American
Iron and Steel
Institute

STEEL BRIDGE BEARING SELECTION AND DESIGN GUIDE

Vol. II, Chapter. 4
HIGWAY STRUCTURES
DESIGN HANDBOOK

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A = Plan area of elastomeric bearing (mm^2).

B = Length of pad if rotation is about its transverse axis, or width of pad if rotation is about its longitudinal axis (mm). Note that L or W were used for this variable in the 1994 AASHTO LRFD Specifications. The nomenclature was changed in this document to improve the clarity of its meaning.

b_{ring} = Width of brass sealing ring in pot bearing (mm).

D = Diameter of the projection of the loaded surface of a spherical bearing in the horizontal plane (mm).

= Diameter of circular elastomeric bearing (mm).

D_p = Internal pot diameter in pot bearing (mm).

d = Distance between neutral axis of girder and bearing axis (mm). Note that this definition is an addition to that used in the 1994 AASHTO LRFD Specifications.

E_s = Young's modulus for steel (MPa).

E_c = Effective modulus in compression of elastomeric bearing (MPa).

F = Friction force (kN).

F_y = Yield strength of the least strong steel at the contact surface (MPa).

G = Shear Modulus of the elastomer (MPa).

H_T = Total service lateral load on the bearing or restraint (kN).

H_u = Factored lateral load on the bearing or restraint (kN).

h_{ri} = Thickness of i^{th} elastomeric layer in elastomeric bearing (mm).

h_{rmax} = Thickness of thickest elastomeric layer in elastomeric bearing (mm).

h_{rt} = Total elastomer thickness in an elastomeric bearing (mm).

h_s = Thickness of steel laminate in steel-laminated elastomeric bearing (mm).

I = Moment of inertia (mm^4).

L = Length of a rectangular elastomeric bearing (parallel to longitudinal bridge axis) (mm).

M = Moment (kN-m).

M_{max} = Maximum service moment (kN-m).

M_u = Factored bending moment (kN-m).

M_x = Maximum moment about transverse axis (kN-m).

N = Normal force, perpendicular to surface (kN).

n = Number of elastomer layers.

P_D = Service compressive load due to dead load (kN).

P_L = Service compressive load due to live load (kN).

P_r = Factored compressive resistance (kN).

P_T = Service compressive load due to total load (kN).

P_u = Factored compressive load (kN).

R = Radius of a curved sliding surface (mm).

S = Shape factor of thickest elastomer layer of an elastomeric bearing

$= \frac{\text{Plan Area}}{\text{Area of Perimeter Free to Bulge}}$

$= \frac{LW}{2h_{rmax}\,(L+W)}$ for rectangular bearings without holes

$= \frac{D}{4h_{rmax}}$ for circular bearings without holes

t_r = Thickness of elastomeric pad in pot bearing (mm).

t_{ring} = Thickness of brass sealing ring in pot bearing (mm).

t_w = Pot wall thickness (mm).

t_{pist} = Piston thickness (pot bearing) (mm).

t_{rim} = Height of piston rim in pot bearing (mm).

W = Width of a rectangular elastomeric bearing
(perpendicular to longitudinal bridge axis) (mm).

α = Coefficient of thermal expansion.

β = Effective angle of applied load in curved sliding bearings.

$= \tan^{-1}(H_u/P_D)$

Δ_O = Maximum service horizontal displacement of the bridge deck (mm).

Δ_s = Maximum service shear translation (mm).

Δ_u = Maximum factored shear deformation of the elastomer (mm).

$(\Delta F)_{TH}$ = Fatigue limit stress from AASHTO LRFD Specifications Table 6.6.1.2.5-3 (MPa).

ΔT = Change in temperature (degrees C).

θ = Service rotation due to total load about the transverse or longitudinal axis (RAD).

θ_D = Maximum service rotation due to dead load (RAD).

θ_L = Maximum service rotation due to live load (RAD).

θ_{max} = Maximum service rotation about any axis (RAD).

θ_T = Maximum service rotation due to total load (RAD).

θ_x = Service rotation due to total load about transverse axis (RAD).

θ_z = Service rotation due to total load about longitudinal axis (RAD).

θ_u = Factored, or design, rotation (RAD).

μ = Coefficient of friction.

σ_D = Service average compressive stress due to dead load (MPa).

σ_L = Service average compressive stress due to live load (MPa).

σ_{PTFE} = Maximum permissible stress on PTFE (MPa).

σ_T = Service average compressive stress due to total load (MPa). Note that this variable is identified as σ_s in the 1994 AASHTO LRFD Specifications.

σ_U = Factored average compressive stress (MPa).

ϕ = Subtended angle for curved sliding bearings.

ϕ_t = Resistance factor for tension (=0.9).

Part I

STEEL BRIDGE BEARING SELECTION GUIDE

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SELECTION OF BEARINGS FOR STEEL BRIDGES

This Selection Guide facilitates the process of selecting cost-effective and appropriate bearing systems for steel girder bridges. Its intended use is to provide a quick reference to assist with the planning stages of construction. The selection process is divided into three steps: Definition of Design Requirements, Evaluation of Bearing Types and Bearing Selection and Design. A more detailed analysis of bearing design is provided in the *Steel Bridge Bearing Design Guide and Commentary* in Part II of this document.

Step 1. Definition of Design Requirements

Define the direction and magnitude of the applied loads, translations and rotations using the AASHTO LRFD Bridge Design Specifications. It is important at this stage to ensure that

- the bridge and bearings have been conceived as a consistent system. In general, vertical displacements are prevented, rotations are allowed to occur as freely as possible and horizontal displacements may be either accommodated or prevented.
- the loads are being distributed among the bearings in accordance with the superstructure analysis.
- and that no inconsistent demands are being made. For instance, only possible combinations of load and movement should be addressed.

Step 2. Evaluation of Bearing Types

After defining the design requirements refer to Table I-A to identify the bearing types which satisfy the load, translation and rotational requirements for the project. This table is organized in ascending order based on the initial and maintenance costs associated with each type of bearing. Read down the table to identify a bearing type which meets the design requirements at the lowest overall cost. It should be noted that the limits are not absolute, but are practical limits which approximate the most economical application of each bearing type. Ease of access for inspection, maintenance and possible replacement must be considered in this step.

Figures I-1, I-2 and I-3 are to be used for preliminary selection of the most common steel bridge bearing types or systems for the indicated design parameters. These diagrams were compiled using components that would result in the lowest initial cost and maintenance requirements for the application. Figure I-1 gives the first estimate of the system for bearings with minimal rotation (maximum rotation $\leq$ 0.005 radians). Figure I-2 gives the first estimate for bearings with moderate rotation ($\leq$ 0.015 radians), and Figure I-3 gives a first estimate for bearings with large rotations.

Consideration of two or more possible alternatives may result from this step if the given set of design requirements plot near the limits of a particular region in the figures. The relative cost ratings in Table I-A are approximate and are intended to help eliminate bearing types that are likely to be much more expensive than others.

Step 3. Bearing Selection and Design

The final step in the selection process consists of completing a design of the bearing in accordance with the AASHTO LRFD Bridge Design Specifications. The resulting design will provide the geometry and other pertinent specifications for the bearing. It is likely that one or more of the preliminary selections will be eliminated in this step because of an undesirable attribute. The final selection should be the bearing system with the lowest combination of first cost and maintenance costs as indicated in Table I-A. If no bearing appears suitable, the selection process must be repeated with different constraints. The most likely cause of the elimination of all possible bearing types is that a mutually exclusive set of design criteria was established. In this case the basis of the requirements should be reviewed and, if necessary, the overall system of superstructure and bearings should be re-evaluated before repeating the bearing selection process. The *Steel Bridge Bearing Design Guide and Commentary* summarizes these design requirements and provides software to aid in the design of a steel reinforced elastomeric bearing.

Bearing Type	Load		Translation		Rotation	Costs	
	Min. (kN)	Max. (kN)	Min. (mm)	Max. (mm)	Limit (Rad.)	Initial	Maintenance
Elastomeric Pads							
Plain (PEP)	0	450	0	15	0.01	Low	Low
Cotton Duck (CDP)	0	1400	0	5	0.003	Low	Low
Fiberglass (FGP)	0	600	0	25	0.015	Low	Low
Steel Reinforced Elastomeric Bearing	225	3500	0	100	0.04	Low	Low
Flat PTFE Slider (Polytetrafluorethylene)	0	>10 000	25	>100	0	Low	Moderate
Curved Lubricated Bronze	0	7000	0	0	>0.04	Moderate	Moderate
Pot Bearing	1200	10 000	0	0	0.02	Moderate	High
Pin Bearing	1200	4500	0	0	>0.04	Moderate	High
Rocker Bearing	0	1800	0	100	>0.04	Moderate	High
Single Roller	0	450	25	>100	>0.04	Moderate	High
Curved PTFE	1200	7000	0	0	>0.04	High	Moderate
Multiple Rollers	500	10 000	100	>100	>0.04	High	High

Note: 1 kip = 4.45 kN and 1 in. = 25.4 mm

Table I-A: Summary of Bearing Capabilities

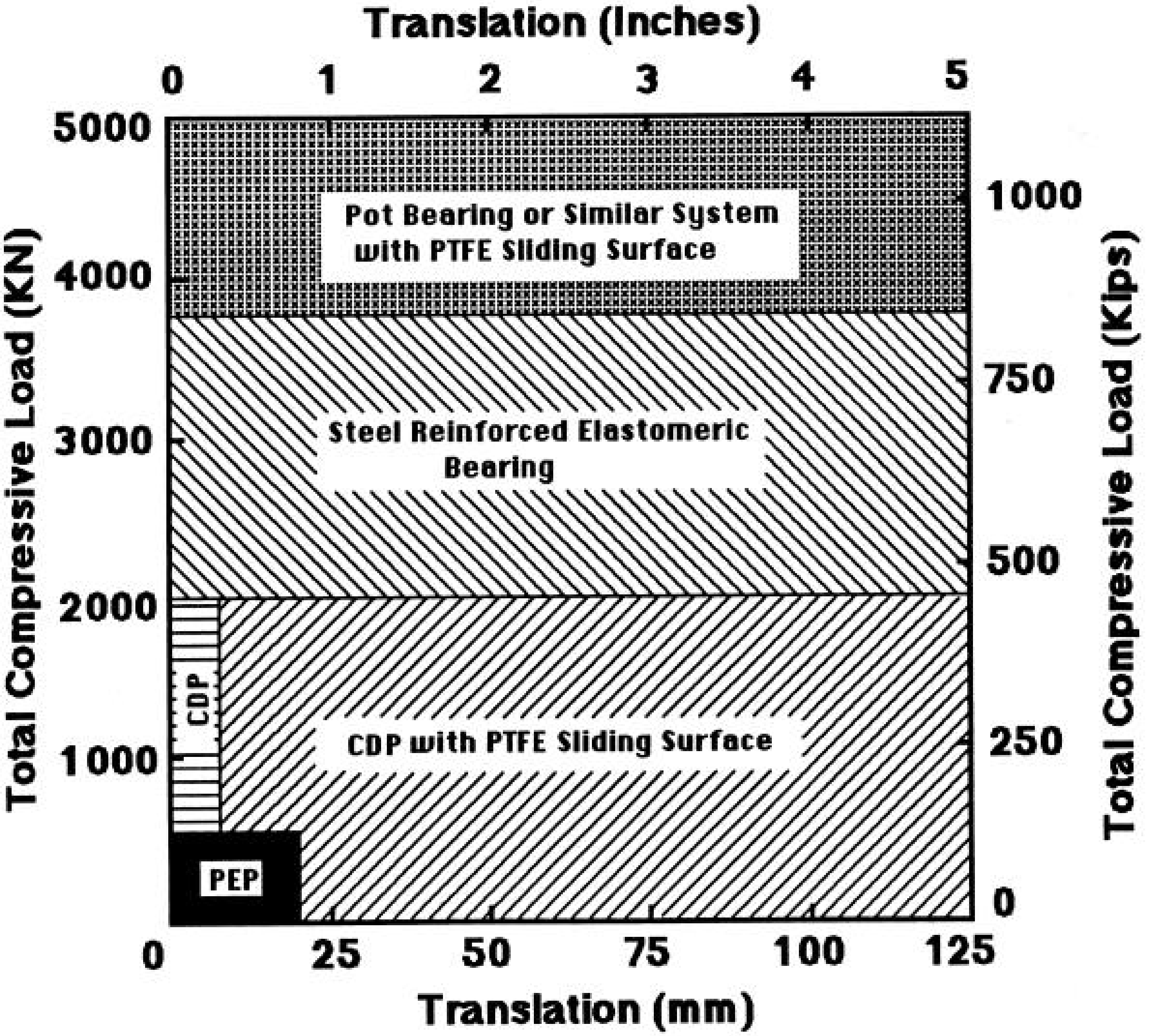


Figure I-1: Preliminary Bearing Selection Diagram for Minimal Design Rotation (Rotation ≤ 0.005 radians)

Note that the limit lines which define the regions in this diagram are only approximate. The limits could move 5% in either direction. As a result, the user should examine both options when the application falls near one of these limit lines.

