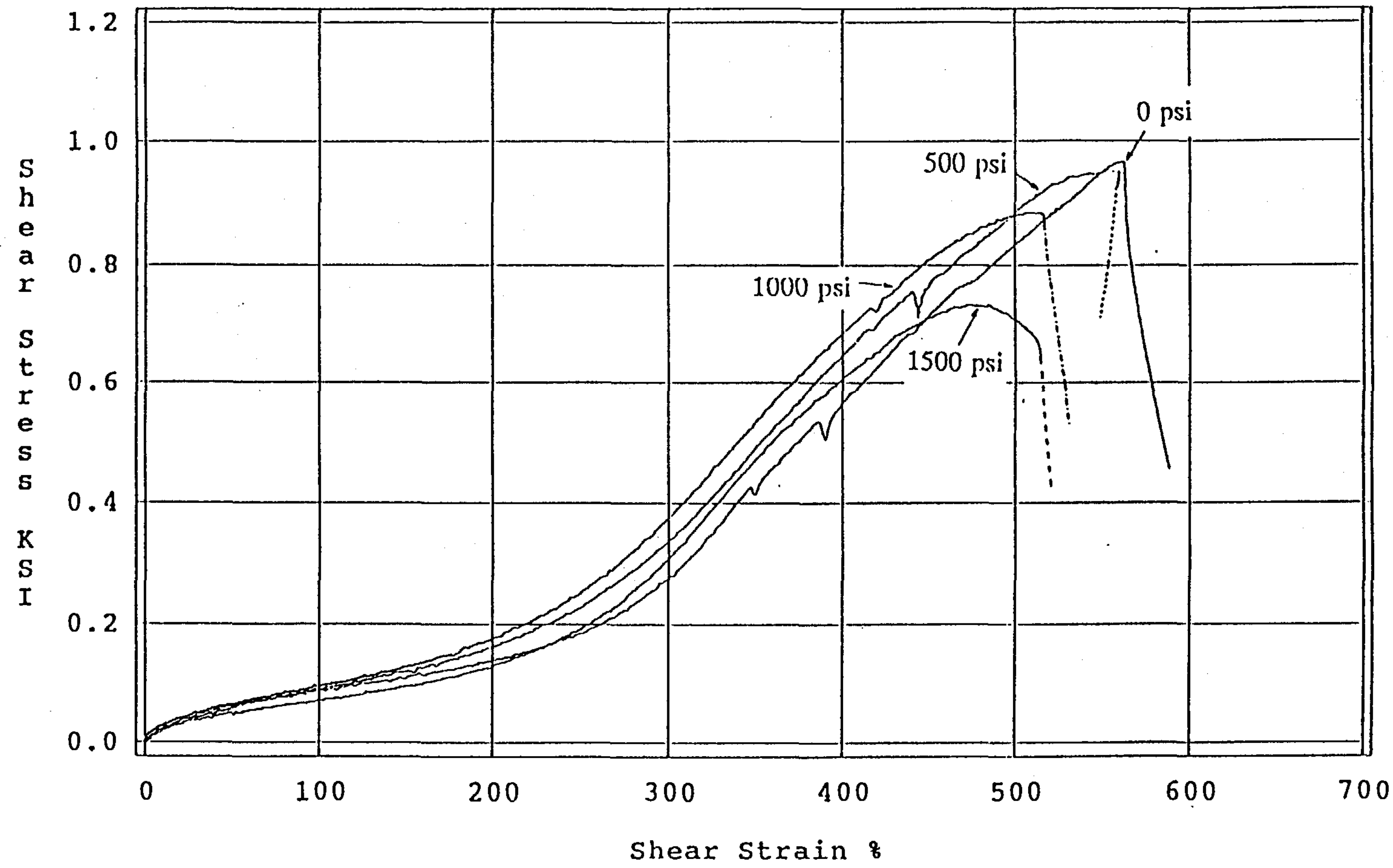

Fig. 2: Stress-Strain Curves for Bearings in Failure Tests