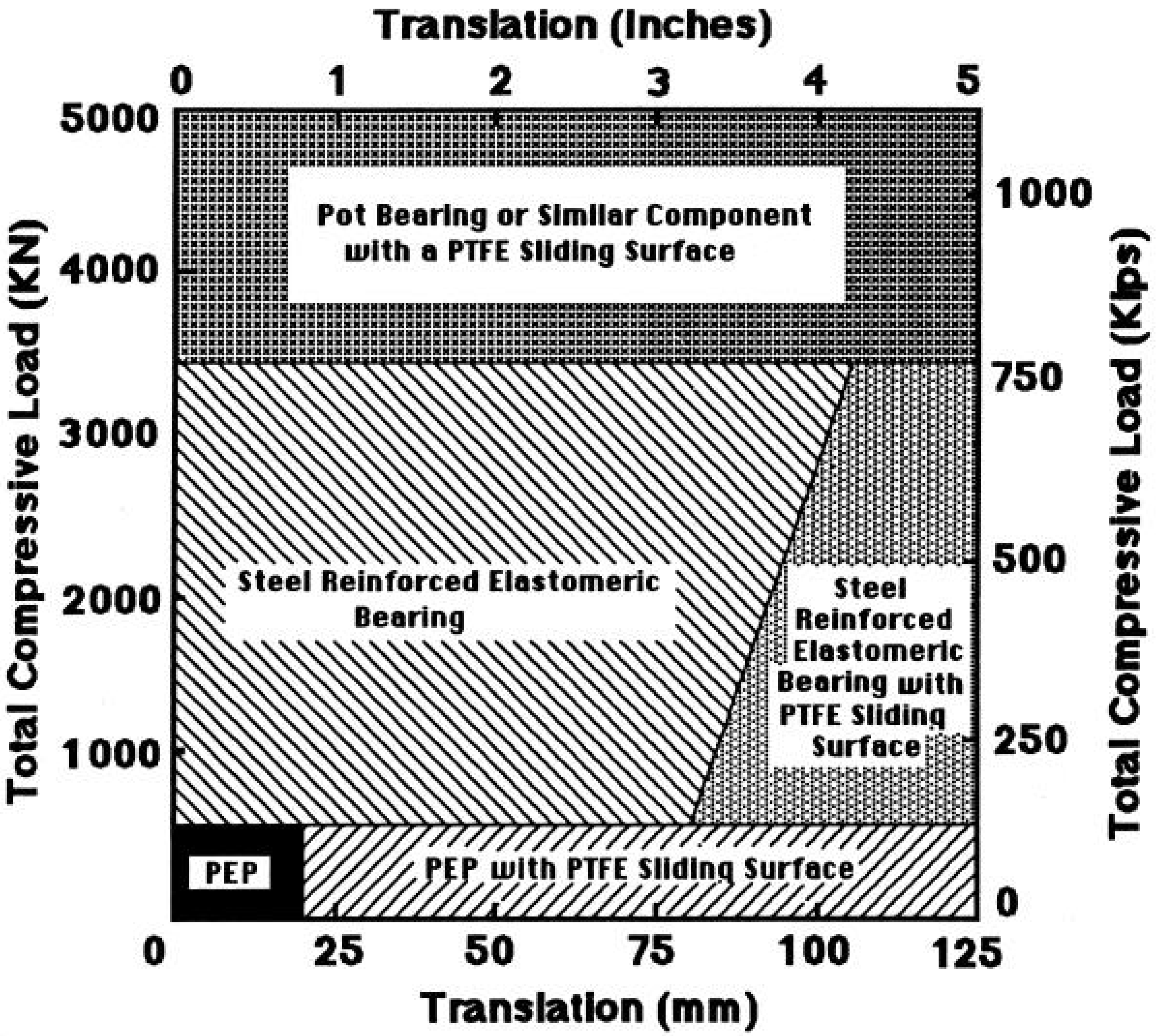
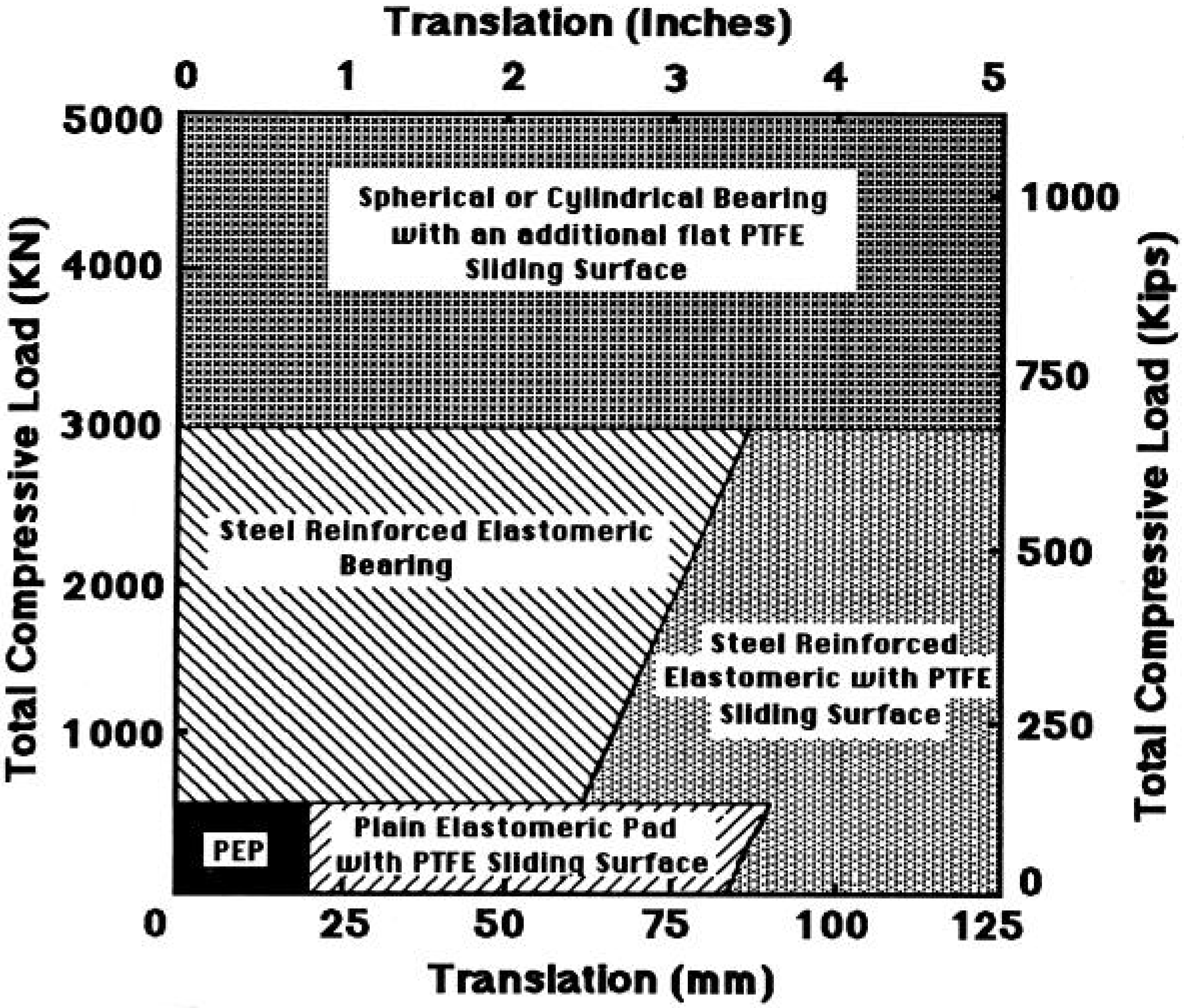


Figure I-2: Preliminary Bearing Selection Diagram for Moderate Design Rotation (Rotation ≤ 0.015 radians)

Note that the limit lines which define the regions in this diagram are only approximate. The limits could move 5% in either direction. As a result, the user should examine both options when the application falls near one of these limit lines.

Figure I-3: Preliminary Bearing Selection Diagram for Large Design Rotation (Rotation > 0.015 radians)



Note that the limit lines which define the regions in this diagram are only approximate. The limits could move 5% in either direction. As a result, the user should examine both options when the application falls near one of these limit lines.

Part II

STEEL BRIDGE BEARING DESIGN GUIDE AND COMMENTARY

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Section 1
General Design Requirements

Bearings assure the functionality of a bridge by allowing translation and rotation to occur while supporting the vertical loads. However, the designer should first consider the use of integral abutments as recommended in Volume II, Chapter 5 of the *Highway Structures Design Handbook*.

MOVEMENTS

Consideration of movement is important for bearing design. Movements include both translations and rotations. The sources of movement include bridge skew and curvature effects, initial camber or curvature, construction loads, misalignment or construction tolerances, settlement of supports, thermal effects, and traffic loading.

Effect of Bridge Skew and Curvature

Skewed bridges move both longitudinally and transversely. The transverse movement becomes significant on bridges with skew angles greater than 20 degrees.

Curved bridges move both radially and tangentially. These complex movements are predominant in curved bridges with small radii and with expansion lengths that are longer than one half the radius of curvature. Further, the relative stiffnesses of the substructure and superstructure affect these movements.

Effect of Camber and Construction Procedures

Initial camber of bridge girders and out of level support surfaces induce bearing rotation. Initial camber may cause a large initial rotation on the bearing, but this rotation may grow smaller as the construction of the bridge progresses. Rotation due to camber and the initial construction tolerances is sometimes the largest component of the total bearing rotation. Both the initial rotation and its short duration should be considered. If the bearing is installed level at an intermediate stage of construction, deflections and rotations due to the weight of the deck slab and construction equipment must be added to the effects of live load and temperature. Construction loads and movements due to tolerances should be included. The direction of loads, movements and rotations must also be considered, since it is inappropriate to simply add the absolute magnitudes of these design requirements. Rational design requires that the engineer consider the worst possible combination of conditions without designing for unrealistic or impossible combinations or conditions. In many cases it may be economical to install the bearing with an initial offset, or to adjust the position of the bearing after construction has started, in order to minimize the adverse effect of these temporary initial conditions. Combinations of load and movement which are not possible should not be considered.

Thermal Effects

Thermal translations, D_O, are estimated by

$$\Delta_O = \alpha \, L \, \Delta T \qquad \text{(Eq. 1-1)}$$

where L is the expansion length, a is the coefficient of thermal expansion, and DT is the change in the average bridge temperature from the installation temperature. A change in the average bridge temperature causes a thermal translation. A change in the temperature gradient induces bending and deflections(1). The design temperature changes are specified by the AASHTO LRFD Specifications(10). Maximum and minimum bridge temperatures are defined depending upon whether the location is viewed as a cold or moderate climate. The installation temperature or an expected range of installation temperatures for the bridge girders are estimated. The change in average bridge temperature, DT, between the installation temperature and the design extreme temperatures is used to compute the positive and negative movements in Eq. 1-1. It should be further noted that a given temperature change causes thermal movement in all directions. This means that a short, wide bridge may experience greater transverse movement than longitudinal movement.

Traffic Effects

Movements caused by traffic loading are not yet a formalized part of the design of bridge bearings, but they are receiving increased recognition. Traffic causes girder rotations, and because the neutral axis is typically high in the girder these rotations lead to displacements at the bottom flange. These movements and rotations can be estimated from a dynamic analysis of the bridge under traffic loading. There is evidence(4) to suggest that these traffic-induced bearing displacements cause significant wear to polytetrafluorethylene (PTFE) sliding bearings.

LOADS AND RESTRAINT

Restraint forces occur when any part of a movement is prevented. Forces due to direct loads include the dead load of the bridge and loads due to traffic, earthquakes, water and wind. Temporary loads due to construction equipment and staging also occur. It should be noted that the majority of the direct design loads are reactions of the bridge superstructure on the bearing, and they can be estimated from the structural analysis. The applicable AASHTO load combinations must be considered. However, care must be taken in the interpretation of these combinations, since impossible load combinations are sometimes mistakenly applied in bearing design. For example, large lateral loads due to earthquake loading can occur only when the dead load is present, and therefore load combinations which include extremely large lateral loads and very small vertical loads are inappropriate. Such impossible load combinations can lead to inappropriate bearing types, and result in a costly bearing which performs poorly.

SERVICEABILITY, MAINTENANCE AND PROTECTION REQUIREMENTS

Bearings are typically located in an area which collects large amounts of dirt and moisture and promotes problems of corrosion and deterioration. As a result, bearings should be designed and installed to have the maximum possible protection against the environment and to allow easy access for inspection.

The service demands on bridge bearings are very severe and result in a service life that is typically shorter than that of other bridge elements. Therefore, allowances for bearing replacement should be part of the design process. Lifting locations should be provided to facilitate removal and re-installation of bearings without damaging the structure. In most cases, no additional hardware is needed for this purpose. The primary requirements are to allow space suitable for lifting jacks during the original design and to employ details which permit quick removal and replacement of the bearing.

Section 2
Special Design Requirements for Different Bearing Types

Once the design loads, translations and rotations are determined, the bearing type must be selected and designed. Some applications will require combinations of more than one bearing component. For example, elastomeric bearings are often combined with PTFE sliding surfaces to accommodate very large translations. These individual components are described in detail in this Section. It should be noted that the design requirements for bridge bearings are frequently performed at service limit states, since most bearing failures are serviceability failures.

An overview of the behavior, a summary of the design requirements and example designs are included for each bearing component. It should be noted that mechanical bearings and disk bearings are not included in this Section. Mechanical bearings are excluded because they are an older system with relatively high first cost and lifetime maintenance requirements. As a result, their use in steel bridges is rare. Disc bearings are excluded because they were a patented item produced by one manufacturer.

Design examples that illustrate some of the concepts discussed are included in this section. Table II-A summarizes the major design requirements used in these examples.

	Elastomeric Bearing Pads	**Steel Reinforced Elastomeric Bearing**	**Pot Bearing**	**PTFE Sliding Surface**
Live Load	110 kN	1200 kN	1110 kN	1200 kN
Dead Load	200 kN	2400 kN	2670 kN	2400 kN
Longitudinal Translation	±6 mm	±100 mm	Cannot Tolerate Translation	±200 mm
Rotation about Transverse Axis	Negligible	0.015 radians	0.02 radians	0.005 radians accommodated by elastomeric bearing
Longitudinal Force			330 kN	

Table II-A: Summary of Design Examples

ELASTOMERIC BEARING PADS AND STEEL REINFORCED ELASTOMERIC BEARINGS

Elastomers are used in both elastomeric bearing pads and steel reinforced elastomeric bearings(10). The behavior of both pads and bearings is influenced by the shape factor, *S*, where

$$S = \frac{\text{Plan Area}}{\text{Area of Perimeter Free to Bulge}} \qquad \text{(Eq. 2-1)}$$

Elastomeric bearing pads and steel reinforced elastomeric bearings have fundamentally different behaviors, and therefore they are discussed separately. It is usually desirable to orient elastomeric pads and bearings so that the long side is parallel to the axis of rotation, since this facilitates the accommodation of rotation.

Elastomeric bearing pads and steel reinforced elastomeric bearings have many desirable attributes. They are usually a low cost option, and they require minimal maintenance. Further, these components are relatively forgiving if subjected to loads, movements or rotations which are slightly larger than those considered in their design. This is not to encourage the engineer to underdesign elastomeric pads and bearings, but it simply notes that extreme events which have a low probability of occurrence will have far less serious consequences with these elastomeric components than with other bearing systems.

Elastomer

Both natural rubber and neoprene are used in the construction of bridge bearings. The differences between the two are usually not very significant. Neoprene has greater resistance than natural rubber to ozone and a wide range of chemicals, and so it is more suitable for some harsh chemical environments. However, natural rubber generally stiffens less than neoprene at low temperatures.

All elastomers are visco-elastic, nonlinear materials and therefore their properties vary with strain level, rate of loading and temperature. Bearing manufacturers evaluate the materials on the basis of Shore A Durometer hardness, but this parameter is not a good indicator of shear modulus, G. Shore A Durometer hardnesses of 60±5 are common, and they lead to shear modulus values in the range of 0.55 to 1.25 MPa (80 to 180 psi). The shear stiffness of the bearing is its most important property since it affects the forces transmitted between the superstructure and substructure. The effect of this shear stiffness is explained in greater detail in the discussion for steel reinforced elastomeric bearings.

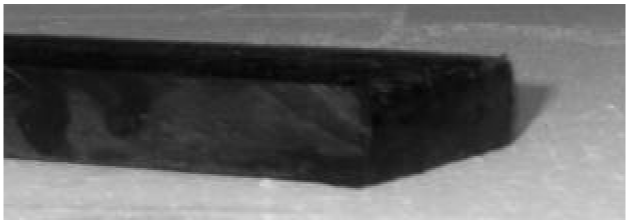
Elastomers are flexible under shear and uniaxial deformation, but they are very stiff against volume changes. This feature makes possible the design of a bearing that is stiff in compression but flexible in shear.

Elastomers stiffen at low temperatures(5,6). The low temperature stiffening effect is very sensitive to elastomer compound, and the increase in shear resistance can be controlled by selection of an elastomer compound which is appropriate for the climatic conditions.

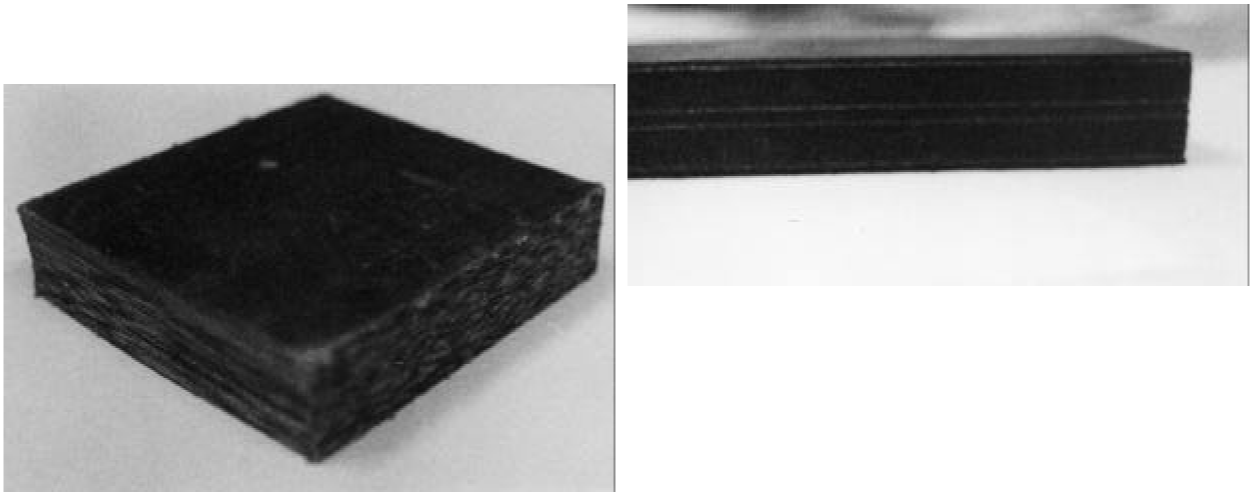
Elastomeric Bearing Pads

Elastomeric bearing pads include plain elastomeric pads (PEP) as shown in Figure II-2.1a, cotton duck reinforced pads (CDP) such as shown in Figure II-2.1b, and layered fiberglass reinforced bearing pads (FGP) as shown in Figure II-2.1c. There is considerable variation between pad types. Elastomeric bearing pads can support modest gravity loads but they can only accommodate limited rotation or translation. Hence, they are best suited for bridges with expansion lengths less than approximately 40 m (130 ft).

Plain elastomeric pads rely on friction at their top and bottom surfaces to restrain bulging due to the Poisson effect. Friction is unreliable and local slip results in a larger elastomer strain than that which occurs in reinforced elastomeric pads and bearings. The increased elastomer strain limits the load capacity of the PEP. The allowable stress depends upon the shape factor of the elastomeric bearing pad, and so PEP must be relatively thin if they are to carry the maximum allowable compressive load. Thin elastomeric bearing pads can tolerate only small translations and rotations. PEP occasionally "walk" from under their loads. This walking is partly caused by vibration and movement in the bridge, but recent research(7) has also attributed it to the reduced friction caused by migration of anti-ozonant waxes to the surface in natural rubber elastomer.



a) Plain Elastomeric Pad



b) Cotton Duck Reinforced Pad **c) Fiberglass Reinforced Pad**

Figure II-2.1: Typical Elastomeric Bearing Pads

Cotton duck reinforced pads as shown in Figure II-2.1b have very thin elastomer layers [less than 0.4 mm ($\frac{1}{60}$ in.)]. They are stiff and strong in compression so they have much larger compressive load capacities than PEP, but they have very little rotational or translational capacity. CDP are sometimes used with a PTFE slider to accommodate horizontal translation.

The behavior of elastomeric pads reinforced with discrete layers of fiberglass (FGP) as shown in Figure II-2.1c is closer to that of steel reinforced elastomeric bearings than to that of other elastomeric bearing pads. The fiberglass, however, is weaker, more flexible, and bonds less well to the elastomer than does the steel reinforcement. Sudden failure occurs if the reinforcement ruptures. These factors limit the compressive load capacity of the fiberglass reinforced bearing pad. FGP accommodate larger gravity load than a PEP of identical geometry, but their load capacity may be smaller than that achieved with CDP. FGP can accommodate modest translations and rotations.

Design Requirements

The capabilities of elastomeric bearing pads are limited and the design procedure is simple. The primary design limit is the compressive stress on the bearing pad. PEP have limited compressive load capacity because bulging is restrained only by friction at the load interface and local slip will result in larger elastomer strain. As a result, the average total compressive stress, s_T under service loading for a PEP must be limited to

$$\sigma_T \leq 0.55\, G\, S \leq 5.5 \text{ MPa (800 psi)} \tag{Eq.2-2}$$

CDP exhibit very small elastomer strains under compressive load and s_T is limited to

$$\sigma_T \leq 10.5 \text{ MPa (1500 psi)} \tag{Eq. 2-3}$$

In a FGP, the strains of the elastomer are considerably smaller than in a PEP with the same nominal compressive stress and shape factor. For FGP, s_T must be limited to

$$\sigma_T \leq 1.00 \text{ G S} \leq 5.5 \text{ MPa (800 psi)} \tag{Eq.2-4}$$

Translations and rotations are also limiting factors in the design of elastomeric pads. CDP have negligible translation capacity, and therefore due to shear limitations the total elastomer thickness, h_{rt} must satisfy

$$h_{rt} \geq 10\, \Delta_s \tag{Eq. 2-5a}$$

where D_s is the maximum translation under service conditions.

PEP and FGP accommodate modest translations the magnitudes of which are controlled by the maximum shear strain in the elastomer. Therefore, to prevent separation of the edge of the elastomeric bearing pad from the girder, maximum service translation, D_s, in PEP and FGP is limited by ensuring that h_{rt} satisfies

$$h_{rt} \geq 2\, \Delta_s \tag{Eq. 2-5b}$$

Rotation in elastomeric pads must also be considered. The AASHTO LRFD Specifications contain requirements intended to prevent net uplift. Rectangular pads must satisfy

$$\sigma_T \;\geq\; 0.5 \text{ G S}\left(\frac{\text{B}}{\text{h}_{\text{rt}}}\right)^2 \theta \tag{Eq. 2-6a}$$

where *B* is the horizontal plan dimension normal to the axis of rotation of the bearing and q is the rotation angle about that axis. This condition must be satisfied separately about the longitudinal and transverse axes of the bearing. For circular bearing pads, the limit is very similar except that

$$\sigma_T \;\geq\; 0.375 \text{ G S}\left(\frac{\text{D}}{\text{h}_{\text{rt}}}\right)^2 \theta_{\max} \tag{Eq. 2-6b}$$

where θ_{max} is the maximum rotation about any axis calculated using the vector sum of the components and D is the diameter of the pad. In these calculations, S is taken as the shape factor for PEP and FGP. CDP have negligible rotation capacity, and therefore these equations may be used but future Interims to the AASHTO LRFD Specifications are likely to require that S be taken as 100, since this better reflects the high rotational stiffness of CDP.

In order to prevent buckling under compressive load, the total thickness of pad is limited by the stability requirements of the AASHTO LRFD Specifications to the smaller of $L/3$, $W/3$, or $D/4$.

Design Example

Elastomeric bearing pads are primarily suitable for relatively short span steel bridge with modest translations and design loads. A design example is presented to illustrate the application of the above design requirements.

Dead Load	200 kN (45 kips)
Live Load	110 kN (25 kips)
Longitudinal Translation	6 mm (0.25 in.)
Rotation	Negligible Rotation

There are no design translations in the transverse direction. The steel girder has a bottom flange width of 250 mm (10 in.). The bearing is to extend no closer than 25 mm (1 in.) to the edge of the flange.

Examination of Figure I-1 of the *Steel Bridge Bearing Selection Guide* contained in Part I of this report illustrates that PEP or CDP are logical alternatives. CDP do not easily accommodate translation and rotation. The design translations are relatively small, but a minimum thickness of 63 mm (2.5 in.) would be required for such a pad. This thickness is possible, but it is likely to be impractical and a CDP is regarded as less suitable for the given application than is an PEP or a FGP.

To satisfy the shear strain limitations, the design translation requires a minimum thickness of 12 mm (0.5 in.) for a PEP or FGP. A PEP is selected here. The 250 mm (10 in.) flange width imposes an upper limit of 200 mm (8 in.) on the width of the bearing, so to satisfy limit of Eq. 2-2, the length, L, of the bearing must be at least

$$L > \frac{310 \text{ kN x } 1000}{5.5 \text{ MPa x } 200 \text{ mm}} = 282 \text{ mm}$$

A typical elastomer with hardness in the range of 65 Shore A durometer and a shear modulus in the range of 0.83 to 1.10 MPa (120 to 160 psi) is proposed. Trial dimensions of 200 x 300 mm are selected, so the shape factor, S, of the unreinforced pad is

$$S = \frac{L\ W}{2\ h_{rt}\left(L\ +\ W\right)} = \frac{200 \text{ x } 300}{2 \text{ x } 12 \text{ x } \left(200 + 300\right)} = 5.00$$

This shape factor is relatively low and it severely limits the stress level on the PEP. Eq. 2-2 requires

$$\sigma_T \leq\ 0.55GS = 0.55\ (0.83)\ 5.0 = 2.28 \text{ MPa}$$

This stress limit results in an increased length requirement. That is,

$$L > \frac{310\ \text{kN x } 1000}{2.28\ \text{MPa x } 200\ \text{mm}} = 680\ \text{mm}$$

and the increased length results in an increased shape factor. After several iterations, it is clear that a 200 x 575 x 12 mm (8 x 23 x 0.5 in.) pad will produce a shape factor of 6.18 and a bearing capacity of 324 kN (73 kips). The geometry of the pad clearly satisfies the $W/3$ stability limit, and this pad would satisfy all design requirements.

This elastomeric bearing pad is quite large and illustrates the severe limitations of PEP. A somewhat smaller bearing pad could be achieved if a FGP were used.

Summary

Elastomeric bearing pads are restricted for practical reasons to lighter bearing loads, in the order of 700 kN (160 kips) or less. CDP may support somewhat larger loads than PEP or FGP. Translations of less than 25 mm (1 in.) and rotations of a degree or less are possible with FGP. Smaller translations and rotations are possible with PEP. No significant movements are practical with CDP. Elastomeric bearing pads are a low cost method of supporting small or moderate compressive loads with little or no translation or rotation.

Steel Reinforced Elastomeric Bearings

Steel reinforced elastomeric bearings are often categorized with elastomeric bearing pads, but the steel reinforcement makes their behavior quite different(8,9). Steel reinforced elastomeric bearings have uniformly spaced layers of steel and elastomer as shown in Figure II-2.2. The bearing accommodates translation and rotation by deformation of the elastomer as illustrated in Figures II-2.3a and b. The elastomer is flexible under shear stress, but stiff against volumetric changes. Under uniaxial compression the flexible elastomer would shorten significantly and sustain large increases in its plan dimension, but the stiff steel layers restrain this lateral expansion. This restraint induces the bulging pattern shown in Figure II-2.3c, and provides a large increase in stiffness under compressive load. This permits a steel reinforced elastomeric bearing to support relatively large compressive loads while accommodating large translations and rotations.

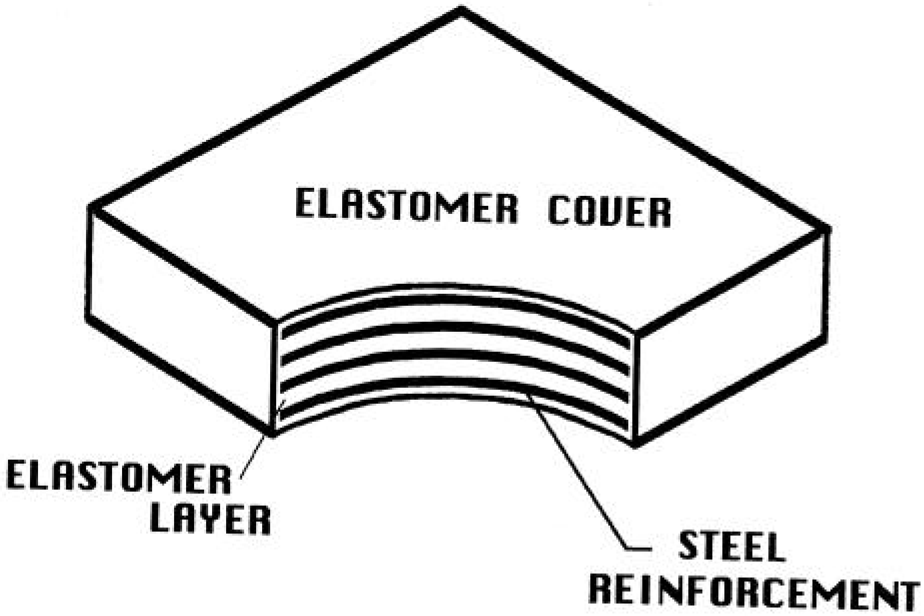


Figure II-2.2: Typical Steel Reinforced Elastomeric Bearing

The design of a steel reinforced elastomeric bearing requires an appropriate balance of compressive, shear and rotational stiffnesses. The shape factor affects the compressive and rotational stiffness, but it has no impact on the translational stiffness or deformation capacity.

A bearing must be designed so as to control the stress in the steel reinforcement and the strain in the elastomer. This is done by controlling the elastomer layer thickness and the shape factor of the bearing. Fatigue, stability, delamination, yield and rupture of the steel reinforcement, stiffness of the elastomer, and geometric constraints must all be satisfied.

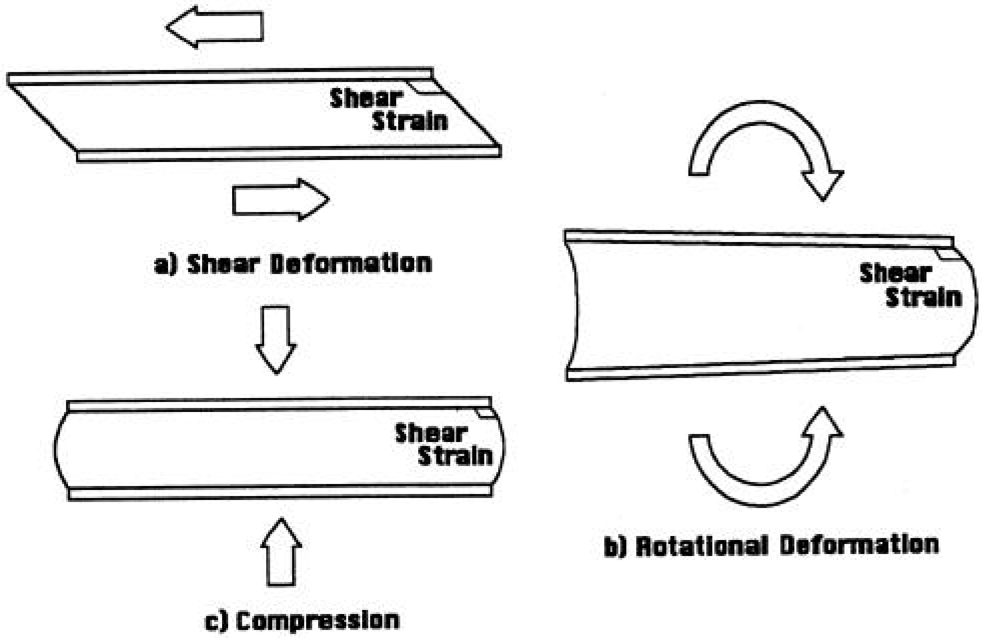


Figure II-2.3: Strains in a Steel Reinforced Elastomeric Bearing`

Large rotations and translations require taller bearings. Translations and rotations may occur about either horizontal axis of a steel reinforced elastomeric bearing, and this makes them suitable for bridges where the direction of movement is not precisely defined. Circular steel reinforced elastomeric bearings are particularly well suited for this purpose.

Steel reinforced elastomeric bearings become large if they are designed for loads greater than about 4500 kN (1000 kips). Uniform heating and curing during vulcanization of such a large mass of elastomer becomes difficult, because elastomers are poor heat conductors. Manufacturing constraints thus impose a practical upper limit on the size of most steel reinforced elastomeric bearings.

Design Requirements

The design of steel reinforced elastomeric bearings requires a balance between the stiffness required to support large compressive load and the flexibility needed to accommodate translation and rotation. The AASHTO LRFD Specifications provide these requirements. The balance is maintained by using a relatively flexible elastomer with a shear modulus, G, between 0.55 MPa and 1.25 MPa (80 and 180 psi) and an appropriate shape factor.

The height of the bearing is controlled by the movement requirements. The shear strains due to translation must be less than 0.5 mm/mm to prevent rollover and excess fatigue damage(8,11). Therefore, Eq. 2-5b also applies to steel reinforced elastomeric bearings, and the total elastomer thickness, h_{rt}, must be greater than two times the design translation, D_S. Separation between the edge of the bearing and the structure must be avoided during rotation, since separation causes tensile stresses in the elastomer and the potential for delamination. Separation is prevented by the combined compression and rotation limits that require

$$\sigma_T \geq 1.0\ G\ S\left(\frac{\theta_{\mathrm{max}}}{n}\right)\left(\frac{B}{h_{ri}}\right)^2 \qquad \text{(Eq. 2-7)}$$

where B is the horizontal plan dimension normal to the axis of rotation, q_{max} is the maximum service rotation about any axis, n is the number of elastomer layers, and h_{ri} is the thickness of an individual elastomer layer. Increased rotation capacity at a given load level may be achieved by an increase in h_{ri} or a reduction in S.

Delamination of the elastomer from the steel reinforcement is also an important consideration. This is controlled by limiting the maximum compressive stress due to combined loads on the elastomer to 11.0 MPa (16 ksi) for bearings subject to shear deformation and 12.0 MPa (1.75 ksi) for bearings fixed against shear deformation.

Steel reinforced elastomeric bearings are also subject to fatigue. The fatigue cracks occur at the interface between an elastomer layer and the steel reinforcement, and are caused by the local shear stresses which may arise from compression, rotation or shear loading. Fatigue damage during the lifetime of the bridge is controlled by limiting the average compressive stress on the bearing to a value that depends on the other loadings that are applied simultaneously. The fatigue design limits are

For bearings subjected to compression alone

$$\sigma_T \leq 2.00\ G\ S \leq 12.0\ \text{MPa}\ (1.75\ \text{ksi}) \qquad \text{(Eq. 2-8a)}$$

and

$$\sigma_L \leq 1.00\ G \qquad \text{(Eq. 2-8b)}$$

For bearings subjected to combined compression and shear deformation

$$\sigma_T \leq 1.66\ G\ S \leq 11.0\ \text{MPa}\ (1.60\ \text{ksi}) \qquad \text{(Eq. 2-9a)}$$

and

$$\sigma_L \leq 0.66\ G\ S \qquad \text{(Eq. 2-9b)}$$

where

σ_T = average compressive stress due to total service load = $\dfrac{P_T}{A}$

σ_L = average compressive stress due to live load = $\dfrac{P_L}{A}$

Steel reinforced elastomeric bearings must also satisfy uplift requirements. For rectangular bearings subjected to combined compression and rotation

$$\sigma_T \leq 2.25\,G\,S\left(1-0.167\left(\frac{\theta_{max}}{n}\right)\left(\frac{B}{h_{ri}}\right)^2\right) \qquad \text{(Eq. 2-10a)}$$

For rectangular bearings with combined translation, compression and rotation

$$\sigma_T \leq 1.875\,G\,S\left(1-0.20\left(\frac{\theta_{max}}{n}\right)\left(\frac{B}{h_{ri}}\right)^2\right) \qquad \text{(Eq. 2-10b)}$$

Elastomeric bearings may also buckle under compressive load and must satisfy stability limitations. Bearings which are susceptible to sidesway must satisfy

$$\sigma_T \leq \left(\frac{G}{\left(\dfrac{3.84(h_{rt}/L)}{S\sqrt{1+2.0\ L/W}}-\dfrac{2.67}{S(S+2.0)(1+L/4.0W)}\right)}\right) \qquad \text{(Eq. 2-11a)}$$

Bearings that are restrained against sidesway must satisfy

$$\sigma_T \le \left(\frac{G}{\left(\frac{1.92\left(h_{rt}/L\right)}{S\sqrt{1+2.0\ L/W}} - \frac{2.67}{S(S+2.0)(1+L/4.0W)} \right)} \right) \qquad \text{(Eq. 2-11b)}$$

The buckling capacity depends upon the shear modulus, the total elastomer thickness h_{rt}, the base dimensions L and W, and the shape factor S. For the buckling equations, L is in the direction of buckling, and W is normal to it.