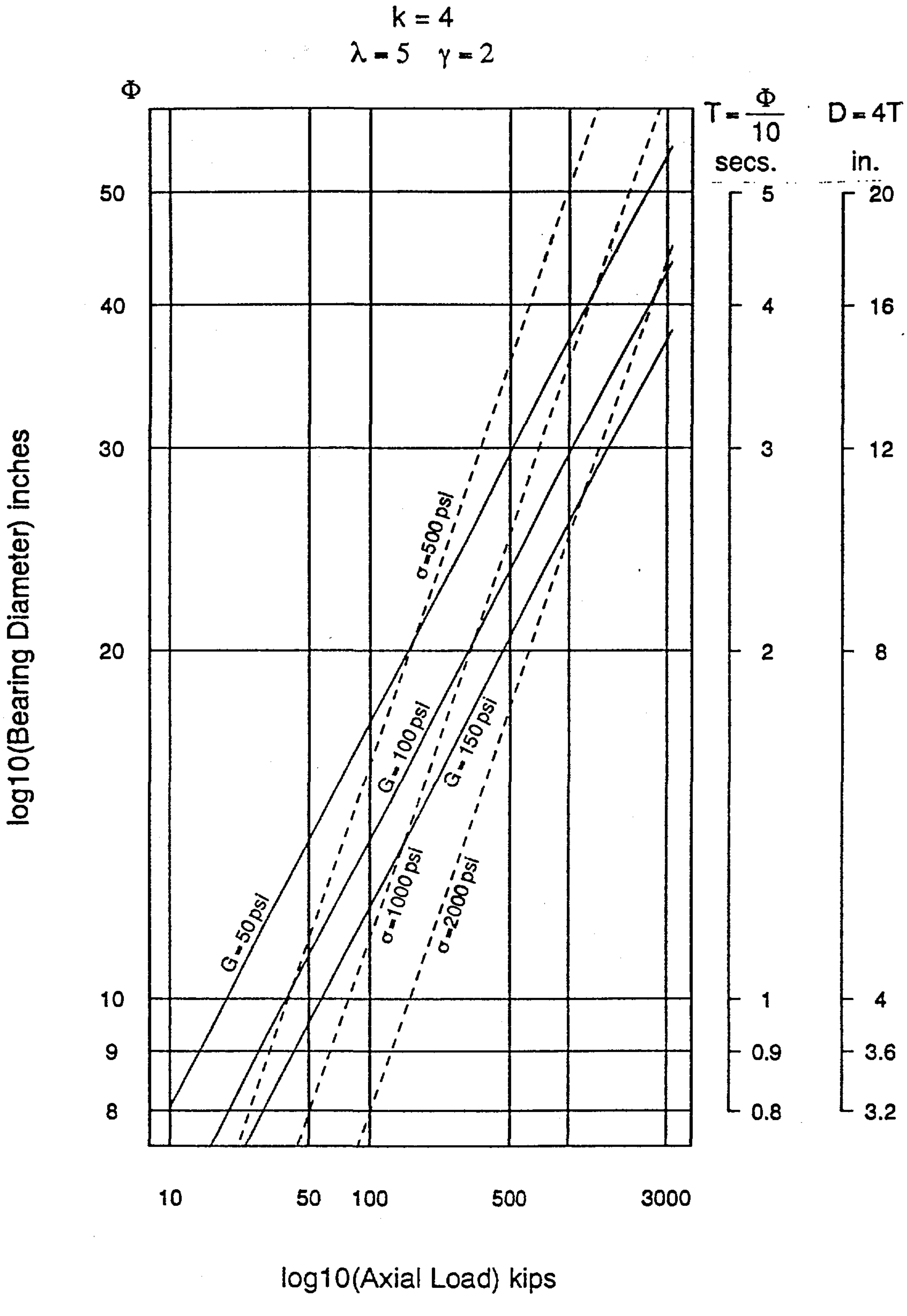

Fig. 3: Design Chart for Bearing Diameter as A Function of Axial Load