Tensile stress develops in the steel reinforcement since it restrains the bulging of the elastomer. This tensile stress may control the thickness of the reinforcement. Therefore, the thickness of the steel reinforcement, h_s, must meet the following requirements. For total compressive stress,

$$h_s \ge \frac{3\,h_{rmax}\sigma_T}{F_y} \qquad \text{(Eq. 2-12a)}$$

and, for live load only

$$h_s \ge \frac{2.0\ h_{rmax}\sigma_L}{(\Delta F)_{TH}} \qquad \text{(Eq. 2-12b)}$$

where $(DF)_{TH}$ is the constant amplitude fatigue threshold given in Table 6.6.1.2.5-3 of the AASHTO LRFD Specifications.

In general, elastomer layer thickness should be selected to satisfy all design requirements, but practical limitations of the bearing manufacturer should also been considered. The thickness should normally be a convenient dimension that the manufacturer will easily understand and can easily maintain during fabrication. Larger thicknesses are appropriate for larger plan dimensions, since manufacturers have increasing difficulty maintaining very thin layer thickness with large bearings.

If the bearing is to be used in a very cold climate the low temperature stiffness must be considered. Certification tests by the manufacturer are required if the elastomer is susceptible to these low temperature conditions which affect a small part of the United States. The AASHTO LRFD Specifications(10) contains a very conservative temperature zone map which shows regions requiring low temperature consideration. Bridge designers should use the written description(5,6) of the temperature zones to design for a more realistic temperature region.

Design Example

A design example is presented to illustrate the above design requirements. A steel reinforced elastomeric bearing is to be designed for the following service loads and translations.

Dead Load	2400 kN (540 kips)
Live Load	1200 kN (270 kips)
Longitudinal Translation	100 mm (4.0 in.)

Rotation	0.015 radians

The above bearing translation is in the longitudinal direction of the bridge with the bridge fixed against movement at the 5th support. The rotation is about the transverse axis. There are no design translations in the transverse direction, but restraint in this direction is provided only by the stiffness of the bearing. The steel girder has a bottom flange bearing width of 750 mm (30 in.). A schematic of the bridge is illustrated in Figure II-2.4.

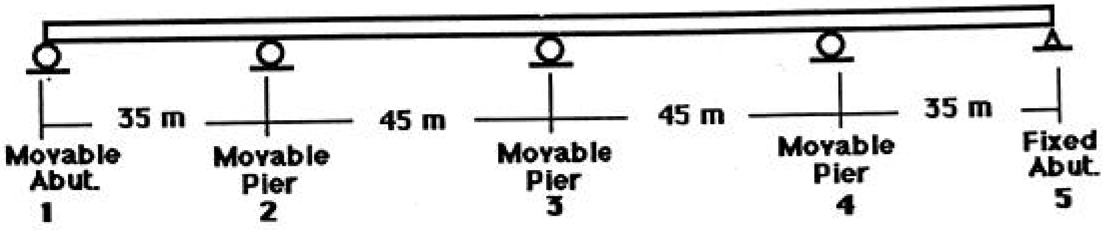


Figure II-2.4: Schematic of Example Bridge Restraint Conditions

These loads, translations and rotations are relatively large compared to those commonly considered acceptable for steel reinforced elastomeric bearings. However, examination of Figure I-2 of the *Steel Bridge Bearing Selection Guide* contained in Part I of this report suggests that a steel reinforced elastomeric bearing may be the most economical alternative. It will be shown that the bearing can indeed be designed for these requirements.

A typical elastomer with hardness in the range of 55 Shore A Durometer and a shear modulus in the range of 0.7 to 0.91 MPa (100 to 130 psi) is proposed. The total compressive load is 3600 kN (810 kips), and the 11.0 MPa (1.60 ksi) delamination stress limit of Eq. 2-9a requires a total plan area of at least

$$A > \frac{3600(1000)}{11} = 327\ 300\ \text{mm}^2$$

The bearing should be slightly narrower than the flange unless a stiff sole plate is used to insure uniform distribution of compressive stress and strain over the bearing area. The bearing should be as wide as practical to permit rotation about the transverse axis and to stabilize the girder during erection. Therefore a bearing width of 725 mm (29 in.) is an appropriate first estimate, and a 475 mm (19 in.) longitudinal dimension will assure that the delamination requirement is met. The longitudinal translation is 100 mm (4 in.), and so a total elastomer thickness of at least 200 mm (8 in.) is required to satisfy the rollover and excessive fatigue damage design requirements. A layer thickness of 15 mm (0.6 in.) is chosen in order to maintain an adequate shape factor. This leads to 14 layers with a total elastomer thickness of 210 mm (8.3 in.) and a preliminary shape factor of

$$S = \frac{725 \text{ x } 475}{2 \text{ x } 15 \text{ x } (725 + 475)} = 9.57$$

Prevention of uplift (Eq. 2-7) may also control the overall bearing dimensions. The base dimension, *B*, normal to the axis of rotation is 475 mm (19 in.), and the maximum compressive stress must satisfy

$$\sigma_T = \frac{P_T}{A} \geq 1.0\ GS \left(\frac{\theta_{max}}{n}\right)\left(\frac{B}{h_{ri}}\right)^2$$

$$\frac{3600(1000)}{475 \text{ x } 725} \geq 1.0 \text{ x } 0.91 \text{ x } 9.57\left(\frac{0.015}{14}\right)\left(\frac{475}{15}\right)^2$$

$$10.45 \text{ MPa} \geq 9.36 \text{ MPa} \qquad \text{ok}$$

G is taken as 0.91 MPa because the AASHTO LRFD Specifications require that, if the elastomer is defined by hardness rather than shear modulus, each calculation should use the least favorable value of *G* from the range that corresponds to the selected hardness.

Fatigue limits must also be checked. Since this bearing is subject to combined compression, shear deformation and rotation, Eqs. 2-9a, 2-9b and 2-10b will control.

$$\sigma_T = 10.45 \text{ MPa} < 1.66\ G\ S \leq 11.0 \text{ MPa}$$

$$< 1.66 \text{ x } 0.7 \text{ x } 9.57 \leq 11.0 \text{ MPa}$$

$$< 11.1 \text{ MPa} \leq 11.0 \text{ MPa}$$

$$10.45 \text{ MPa} < 11.0 \text{ MPa} \qquad \text{OK}$$

and

$$\sigma_L = \frac{1200 \text{ x } 1000}{475 \text{ x } 725} = 3.48 \text{ MPa} < 0.66\ G\ S$$

$$< 0.66 \text{ x } 0.7 \text{ x } 9.57 = 4.42 \text{ MPa} \qquad \text{ok}$$

Both are satisfied indicating that the bearing is acceptable for fatigue with combined shear and compression. The limit for combined shear, rotation and compression determined with Eq. 2-10b must also be checked, and

$$\sigma_T \leq 1.875\ G\ S\left(1 - 0.20\left(\frac{\theta_{max}}{n}\right)\left(\frac{B}{h_{ri}}\right)^2\right)$$

$$10.45 \text{ MPa} \leq 1.875 \text{ x } 0.7 \text{ x } 9.57\left(1 - 0.20\left(\frac{0.015}{14}\right)\left(\frac{475}{15}\right)^2\right) = 9.86 \text{ MPa} \qquad \text{NG}$$

This condition is not satisfied, because of the large rotation and the compressive load. However, this equation will be satisfied if the number of layers is increased to 20, and the total internal elastomer thickness is increased to 300 mm (12 in.).

Stability limits must also be checked. The bearing is free to sidesway in the transverse direction but is fixed against translation in the longitudinal direction. Thus, longitudinally Eq. 2-11b must be satisfied,

$$\sigma_T \le \left(\frac{G}{\left(\frac{1.92(h_{rt}/L)}{S\sqrt{1+2.0L/W}} - \frac{2.67}{S(S+2.0)(1+L/4.0W)} \right)} \right)$$

$$10.45\text{ MPa} \le \left(\frac{0.7}{\frac{1.92(300/475)}{\left(9.57\sqrt{1+2.0(475)/725}\right)} - \frac{2.67}{9.57(11.57)(1+475/4.0(725))}} \right)$$

$$10.45\text{ MPa} \le 11.17\text{ MPa} \qquad \text{ok}$$

and transversely Eq. 2-11a must be satisfied,

$$\sigma_T \le \left(\frac{G}{\left(\frac{3.84(h_{rt}/L)}{S\sqrt{1+2.0L/W}} - \frac{2.67}{S(S+2.0)(1+L/4.0W)} \right)} \right)$$

$$10.45\text{ MPa} \le \left(\frac{0.7}{\frac{3.84(300/725)}{\left(9.57\sqrt{1+2.0(725)/475}\right)} - \frac{2.67}{9.57(11.57)(1+725/4.0(475))}} \right)$$

$$10.45\text{ MPa} \le 10.77\text{ MPa} \qquad \text{ok}$$

Equations 2-12a and 2-12b must also be checked for reinforcement thickness. Assuming a steel with a 250 MPa (36 ksi) yield stress, the limit for total compressive stress is

$$h_s \ge \frac{3\, h_{rmax} \sigma_T}{F_y} = \frac{3 \text{ x } 15 \text{ x } 10.45}{250} = 1.88 \text{ mm}$$

The fatigue limit is less critical since the reinforcement has no holes or discontinuities, and can be treated as a plain member with a fatigue limit of 165 MPa (24 ksi).

$$h_s \ge \frac{2.0\, h_{rmax} \sigma_L}{(\Delta F)_{TH}} = \frac{2 \text{ x } 15 \text{ x } 3.48}{165} = 0.63 \text{ mm}$$

The required steel reinforcement thickness is approximately 2 mm (0.08 in.). It may also be desirable to use a thicker (say 3 mm) plate, since this may simplify manufacture and tolerance control, although it would also slightly increase the weight. Discussion with bearing manufacturers used by the bridge owner would help to establish the desirability of this final adjustment. Under these conditions, the finished bearing would be designed as shown in Figure II-2.5.

These design equations appear relatively cumbersome because several features must be checked and the behavior of steel reinforced elastomeric bearings is governed by relatively unusual principles of mechanics. The different requirements also interact, so design may involve some trial and error. However, they can easily be programmed into a spreadsheet, in which case the design becomes very simple. An example spreadsheet is given in Appendix B.

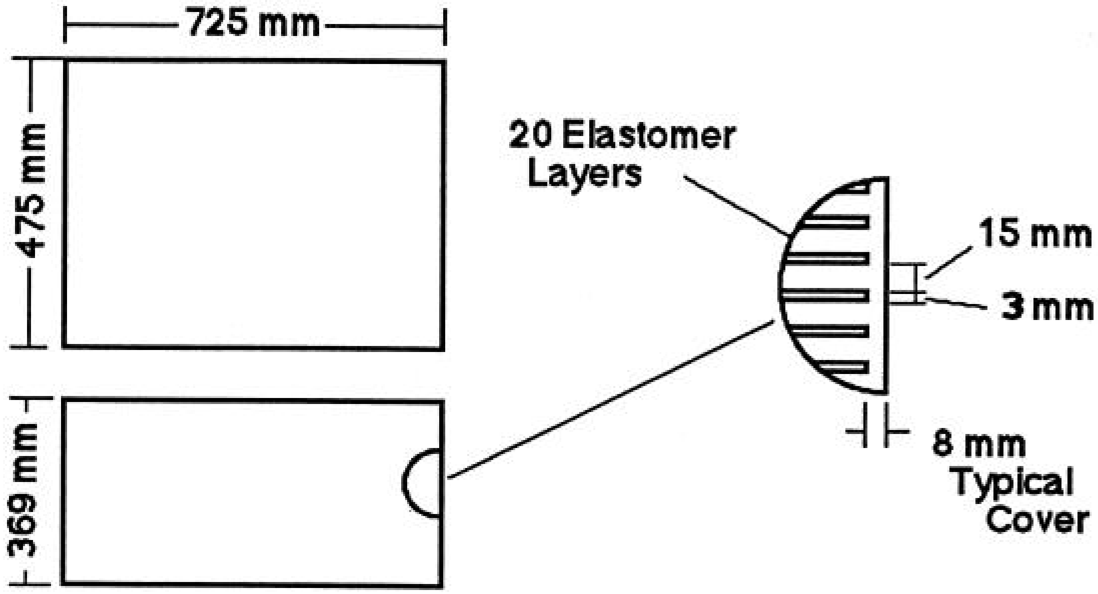


Figure II-2.5: Final Design of a Steel Reinforced Elastomeric Bearing

Summary

Many engineers incorrectly assume that steel reinforced elastomeric bearings are unsuitable for steel bridges because of the relatively large translations and rotations of the bridge. If proper design, materials, manufacturing and construction requirements are used, steel reinforced elastomeric bearings are very versatile. They may support loads as large as 4500 kN (1000 kips) and accommodate translations up to 150 mm (6 in.). Rotations of 2 or 3 degrees are achievable. Steel reinforced elastomeric bearings have an advantage over pot and spherical (HLMR) bearings where the rotations are large and their orientation is uncertain. Over-rotation of HLMR bearings causes metal to metal contact and possible permanent damage. An elastomeric bearing, by contrast, can accept a small number of short-term over-rotations with a low probability of damage.

The economy of the elastomeric bearing depends on both the load and displacement. In the 450 to 2200 kN (100 to 500 kips) range with moderate displacement and rotation requirements, a steel reinforced elastomeric bearing is likely to be less expensive than other alternatives. At higher loads or displacements, elastomeric bearings may still be the most economical alternative. However, the most economical alternative may be a combination of steel reinforced elastomeric bearings with other components such as a PTFE sliding surface to accommodate translations larger than 100 mm (4 in.).

POT BEARINGS

Elements and Behavior

The basic elements of a pot bearing are a shallow cylinder, or pot, an elastomeric pad, a set of sealing rings and a piston as shown in Figure II-2.6. Masonry plates and base plates are common, because they allow attachment of the bearing and increase the support area on the pier or abutment. Pot bearings are fixed against all translation unless they are used with a PTFE sliding surface.

The pot and piston are almost always made from structural carbon steel, although stainless steel and aluminum have occasionally been used if corrosion control is a concern. A variety of types of sealing ring have been used. Most sealing rings are either a single brass ring of circular cross-section, or a set of two or three flat brass rings. The circular rings have traditionally been brazed into a closed circle, whereas the flat ones are usually bent from a strip and the ends are not joined. Brass rings are placed in a recess on the top of the elastomeric pad. PTFE rings have been tried, but have been abandoned because of their poor performance. Other proprietary sealing ring systems have been used.

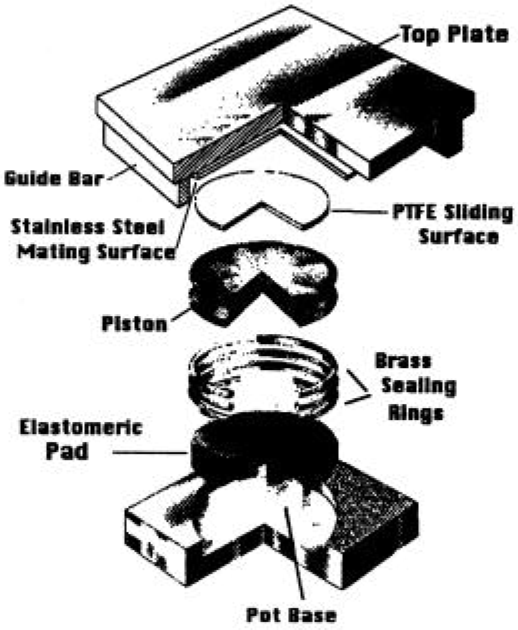


Figure II-2.6: Components of a Typical Pot Bearing

Compression

Vertical load is carried through the piston of the bearing and is resisted by compressive stress in the elastomeric pad. The pad is deformable but almost incompressible and is often idealized as behaving hydrostatically. In practice the elastomer has some shear stiffness and so this idealization is not completely satisfied. Experiments(12) have shown that pot bearings typically have a large reserve of strength against vertical load.

Deformation of the pot wall is a concern, since this deformation changes the clearances between the pot and the piston and may lead to binding of the bearing or to elastomer leakage. Two effects influence the displacements of the pot wall. First, compression in the elastomeric pad causes outward pressure on the pot wall, and this induces tension in the baseplate and outward bending of the pot wall. Second, the compressive stress on the bottom of the pot causes elastic deformation(13,14) of the concrete under the bearing. This deformation leads to downward dishing of the baseplate under the compressive load, and the baseplate deformation causes the pot wall to rotate inward. The bending stresses associated with this rotation of the pot wall are largest at the inside corner of the pot, and must be considered in the bearing design. Failures of pot bearings that were constructed by welding a ring to a flat baseplate have occurred because the weld, located at the critical location, was not designed to account for this load.

Rotation

Pot bearings are often regarded as suitable for use when bridge bearing rotations are large. Rotation may occur about any axis and is accommodated by deformation of the elastomeric pad. Large cyclic rotations can be very damaging to pot bearings in a relatively small number of cycles due to abrasion and wear of the sealing rings and elastomeric pad. However, pot bearings can sustain many cycles of very small rotations with little or no damage.

During rotation, the elastomeric pad compresses on one side and expands on the other, so the elastomer is in contact with the pot wall and slips against it. This causes elastomer abrasion and sometimes contributes to elastomer leakage. Lubrication is often used to minimize this abrasion, but experiments(14,15) show that the lubricant becomes less effective over time. Silicone grease, graphite powder and PTFE sheets have all been used as lubricants and, of these, the silicone grease has proven to be the most effective.

Inadequate clearances represent a second potential problem during rotation of pot bearings. These may cause binding of the bearing, and may induce large moments into the support or superstructure. However, these problems can be controlled by proper design. Figure II-2.7 illustrates typical clearances required in the design of the bearing.

Cyclic rotation may also be damaging to the sealing rings of pot bearings. Flat brass rings are more susceptible to ring fracture and elastomer leakage, while circular brass rings are susceptible to severe wear. Contamination of the pot by dirt or debris increases the potential for wear and damage to both the elastomeric pad and the sealing rings. A rough surface finish on the inside of the pot and piston produced by metalization or a rough machined surface produces results similar to those caused by contamination. A smooth finish results in less wear and abrasion. Bearings with a smooth finish, no internal metalization, and a dust seal appear to offer substantial benefits.

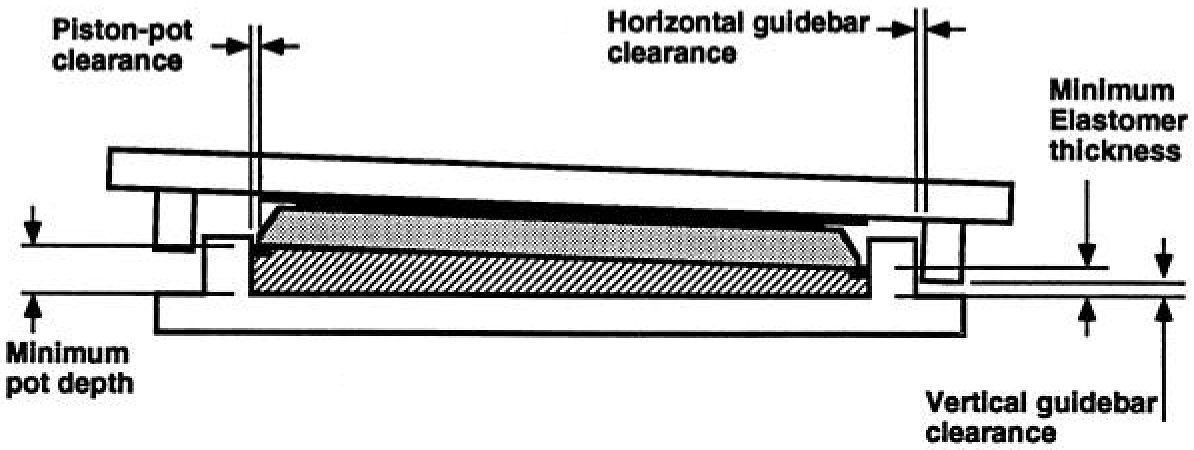


Figure II-2.7: Tolerances and Clearances for a Typical Pot Bearing.

Pot bearings have traditionally been designed so that the maximum compressive strain in the elastomer due to rotation is 15 percent. For 0.02 radians of rotation, the ratio D/t of the elastomeric pad must then be 15 at most. Tests have been performed on pot bearings with D/t ratios as large as 22 and as small as 12. Increasing the pad thickness accommodates higher rotations but increases the required depth, and therefore the cost of the pot.

Lateral load

Lateral loads on the bearing must also be accounted for in design. Lateral load is transferred from the piston to the pot by contact between the rim of the piston and the wall of the pot. The contact stresses can be high because the piston rim may be relatively thin to avoid binding when the piston rotates and the rim slides against the pot. The pot wall must transfer the load down into the baseplate and this is done by a combination of shear stresses in the part of the wall oriented parallel to the direction of the load and cantilever bending of the part in contact with the piston. The loads are then transferred into the substructure through friction under the base of the bearing and shear in the anchor bolts. Lateral loads may also contribute to increased wear of the elastomeric pad and greater potential for wear and fracture of the sealing rings. The damage observed in tests suggest that lateral loads should be carried through an independent mechanism wherever possible.

Design Requirements

The components of a pot bearing that need to be designed are the elastomeric pad, the metal pot and piston and the concrete or grout support. The sealing rings are perhaps the most critical element of all, but they are not amenable to calculation because no adequate mechanical model for their behavior has yet been proposed. In the absence of such a model, there is little choice but to use a type of sealing ring that has performed adequately in the past. As a result, closed circular brass rings and sets of two or three flat brass rings are permitted. The sealing rings of circular cross section must have a diameter no less than the larger of $0.0175D_p$ and 8 mm (0.375 in.), and sealing rings with a rectangular cross-section must have a width greater than at least $0.02D_p$ and 6 mm (0.25 in.) and a thickness of at least 0.2 times the width, where D_p is the internal diameter of the pot.

Elastomeric Pad

Pot bearings are designed for a compressive stress of 25 MPa (3.5 ksi) on the elastomeric pad under total service load. This controls the diameter of the pot and the pad. The pad thickness is controlled by the permissible compressive strain. The required thickness is

$$t_r \geq 3.33\ \theta_u\ D_p \qquad \text{(Eq. 2-13)}$$

where t_r is the pad thickness, θ_u is the design rotation angle of the piston, and D_p is the internal diameter of the pot. This limits the compressive strain in the elastomeric pad due to rotation to 15 percent. The strain may be larger under the sealing ring recess, since the effective thickness of the pad is reduced there. Therefore, the recess for the sealing rings should be shallow relative to the total thickness of the elastomeric pad in order to prevent damage to the thinner elastomer layer below the rings.

The pad should be made of an elastomer with a hardness in the range of 55 to 65 Shore A Durometer, and should provide a snug fit into the pot. The elastomer should be lubricated, preferably with silicone grease, and the pot should be sealed against dust and moisture.

Pot Walls and Base

The pot walls must be strong enough to withstand the large internal hydrostatic pressure in the elastomeric pad. This is ensured if

$$t_w \geq \frac{\sigma_u\ D_p}{2\phi_t F_y} \qquad \text{(Eq. 2-14)}$$

where t_w is the pot wall thickness, σ_u is the factored average compressive stress or hydrostatic pressure in the elastomer, D_p is the internal diameter of the pot, and F_y is the yield stress of the steel. The term ϕ_t is the resistance factor for tension (0.9). Using the normal 25 MPa (3.5 ksi) service stress with a load factor of 2 and a 345 MPa (50 ksi) yield stress for the steel leads to $t_w \geq 0.08D_p$.

The pot wall must be deep enough to assure that the piston does not lift out of the pot under any load or rotation. This results in a clearance requirement as illustrated in Figure II-2.7, and it is best satisfied as a performance requirement based on the design requirements and the geometry of the bearing.

If the bearing is subjected to lateral load, the analysis becomes more complicated. The wall thickness must be a minimum of

$$t_w \geq \sqrt{\frac{62\ H_T\theta}{F_y}} \qquad \text{(Eq. 2-15)}$$

where H_T is the service lateral load (kN), and θ is the service rotation angle (radians) about the axis normal to the direction of load. The wall thickness of the pot is controlled by the larger of the thicknesses produced by Eqs. 2-14 and 2-15. It should be noted that a version of Eq. 2-14 is included in the current pot bearing section of the AASHTO LRFD Specifications and it will control the wall thickness for pot bearings with lateral loads less than approximately 10 percent of the maximum compressive load. However, Eq. 2-15 is rational(14) and will likely be included in future Interim revisions to the AASHTO LRFD Specifications, since it controls the wall thickness when larger lateral loads are present [a Customary U.S. Units version of Eq. 2-15 would use a constant of 40 in place of 62].

The base must be thick enough to resist the moments from the cantilever bending of the wall and so should have a thickness at least equal to that required by Eq. 2-15. In addition, the base thickness should be no less than the larger of $0.06D_p$ and 19 mm (0.75 in.) for a base bearing directly against concrete or grout, and no less than $0.04D_p$ and 12.5 mm (0.5 in.) for a pot bearing base resting on load distribution plates.

In order to minimize the wear on the sealing rings and damage to the elastomeric pad, the inside of the pot walls should be machined to a fine surface finish [e.g., 1.5 micrometers (64 microinches) or better] and should not be metalized. The pot wall should not be metalized because the rough surface damages the piston, sealing rings and elastomeric pad. Corrosion protection should be provided by other means such as lubrication and sealing.

Piston

The piston must have adequate clearance between the rim of the piston and the wall of pot as illustrated in Figure II-2.7 to permit rotation of the bearing without elastomer leakage. This also results in a clearance requirement (illustrated in Figure II-2.7) which is best satisfied as a performance requirement based on the design requirements and the geometry of the bearing. However, a minimum clearance of 0.5 mm is required. Equation 14.7.4.7-2 of the 1994 AASHTO LRFD Specification is an approximate equation for determining the required clearance as a function of rotation and pot diameter. This equation is conservative for most practical cases, but it may also be deficient under some circumstances and is not repeated here.

The piston must be stiff enough not to deform significantly under load. As a minimum the piston thickness must satisfy

$$t_{pist} \geq 0.06\ D_p \qquad \text{(Eq. 2-16)}$$

The piston rim also must be thick enough to carry the contact stresses caused by lateral load, when the lateral load is transferred to the pot through the piston. The rim thickness must satisfy

$$t_{rim} \geq \frac{2.5\, H_T}{D_p\, F_y} \qquad \text{(Eq. 2-17)}$$

Eq. 2-17 is presently not included in the AASHTO LRFD Specifications, but it is likely(14) to be included in the future Interims to the specification. The diameter and shape of the rim should be selected so as to prevent binding of the piston in the pot when it undergoes its maximum rotation.

Concrete Bearing Stresses and Masonry Plate Design

A masonry plate is often supplied below the bearing, although in Europe many pot bearings have been installed without one. However, as discussed in Section 3, the use of a masonry plate may be desirable because it simplifies bearing removal and replacement. The masonry plate must be designed by normal bearing strength base plate design methods. These methods are also used for a wide range of other bridge components and as a result are not summarized here.

Design Example

Design a movable bearing for the following conditions:

Dead Load	2670 kN (600 kips)
Live Load	1110 kN (250 kips)
Lateral Load	330 kN (75 kips)
Rotation	± 0.02 radians

The design rotation falls near the boundary that separates the use of Figures I-2 and I-3 of the *Steel Bridge Bearing Selection Guide* in Part I of this document. Those figures suggests that a pot bearing or a spherical bearing would be viable alternatives. However, Table I-A indicates that the pot bearing has a lower initial cost. Therefore, a movable pot bearing is designed.

Use AASHTO M270 Grade 345W (ASTM A709M Grade 345W) structural weathering steel. A PTFE pad is to be recessed into the top of the piston. The concrete piercap is 1050 mm (3.5 ft) wide; f'_c is 28 MPa (4 ksi).

The diameter of the pot and the elastomeric pad are determined by the maximum stress, 25 MPa (3.5 ksi), permitted on the pad at the maximum load.

$$A \geq \frac{P_D + P_L}{25} = \frac{3780 \text{ x } 1000}{25} = 151 \text{ x } 10^3 \text{ mm}^2$$

or $D_p \geq 439$ mm (use 450 mm). The thickness of the pad is determined by the strain in the elastomeric pad. Eq. 2-13 requires

$$t_r \geq 3.33\ \theta_u\ D_p = 3.33 \text{ x } 0.02 \text{ x } 450$$

$$= 30 \text{ mm (use 30 mm)}$$

The sealing rings are selected to be 3 flat brass rings of width, b_{ring}, and thickness, t_{ring}, where

$$b_{ring} \geq \max(0.02D_p, 6 \text{ mm}) = \max(0.02 \text{ x } 450, 6)$$

$$= 9 \text{ mm (use 9 mm)}$$

$$t_{ring} \geq 0.2\ b_{ring} = 1.8 \text{ mm (use 2 mm)}$$

The total thickness of the three rings is 6 mm (¼ in.). This is less than 1/3 the total thickness of the pad, which is the limit commonly employed to control the concentration in elastomer strain at this location

The piston should have a minimum thickness of $t_{pist} \geq 0.06\ D_p = 0.06 \text{ x } 450 = 27$ mm (use 27 mm). The minimum thickness of the rim, t_{rim}, is

$$t_{rim} \geq \frac{2.5\,H_T}{D_p F_y} = \frac{2.5 \text{ x } 330\,000}{450 \text{ x } 345} = 5.3 \text{ mm } (\text{use 6 mm})$$

The PTFE must be designed and recessed as required by PTFE design criteria, and the minimum piston thickness will need to consider the loss of thickness produced by the recess.

The pot wall thickness is controlled by the larger of Eqs. 2-14 and 2-15. Vertical load alone, Eq. 2-14, requires

$$t_w \geq \frac{\sigma_u D_p}{2\,\phi_t\,F_y} = \frac{\dfrac{2 \text{ x } 3\,780\,000}{\pi\,(225)^2}(450)}{2 \text{ x } 0.9 \text{ x } 345} = 34.4 \text{ mm}$$

and for horizontal load

$$t_w \geq \sqrt{\frac{62\,H_T\,\theta}{F_y}} = \sqrt{\frac{62 \text{ x } 330\,000 \text{ x } 0.02}{345}} = 34.4 \text{ mm}$$

The pot base thickness is determined as follows

$t_{base} \geq 0.06 \text{ x } 450$ and $t_{base} \geq t_w$

$t_{base} \geq 27 \text{ mm} < 34.4 \text{ mm}$ (use 35 mm)

Thus, the 35 mm thickness controls both the pot base and wall thickness. Masonry plates are selected by the normal concepts for steel bearing on concrete. Figure II-2.8 illustrates the final design for this example.

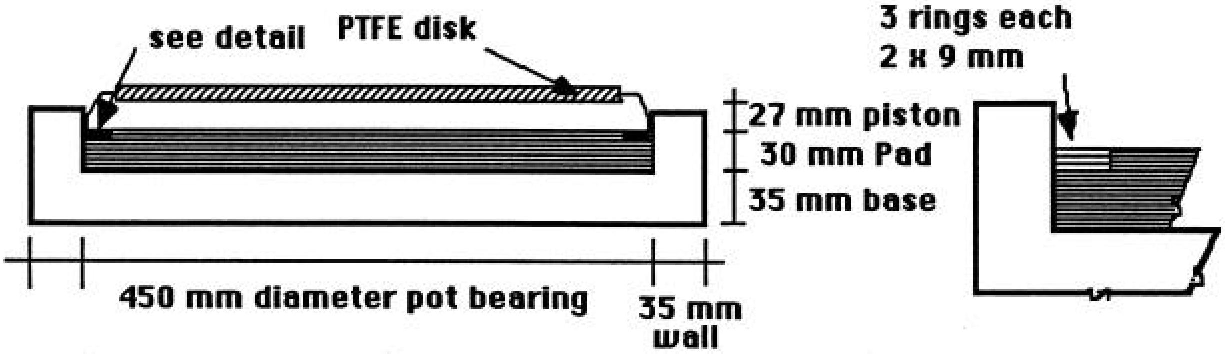


Figure II-2.8: Final Pot Bearing Design

SLIDING SURFACES

General

Lubricated bronze and PTFE (polytetrafluorethylene) sliding surfaces(14) are commonly used as components of bridge bearings. Sliding surfaces develop a frictional force that acts on the superstructure, substructure and the bearing. As a result, friction is an important design consideration. The friction force, *F*, can be estimated by

$$F = \mu N \qquad \text{(Eq. 2-18)}$$

where m is the coefficient of friction and N is the normal force on the sliding surface. While both lubricated bronze and PTFE are used for sliding surfaces, there are many differences in their behavior, and as a result they are discussed separately.

Lubricated Bronze Sliding Surfaces

Flat lubricated bronze sliding surfaces are used to accommodate very large translations. Cylindrical surfaces as shown in Figure II-2.9 (or spherical surfaces) may be used to accommodate rotation about one (or two) axes. The magnitude of the translation and rotation are limited only by the dimensions of the sliding surface. The displacement may be multidirectional unless guideways or geometric constraints (such as spherical or cylindrical geometry) are provided. The load capacity can be very large since it is limited only by the surface area. The mating surface should be significantly harder than the bronze surface and have a comparable surface finish. The mating surface is normally structural steel and is often supplied by the fabricator.

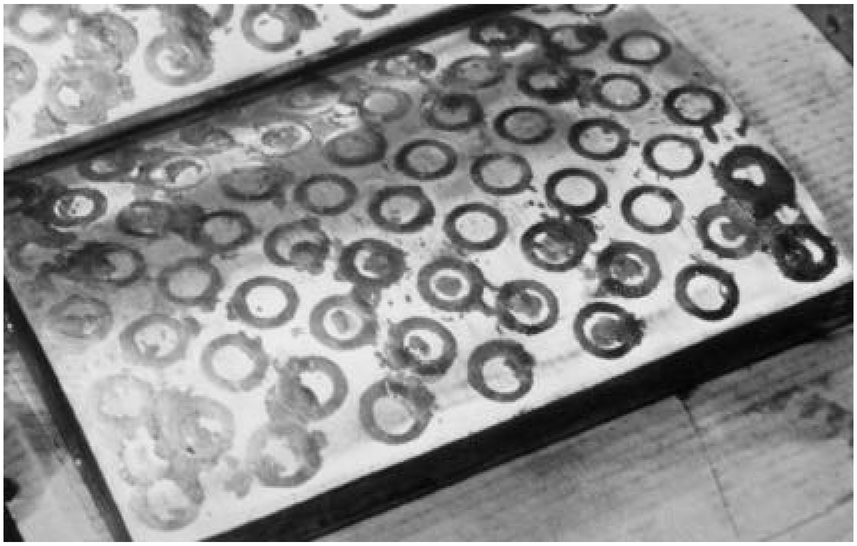


Figure II-2.9: Lubricated Bronze Sliding Cylindrical Surface

Lubricated bronze bearings use a regularly spaced pattern of recesses for lubricant as shown in Figure II-2.9. The recesses are usually in the order of 13 mm (½ in.) deep. Individual bearing manufacturers regard the recess pattern and the lubricant compound as proprietary, but the patterns used by most manufacturers are similar. The recesses are formed by casting the bronze in a mold and then machining to the proper geometry and surface finish. The bronze surface is cut to a fairly smooth but not highly polished finish. The lubricant is placed into the recesses under pressure and projects above the bronze approximately 1.5 mm (1⁄16 in.). The mating surface grips the lubricant in its asperities and spreads it over the bronze surface as movement occurs. The surface lubrication dissipates with time and movement, and eventually direct contact is developed between the bronze and the mating surface. After this, further movement causes the harder mating surface to abrade the bronze surface.

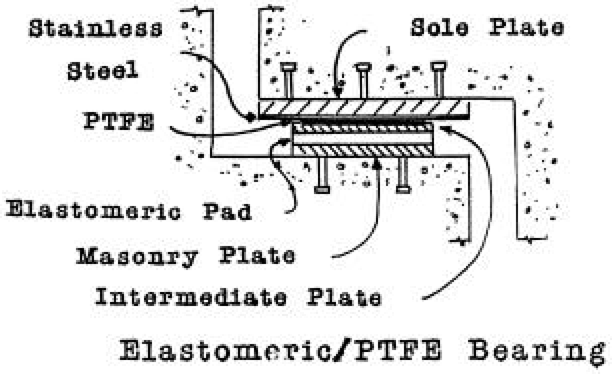
According to the AASHTO LRFD Specifications, the coefficient of friction is typically in the order of 0.07 under initial lubricated conditions, and it increases to approximately 0.1 after the bronze starts to erode. Coefficients of friction in the order of 0.4 must be expected for unlubricated bronze or for lubricated bronze bearings after the lubrication has completely dissipated.

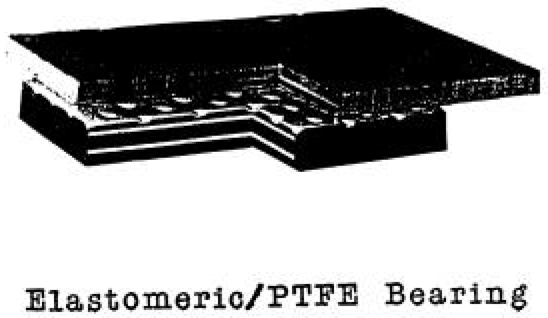
Bronze bearings are economical and do not require the high degree of quality control required for PTFE sliding surfaces. They do not require a highly polished mating surface, nor do they require tight geometric constraints since the material is thicker than typical PTFE and significant wear is expected. However, the frictional resistance may be considerably larger than that achievable with PTFE surfaces.

PTFE Sliding Surfaces

PTFE (polytetrafluorethylene) sliding surfaces as shown in Figure II-2.10 are also used to accommodate large translations and rotations when combined with spherical or cylindrical bearings. These surfaces have similarities with lubricated bronze sliding surfaces, but they may develop substantially smaller friction forces. PTFE sliding surfaces require greater care in design and greater quality control in construction and installation. PTFE is used with mating surfaces made of very smooth stainless steel (for all flat sliding surfaces and many curved surfaces) or anodized aluminum (for some spherical or cylindrical surfaces). The stainless steel surface must be larger than the PTFE surface so that the full movement can be achieved without exposing the PTFE and, whenever possible, the stainless steel is placed on top of the PTFE to prevent contamination with dust or dirt. PTFE sliding surfaces are used in combination with a wide range of other bearing systems.

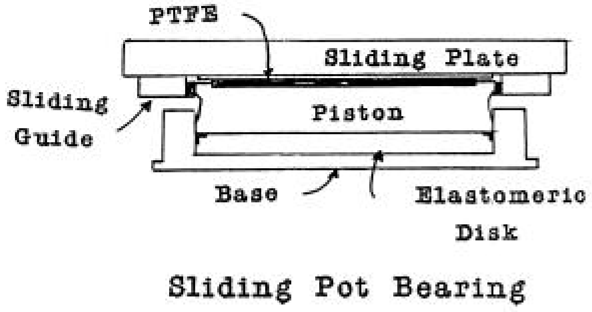
The low frictional resistance(15,17,18,19) of PTFE is its most important characteristic. The coefficient of friction decreases with increasing contact compressive stress between the PTFE and the mating surface. Friction is smaller for static or slowly applied translations than it is for moderate dynamic translations, and it is larger for the first cycle of movement than for later ones. At much higher sliding speeds such as are found in seismic isolation bearings, the friction is considerably higher. The coefficient of friction of PTFE increases at very low temperatures and if the mating surface is rough or contaminated with dust or dirt. The friction is significantly reduced if the interface is lubricated, and it is increased if the PTFE contains filler such as fiberglass. Dimpled PTFE (as shown in Figure II-2.11) is sometimes used to prevent the lubricant from seeping out under cyclic translations.

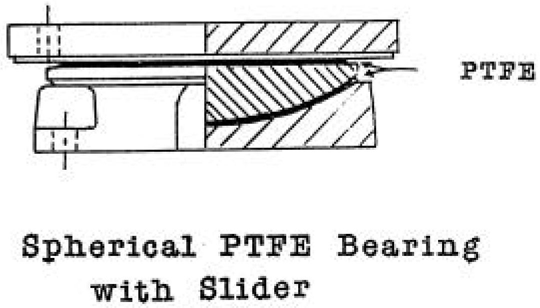




Elastomeric/PTFE Bearing

Elastomeric/PTFE Bearing





Sliding Pot Bearing

Spherical PTFE Bearing with Slider

Figure II-2.10: Typical PTFE Sliding Surfaces

PTFE may creep (or cold flow) laterally when subjected to high compressive stress, and shorten the life of the bearing. The reduction in PTFE thickness may also allow hard contact between metal components. Thus, while the compressive stress should be high to reduce friction, it must also be limited to control creep. PTFE is frequently recessed for one half its thickness to control creep and permit larger compressive stress. Filled PTFE is reinforced with fiberglass or carbon fibers, and it is sometimes used to resist the creep or cold flow.

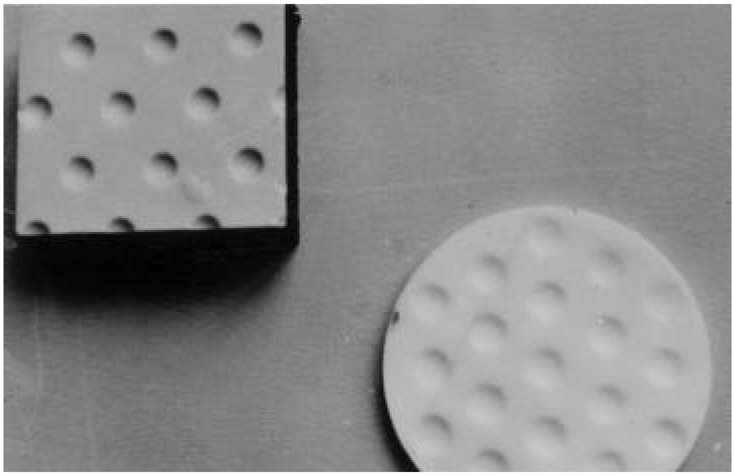


Figure II-2.11: Dimpled PTFE

PTFE is sometimes woven into a fabric or mat and used as a sliding surface in bridge bearings as shown in Figure II-2.12. The woven mat is often placed over a gridlike metal substrate to control creep without increasing the friction. In some cases, the woven mat is reinforced with strands of material that are woven and interlocked into the strands of PTFE, but the reinforcement should not come to the surface. It is recommended that the bridge engineer require certification tests for all types of PTFE to ensure that they meet the design requirements.

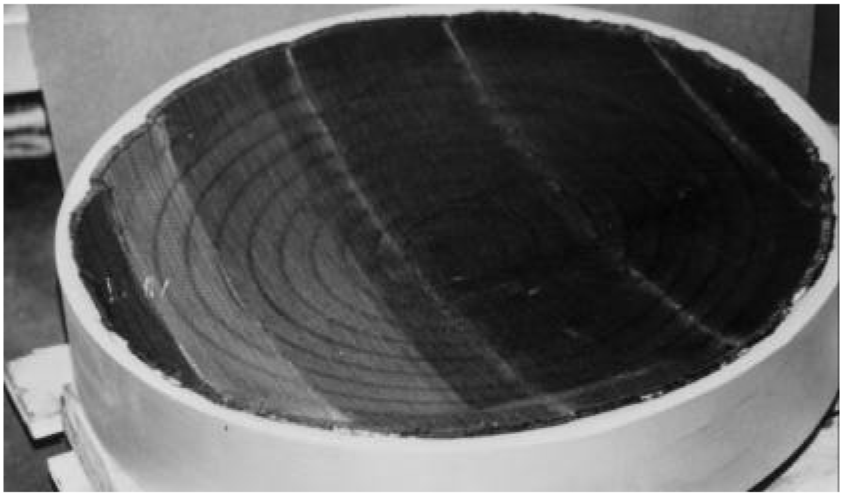


Figure II-2.12: Woven PTFE Sliding Surface

PTFE wears under service conditions and it may require replacement after a period of time. Low temperatures, fast sliding speeds, rough mating surfaces, lack of lubrication, and contamination of the sliding interface increase the wear rate. Relatively thin layers of from 1.5 to 3 mm (1⁄16 to ⅛ in.) are commonly used in the United States, but engineers in other countries often use thicker PTFE layers 4.5 to 6 mm (3⁄16 to ¼ in.) to account for recess thickness and accommodate the potential for wear.

Design Requirements

The coefficient of friction, m, is the most critical design requirement for sliding surfaces. The design coefficient of friction is taken as 0.1 for self-lubricating bronze components and up to 0.4 for other types of bronze sliding surfaces, unless better experimental data is available. The design coefficients of friction are smaller with PTFE sliding surfaces, but m varies widely for different types of PTFE. Table II-B provides the design coefficient of friction values to be used in the absence of better experimental data. Dimpled lubricated, unfilled sheet, woven and filled sheet PTFE are all recognized by the AASHTO LRFD Specification, but all types of PTFE must be made of virgin material.

Type of PTFE	Pressure (MPa)	3.5	7	14	³ 21
	Temperature (°C)	m	m	m	m
Dimpled Lubricated	20	0.04	0.03	0.025	0.02
	-10	0.06	0.045	0.04	0.03
	-45	0.10	0.075	0.06	0.05
Unfilled	20	0.08	0.07	0.05	0.03
	-10	0.20	0.18	0.13	0.10
	-45	0.20	0.18	0.13	0.10
Filled	20	0.24	0.17	0.09	0.06
	-10	0.44	0.32	0.25	0.20
	-45	0.65	0.55	0.45	0.35
Woven	20	0.08	0.07	0.06	0.045
	-10	0.20	0.18	0.13	0.10
	-45	0.20	0.18	0.13	0.10

Table II-B: Design Coefficients of Friction for PTFE

The mating surface for a flat PTFE sliding surface should be Type 304 stainless steel with a #8 mirror finish, and anodized aluminum may be used with some curved sliding surfaces. A slightly rougher #3 finish may be desirable with the woven material. The coefficient of friction data provided in Table II-B are design values that are based on laboratory experiments. They are larger than the average values recorded in the experiments in order to allow for the differences between laboratory and field conditions. Note that Table II-B is different than the table presently used in AASHTO LRFD Specifications, but it is likely(14) to be included in future Interim revisions to the Specifications.

The mating surface for lubricated bronze bearings should be steel, and it should be machined to have a surface finish of 3 micro meters (125 micro inches) rms or better.

The contact stress between the sliding and the mating surface must be checked as an average stress on the projected contact area for both lubricated bronze and PTFE. In addition, eccentricity and edge loading must also be considered for PTFE, where the contact stress at the edge is computed by taking into account the maximum moment and eccentricity using a linear distribution of stress across the PTFE. The average contact stress must be limited to 21 MPa (3 ksi) for most commonly used lubricated bronze. The stress limits for PTFE are controlled by creep and cold flow of PTFE as illustrated in Table II-C. This table is slightly different than the table presently used in AASHTO LRFD Specifications, but it is likely(14) to be included in future changes.

Material	Average Contact Stress (MPa)		Edge Contact Stress (MPa)	
	Dead Load	**All Loads**	**Dead Load**	**All Loads**
Unconfined PTFE:				
Unfilled sheets	14	20	18	25
Filled sheets—these figures are for maximum filler content	28	40	35	55
Confined sheet PTFE	30	40	35	55
Woven PTFE over a metallic substrate	30	40	35	55
Reinforced woven PTFE over a metallic substrate	35	50	40	65

Table II-C. Permissible Contact Stress for PTFE

Attachment and confinement of the PTFE are also design considerations. Sheet PTFE should preferably be confined in a recess in a rigid metal backing plate for one half its thickness. Recessed PTFE must normally be thicker, since half of its thickness is recessed into the steel backing. Woven PTFE is normally attached to a metallic substrate by mechanical interlocking which can resist a shear force no less than 0.10 times the applied compressive force. Sheet PTFE which is not confined must be bonded to a metal surface or an elastomeric layer with a Shore A Durometer hardness of at least 90.

Design Example

As a design example, consider a bearing with the following design loads and movements.

Dead Load	2400 kN (540 kips)
Live Load	1200 kN (270 kips)
Longitudinal translation	±200 mm (±8.0 in.)
Rotation	0.005 radians

The above bearing translations are in the longitudinal direction. The rotation is about the transverse axis. There are no design translations in the transverse direction; translation in this direction is restrained by the stiffness of the bearing. The steel girder has a bottom flange bearing width of 750 mm (30 in.).

Examination of Figure I-1 of the *Steel Bridge Bearing Selection Guide* contained in Part I of this report illustrates that a CDP or a steel reinforced elastomeric bearing with a PTFE sliding surface is a logical alternative. PTFE sliding surfaces are not able to accommodate rotation without some other bearing component, and CDP have limited rotational capacity. Therefore, the very small rotation combined with the relatively large compressive load suggest that the steel reinforced elastomeric bearing combined with a PTFE sliding surface is the most viable. The loads on this bearing are identical to those used for the steel reinforced elastomeric bearing example except that the rotation is now smaller. The steel reinforced elastomeric bearing was 475 mm (19 in.) long by 725 mm (29 in.) wide with a layer thickness of 15 mm (0.6 in.) and a shape factor of 9.57. This same elastomeric bearing will be able to support all of the loads based on calculations described earlier, if it is shown that the steel reinforced elastomeric bearing can tolerate the rotation and the horizontal translation is accommodated by a PTFE sliding surface.

The average compressive stress under maximum loading as determined previously is 10.45 MPa (1.5 ksi). The elastomeric bearing can tolerate the rotation if it satisfies

$$\sigma_T = 10.45\text{ MPa} \le 1.875(0.7)9.57\left(1 - 0.20\left(\frac{0.005}{n}\right)\left(\frac{475}{15}\right)^2\right)$$

if *n* is equal to 7, then the condition becomes

$$\sigma_T \le 1.875(0.7)9.57\left(1 - 0.20\left(\frac{0.005}{7}\right)\left(\frac{475}{15}\right)^2\right) = 10.76\text{ MPa}$$

Therefore, 7 layers will be adequate. The total elastomer thickness would be 105 mm (4.1 in.), and the shear deformation limit indicates that this elastomeric bearing could tolerate a maximum translation of 52 mm (2.0 in.). Thus, a PTFE slider must be used to accommodate at least 148 mm (6.0 in.) of translation and preferably the entire 200 mm (8 in.).

The PTFE could be attached in several ways. Two of these options are illustrated in Figure II-2.13. A steel plate could be vulcanized to the top of the steel reinforced elastomeric bearing, and the PTFE could be recessed into the plate. Under these conditions, the actual contact area for the PTFE would be smaller than the plan area of the steel reinforced elastomeric bearing and the coefficient of friction achieved with the PTFE would be smaller than if the PTFE covered the entire area. It will be necessary to ensure that the top plate is stiff and strong enough to accommodate the load transfer. As an alternative, the PTFE could be directly bonded to the top cover layer of elastomeric bearing. The top cover layer of the elastomer must be very hard (90 Durometer) for this arrangement. This second option is likely to produce a somewhat more simple and economical bearing and attachment detail, but it will result in slightly larger coefficient of friction and slightly inferior overall behavior.

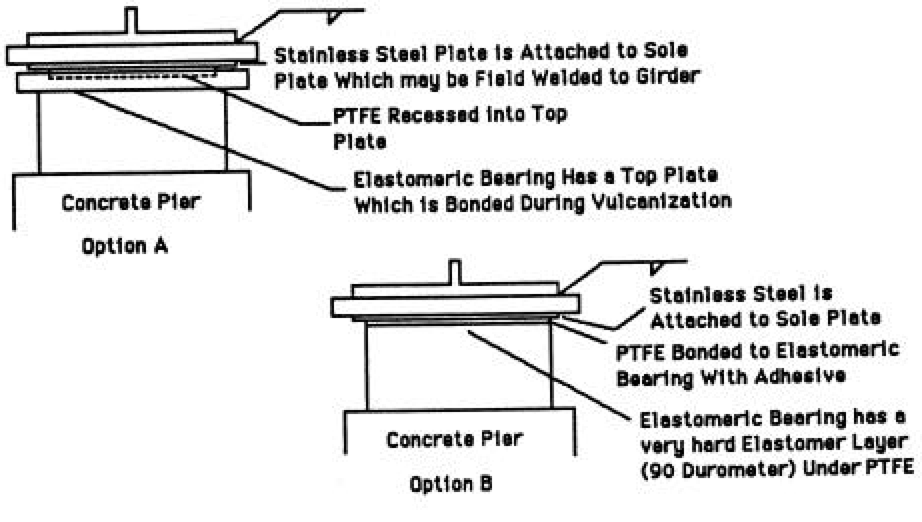


Figure II-2.13: Two Options for the Attachment of A PTFE Sliding Surface to a Steel Reinforced Elastomeric Bearing

The second option is selected here and it is to be used with flat, dry sheet unfilled PTFE. By interpolation of the data in Table II-B, this application achieves a coefficient of friction of approximately 0.06 at room temperature. Larger friction must be expected at very low temperature. The average contact stress under full loading is 10.45 MPa (1.5 ksi) and under dead loading 6.97 MPa (1.0 ksi), and Table II-C shows that these are well below the limits for unconfined PTFE for control of creep and cold flow. The maximum force transferred by the sliding surface at room temperature should be in the order of

$$F = 0.06\ (3600) = 216\ \text{kN}$$

If this force is unacceptable to the structure or substructure, another type of PTFE could be employed or the alternative attachment procedure could be used. The edge contact stress must also be checked. It should be recognized that part of the movement will be taken up by deformation of the steel reinforced elastomeric bearing, and part by sliding action. The deflection of the elastomeric bearing can be estimated as

$$\Delta_s = \frac{F \text{ x } h_{rt}}{G \text{ x } W \text{ x } L} = \frac{216\ 000 \text{ x } 105}{0.7 \text{ x } 725 \text{ x } 475} = 94 \text{ mm}$$

This 94 mm (3.7 in.) deflection exceeds the allowable shear deformation of the steel reinforced elastomeric bearing acting alone, and is cause for rejecting the proposed system. The force and the elastomer deformation may be reduced by using a PTFE with a lower coefficient of friction. A dimpled lubricated PTFE will have a coefficient of friction less than 0.03. This will produce a maximum friction force of 108 kN., and the elastomeric bearing deformation will be below acceptable limits. As an alternative, a stiffer elastomer could also be employed. It can be shown that, in order to satisfy deflection limits of Eq. 2-5b

$$\mu \le \frac{0.5\, G}{\sigma_T}$$

The maximum resisting moment about the transverse axis, M_x, of the elastomeric bearing can be estimated at the maximum service rotation, θ_x, by the equation

$$M_X = (0.5\ E_C I)\theta_X/h_{rt} \qquad \text{(Eq. 2-19)}$$

where I is the moment of inertia of plan shape of bearing, and E_c is the effective modulus of the elastomeric bearing in compression. The values of I, θ_x and h_{rt} are reasonably clear. The value of E_c can be estimated by the equation(8).

$$\begin{aligned} E_c &= 3G\left(1 + 1.3\ S^2\right) = 3 \text{ x } 0.91 \text{ x } \left(1 + 1.3(9.57)^2\right) \\ &= 328 \text{ MPa} \end{aligned}$$

It should be noted the E_c is sometimes conservatively approximated as $6GS^2$ in these stiffness calculations. Thus,

$$\begin{aligned} M_x &= (0.5\ E_c I)\theta_x/h_{rt} \\ &= 0.5 \text{ x } 328 \text{ x } (1/12) \text{ x } 725(475)^3 \frac{0.005}{105} \\ &= 50.57 \text{ x } 10^6 \text{ N-mm} \end{aligned}$$

The maximum contact stress on the edge is then

$$\sigma = 10.45 + \left(\frac{50.57 \text{ x } 10^6}{(1/6) \text{ x } 725(475)^2} \right) = 12.3 \text{ MPa}$$

This is well below the allowable stress due to edge loading listed in Table II-C. Similar calculations would be used to account for the moment about any other axis.

The mating surface should be Type 304 stainless steel with a #8 mirror finish or better. The stainless steel should be long enough that the full 200 mm (8 in.) translation can be accommodated in each direction without exposing the PTFE, although a significant part of the total translation will be accomplished by elastomer deformation. In addition there should be adequate freeboard, say 50 mm (2 in.) at each end, to cover uncertainties. Thus, the total length of the stainless steel mating surface should be 975 mm (39 in.), and the stainless steel should be centered over the initial zero movement position of the bearing.

Summary

Lubricated bronze and PTFE sliding surfaces can support a wide range of compressive loads and accommodate large translations if they are properly designed. Movements in excess 1000 mm (39 in.) are possible. These bearings can accommodate rotation only if machined into a curved (spherical or cylindrical) surface or if combined with another bearing component such as a steel reinforced elastomeric bearing or pot bearing. A lubricated bronze sliding surface is a relatively robust system and is less sensitive to abnormalities than a PTFE sliding surface, but it induces larger forces into the structure and substructure. Less care is required in the design and manufacture of lubricated bronze sliding surfaces than in comparable PTFE sliding surfaces, but they are less versatile in achieving many design objectives. A PTFE sliding surface is frequently used in conjunction with other bearing systems. For example, PTFE is often used as a sliding surface in conjunction with steel reinforced elastomeric bearings as shown in Figure II-2.10 to accommodate large translations. PTFE sliding surfaces may also be used on top of a pot bearing to allow lateral displacement.

BEARINGS WITH CURVED SLIDING SURFACES

General Behavior

Bearings with curved sliding surfaces include spherical and cylindrical bearings, and they are special cases of lubricated bronze or PTFE sliding surfaces. Figure II-2.9 illustrates a cylindrical bearing of lubricated bronze, and Figure II-2.12 shows a spherical bearing with a woven PTFE sliding surface. They are used primarily for sustaining large rotations about one or more axes. The rotation occurs about the center of radius of the curved surface, and the maximum rotation is limited by the geometry and clearances of the bearing.

Spherical and cylindrical bearings may develop horizontal resistance by virtue of the geometry. This lateral load capacity is limited and large lateral loads require an external restraining system. Spherical and cylindrical bearings rotate about their center of radius, and they are fixed against translation. The center of rotation of the bearing and the neutral axis of the beam seldom coincide, and this eccentricity introduces additional translation and girder end moment which must be considered in the design. An additional flat sliding surface as shown in Figure II-2.14 must be added if the bearing is to accommodate displacements or to reduce the girder end moment. The moment, *M*, on the end of the girder can be estimated by

$$M = \mu N\ d \qquad \text{(Eq. 2-20)}$$

where *m* is the coefficient of friction, *N* is the normal load on the projected area of the bearing, and the moment arm, *d*, is the distance between the center of radius of the bearing and the center of rotation of the girder. This additional moment must be considered in the design of the bearings, the superstructure, and the substructure. However, the end moment cannot be used to develop continuity or restraint for the piers or the girders, since it will change with time.

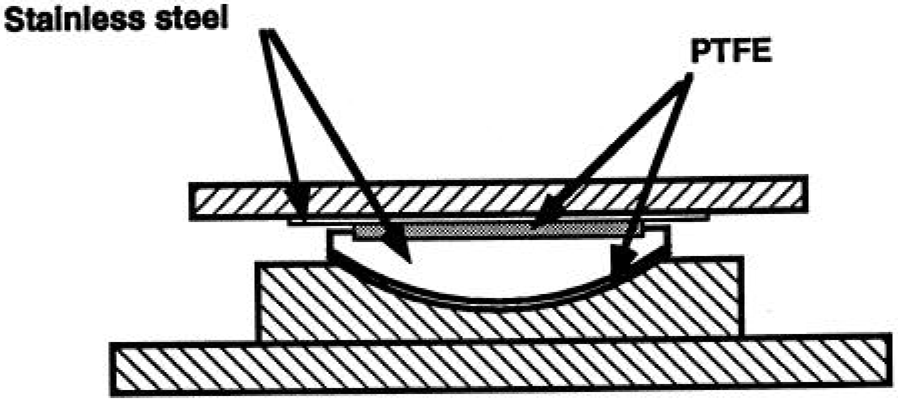


Figure II-2.14: Flat Sliding Surface Used in Conjunction with a Curved Sliding Surface

The inside and outside radii of spherical and cylindrical bearings must be accurately controlled and machined to assure good performance. When using PTFE, a small tolerance between the two radii and a smooth surface finish is required to prevent wear, creep or cold flow damage due to nonuniform contact and to ensure a low coefficient of friction. A realistic estimate of the thickness of the PTFE under load is also necessary. Tolerances for lubricated bronze bearings are less critical because some wear of the bronze is expected. However, the tolerances must be tight enough to prevent fracture of the bronze due to point or line contact on the steel mating surface.

Design Requirements

The design of bearings with curved sliding surfaces uses many of the parameters required to design flat sliding surfaces. The coefficient of friction, *m*, and allowable contact stresses are the same. The moment transferred by the curved surface about its center of rotation is given by the friction force multiplied by the lever arm. For curved sliding bearings with a companion flat sliding surface

Error! AutoText entry not defined. $= \mu\ P\ R$ (Eq. 2-21a)

and for curved sliding bearings without a companion flat sliding surface

$$M_u = 2\ \mu\ P\ R \qquad \text{(Eq. 2-21b)}$$

The allowable contact stresses are applied over the projected area of the curved surface, so that for cylindrical bearings

$$\sigma_T = \frac{P}{B\,W} \qquad \text{(Eq. 2-22a)}$$

and for spherical bearings

$$\sigma_T = \frac{4\,P}{\pi\,D^2} \qquad \text{(Eq. 2-22b)}$$

where s_T is the maximum total stress due to maximum loading on the projected area, D is the diameter of the projection of the loaded surface, W is the length of the cylinder and B is the plan dimension of the cylindrical surface perpendicular to its axis.

The lateral load capacity inherent in a curved bearing without an added restraint can be determined from

$$H_u \leq 2\;R\;W\left(\sigma_{PTFE}\right)\sin\left(\phi - \beta - \theta_u\right)\,\sin\beta \qquad \text{(Eq. 2-23a)}$$

for a cylindrical sliding surface where

$$\beta = \tan^{-1}\left(\frac{H_u}{P_D}\right) \qquad \text{(Eq. 2-23b)}$$

and

$$\phi = \sin^{-1}\left(\frac{D}{2\,R}\right) \qquad \text{(Eq. 2-23c)}$$

where D is the projected length of the sliding surface perpendicular to the rotation axis, R is the radius of the curved sliding surface, H_u is the maximum factored horizontal load, P_D is the factored compressive dead load, b is the resultant angle of the applied loads, f is the corresponding subtended angle of the curved sliding surface, s_{PTFE} is the maximum average contact stress permitted on the PTFE for all loads from Table II-C and W is the length of the cylindrical sliding surface. For spherical bearings

$$H_u \leq \pi\,R^2\left(\sigma_{PTFE}\right)\sin^2\left(\phi - \beta - \theta_u\right)\,\sin\beta \qquad \text{(Eq. 2-23d)}$$

It should be noted that these equations are different than those presently appearing the AASHTO LRFD Specifications, but those equations are in error and will be corrected in future Interims to the Specifications.

Summary

Cylindrical and spherical bearings tend to be relatively costly bearings which become a practical choice primarily when the gravity load or the required rotation is large. They are able to support loads up to several thousand tonnes and may accommodate rotations of more than 5 degrees if the bearing is properly designed and constructed. They are likely to be more expensive than a pot bearing, but they can be designed to tolerate larger rotations than pot bearings. As with pot bearings, translational displacements require the addition of a flat sliding surface.

Section 3
Construction, Installation and Attachment Details

INTRODUCTION

Steel bridges contain special features that influence the selection, design, and installation of suitable bearing systems and attachment details. The influence of these features is discussed in this section.

SELECTION AND DESIGN ISSUES

Lateral Forces and Uplift

Bearings in steel bridges may be subjected to lateral forces or uplift. However, bridges in which these load effects have a significant influence on the bearing selection and design are the exception rather than the rule. In past years, steel bridge design specifications required that steel bridges be anchored against uplift in all cases, but the AASHTO LRFD Specifications do not contain this arbitrary requirement. Thus the bearings for the majority of steel bridges can be simple and economical.

Lateral forces may arise from wind, traffic, seismic or hydraulic loads. For stream crossings, hold downs, such as anchor bolts, are recommended if the elevation of the bottom of the superstructure is within 600 mm (2 ft) of the design flood elevation. Earthquake forces may be mitigated by the use of seismic isolation bearings, which are beyond the scope of this report. These lateral forces must be accommodated. However the engineer should determine the true magnitudes of the loads and the combinations that can plausibly occur and base the design on them, rather than on empirical rules. Lateral forces are also induced by the resistance to imposed displacements caused, for example, by temperature change.

The potential for uplift under gravity load exists in bridges that are continuous with a high live load to dead load ratio, very uneven span lengths, curved, or heavily skewed. In many cases neither uplift nor lateral loading will occur, in which case the bearing attachment details will be simple and economical.

A variety of attachment details are possible. They generally fall into two categories: those suitable for flexible systems with no mechanical moving parts such as steel reinforced elastomeric bearings, and those suitable for relatively stiff systems such as pot bearings. In all cases and in all potential load directions the engineer is faced with the choice of allowing a displacement to occur or inducing a force if the displacement is restrained. The design will influence the bearing attachment details. Generally, vertical displacements are resisted, rotations are allowed to occur as freely as possible and horizontal displacements may be either accommodated or resisted. The attachment details should be consistent with the behavior of the bridge.

Small Lateral Force and No Uplift

The majority of bearings fall into this category, so it is important. Lateral forces are small in bearings that are equipped with a PTFE slider, or in a flexible bearing adjacent to some fixed point in the bridge. Attachment details for flexible (e.g. elastomeric) and stiff systems are discussed separately. In most cases the details are economical because the requirements are modest.

Minimum Attachment Details for Flexible Bearings

An elastomeric bearing pad or steel reinforced elastomeric bearing may simply be placed under the girder with no positive attachment, as shown in Figure II-3.1. It is held in place by friction and its main function is to accommodate rotations. The detail is the most economical possible.

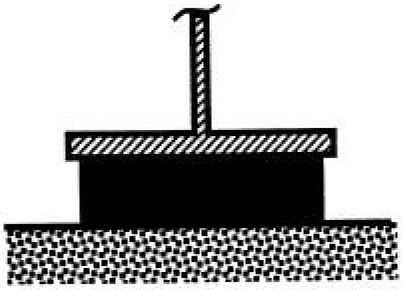


Figure II-3.1: Attachment of an Elastomeric Bearing with Small Lateral Load and No Uplift

The possibility of slip should be checked using the load combination with the maximum possible concurrent ratio of horizontal load/vertical load. Elastomers typically exhibit less friction against steel than against concrete, especially if the latter has been intentionally left rough, so the steel-elastomer interface is the likely location for potential slip. The friction coefficient between elastomer and steel varies with pressure and surface condition, but a value of 0.2 is usually attainable and is recommended in the AASHTO LRFD Specifications(10). This friction value will be high enough to prevent slip, provided that the maximum horizontal load does not occur in conjunction with an exceptionally light vertical load. This follows from the fact that the bearing's shear deformation is limited by the AASHTO LRFD Specifications to 0.5 h_{rt}, and small shear deformations imply small lateral loads.

It should be noted that a recent study(7) has shown that some elastomer compounds exhibit very low friction and that bearings made from them have slipped out of place. The effect was found to occur only with bearings made from certain natural rubber compounds which contain large quantities of anti-ozonant waxes. Furthermore, some of the bearings in question were set on very smooth concrete surfaces.

Minimum Attachment Details for HLMR Bearings

HLMR bearings, such as pot or spherical bearings, theoretically need no attachment for service load since, under the specified conditions of small lateral load and no uplift, friction will be adequate to prevent movement. However, they contain mechanical moving parts, and the consequences of these components becoming misaligned by unexpected bearing movements are grave. Furthermore, small superstructure movements could lead to large forces in stiff bearing systems. Therefore HLMR bearings are required to be bolted to the support.

Uplift Alone

Potential uplift displacements may either be permitted to occur or they may be restrained, in which case a force is developed in the restraining system. Mechanical bearings are almost always restrained against uplift to prevent the bearing damage that might occur if components become misaligned. In elastomeric systems, uplift displacements may be acceptable provided that expansion joint and girder misalignment cannot occur and that the impact loading caused by renewed contact with the piercap is acceptable. Elastomeric bearings are likely to return to their zero strain position during uplift, and therefore the effective installation temperature of the bearing will be the temperature of the bridge when the superstructure and bearing return to contact. This change in effective installation temperature is not a major concern with flexible bearings, since elastomers are quite forgiving of overly large deformations that are infrequently applied. Only in extreme cases, are elastomeric bearings likely to required repositioning after temporary uplift.

Uplift Attachment Details for Flexible Bearings

Elastomeric bearings may be restrained by a simple bolted detail, as shown in Figure II-3.2. Two bolts placed at the axis of rotation provide the least restraint to rotation while preventing the uplift. A sole plate (shown in the Figure) is often used to avoid drilling the girder flange. It also allows some tolerance in the placement of the girder on the sole plate, if the sole plate can be field welded to the girder. (The sole plate is wider than the girder flange so this weld can be made downhand). The erector may also prefer to shop weld this connection. Possible methods are discussed under "Erection Issues" at the end of this section.

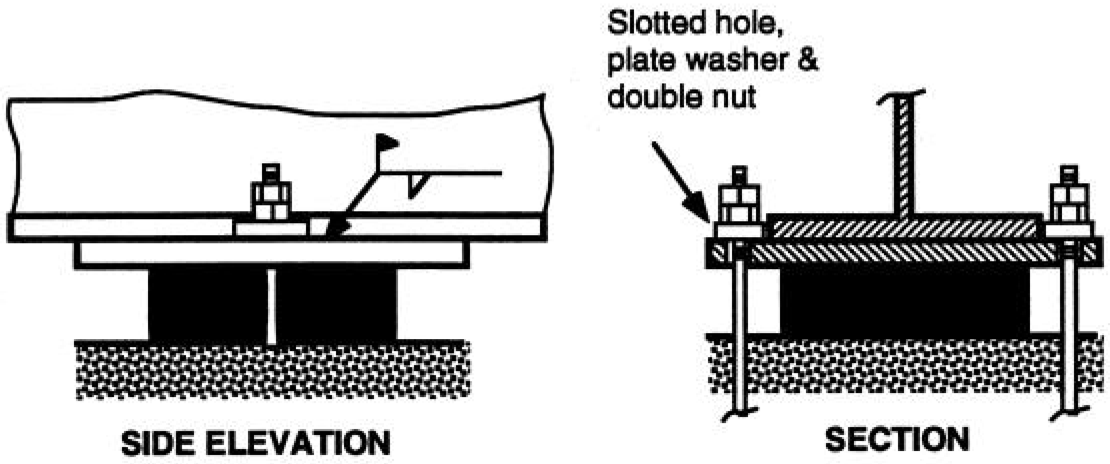


Figure II-3.2: Elastomeric Bearing with Uplift Restraint

Uplift Attachment Details for HLMR Bearings

Uplift restraint of HLMR bearings poses difficult problems. The restraining system must be sufficiently rigid to prevent vertical movement, but it must contain sufficient articulation to allow relative rotation, and possibly relative horizontal movement, of the components. Individual manufacturers have proposed their own hold-down details. Most add significantly to the price of the bearing.

Lateral Load Alone

Some degree of lateral load on a bearing is common. The engineer must decide how many of the bearings are to resist such loads. In stiff bearing systems, such as pot or spherical bearings, it is often best to carry the lateral loads on a small number of bearings. This avoids not only the potential additional loads from restraint of transverse temperature expansion but also the uneven distribution of applied lateral load that can occur with stiff bearing systems. If this philosophy causes the lateral load on a single bearing to be too large, particularly compared with its vertical load, a separate guide system may be used to resist lateral load, as illustrated in Figure II-3.3. The advantage of this approach is that it separates the functions of carrying the lateral and vertical loads and permits a wider variety of choices for the individual components.

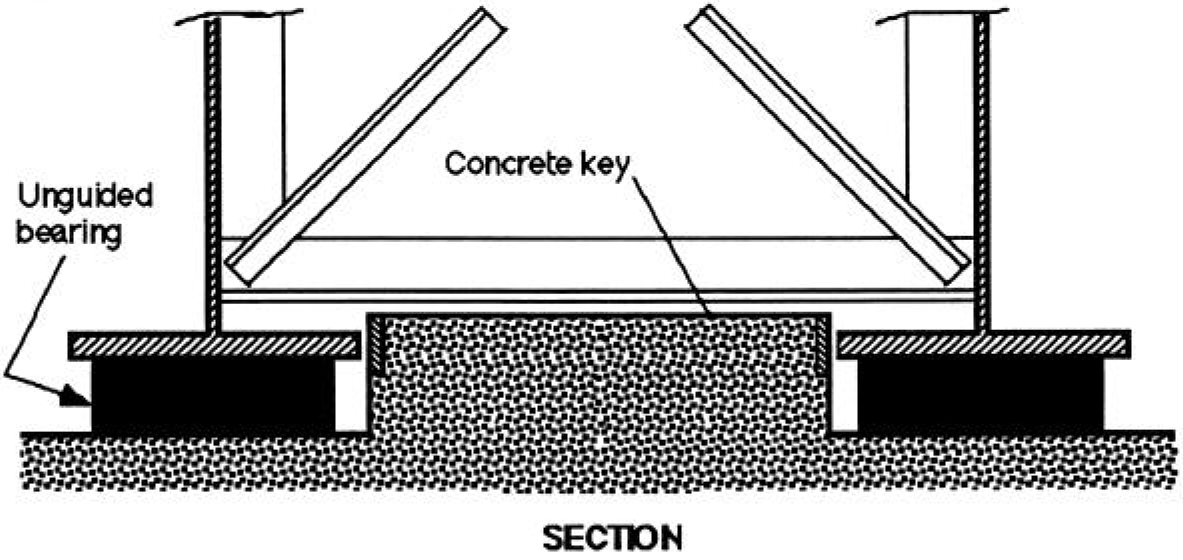


Figure II-3.3: Separate Guide System for Resisting Lateral Loads

With flexible bearing systems, the deformation needed to accommodate the transverse temperature expansion is small compared with the overall bridge movements, so all the bearings can be used for resisting lateral loads.

Lateral Load Attachment Details for Flexible Bearings

Applied lateral loads, such as from wind forces, should be distinguished from applied longitudinal displacements, such as caused by thermal expansion. In the former case the bearing should be stiff enough to prevent excessive movement, or an independent horizontal force resisting system should be used. In the case of expansion, the displacement is a given so the bearing should be flexible in order to limit the forces between the substructure and superstructure.

The simplest arrangement for resisting applied loads is to use a relatively low-profile elastomeric bearing with no external restraint as shown in Figure II-3.1. The thickness and plan area are selected to furnish the required stiffness, but the bearing must still be thick enough to accommodate the required rotation. The possibility of slipping should also be checked. If the lateral loads are caused by wind or traffic forces, they are likely to be small compared to the dead weight of the bridge, in which case this detail is viable.

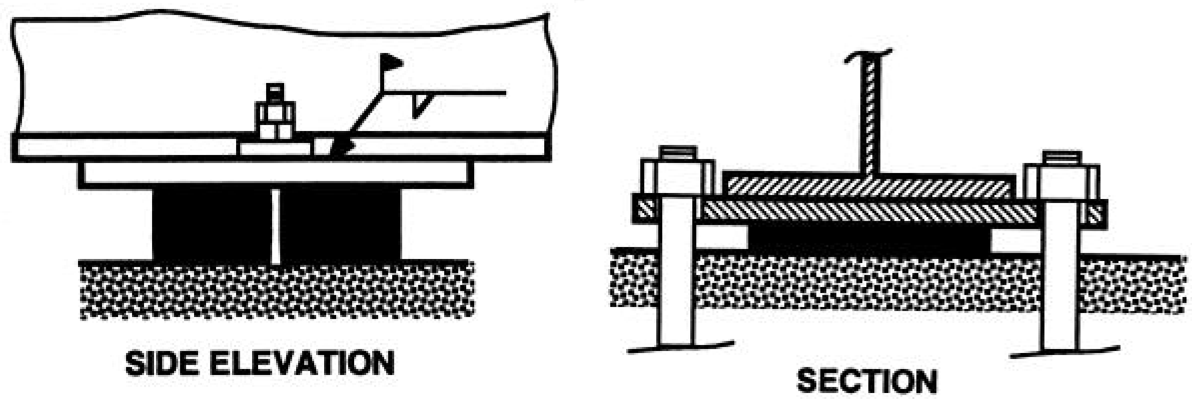


Figure II-3.4: Bolt Detail for Resisting Lateral Loads

If the lateral force is too large for this simple detail, bolts may be used, as shown in Figure II-3.4. The bolts are loaded in bending and shear, so they should be designed properly. Such a detail works if motion in both horizontal directions is to be prevented. If the bearing is to be free to move in one direction and fixed in the other, slotted holes may theoretically be used. However in practice they risk freezing up from accumulation of dirt, corrosion and layers of paint. In this case some separate guide system, such as the one shown in Figure II-3.5, may be used.

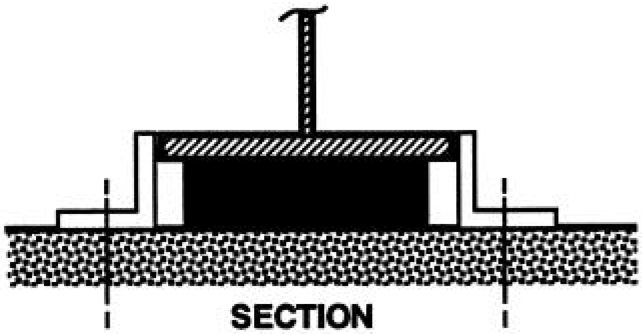


Figure II-3.5: Guide Detail for Resisting Lateral Loads

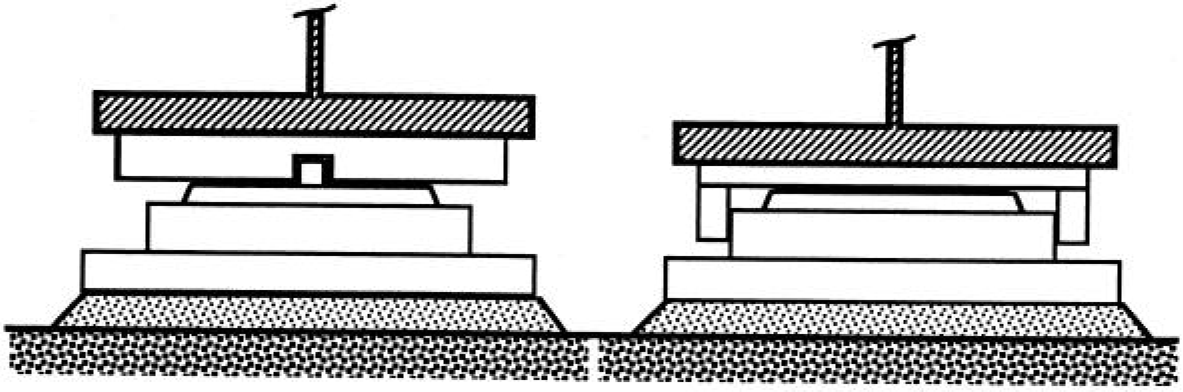
Lateral Load Attachment Details for HLMR Bearings

In stiffer systems such as HLMR bearings, the ability to permit movement or resist load depends on the bearing type.

Among pot bearings, the simplest type is fixed in all directions and permits only rotation. A pot bearing that is free to slide in all directions can be made by adding a PTFE slider, but resisting load in one direction while permitting movement in the other requires both a slider and a guide system. This is therefore the most complex and expensive bearing system.

The same ranking also holds for spherical bearings. However use of spherical bearings should be considered carefully because of their geometry. A nominally fixed bearing uses only a spherical sliding surface, but it is not truly fixed because it rotates about the center of the sphere. This point is usually not at the location of the neutral axis of the girder, so some longitudinal movement must be allowed to occur or else a longitudinal force will be introduced. Use of a sliding bearing at the other end of the bridge allows this movement to occur.

The geometry of the guide system may exert a considerable influence on the forces carried by individual bearing components. For example, in a pot bearing, two external guides or one central 'internal' guide may be used, as illustrated in Figure II-3.6. If the guides bear against the piston (Figure II-3.6a) the lateral forces must then be transmitted from the piston to the pot wall by contact stresses. This arrangement introduces the possibility of heavy wear on the piston rim and so is suitable only if the horizontal loads are low, say less than about 5% of the vertical load. Larger horizontal loads should be carried by external guides that bear against the outside of the pot wall (Figure II-3.6b), but then enough clearance must be left to permit rotation of the bearing. For this arrangement, the outside of the pot wall must also be straight, rather than circular, in plan so a slider can be mounted there. Binding of the guides during rotation will be minimized if the center of the guide is at the same elevation as the center of rotation of the bearing. This may be taken as the top surface of the elastomeric pad in a pot bearing.



a) Internal guide b) External guide

Figure II-3.6: Guides for HLMR Bearing

The guides should be designed according to principles of structural mechanics. A horizontal force on a guide typically induces both shear and bending (or overturning) moments. Since guidebars are usually bolted to the top plate, the connection must be designed for the moment as well as the shear. If the bolts are fitted into drilled and tapped holes in the top plate, the plate thickness must be adequate to develop the full strength of the bolt within the thread length available.

Clearances and tolerances are important in the design of guides. Clearance refers to the distance intentionally placed between two components to permit relative movement. Tolerances are the unintentional but inevitable variations from nominal values in component dimensions and locations. They arise from both fabrication and erection. The net clearance is therefore the nominal clearance plus or minus the tolerances on the adjacent parts.

A net clearance that is too small may restrict movement, while one that is too large may cause any lateral loads to be carried by a single bearing, because the guides of the others are not in contact. All guides at a bent must be installed parallel to each other within a small enough angular tolerance to prevent binding of the system. Furthermore, the direction selected for free motion at each bent should be consistent with the that of the movements of the total bridge system, especially in curved or skewed bridges. The use of unguided bearings, possibly in combination with an independent guide system as illustrated in Figure II-3.3, should be considered, since this is frequently the most reliable method of developing large restraint forces or directional guidance for the bearings.

It is clear that guides and restraints should be used only if a clearly identified need for them exists. They have the potential for inducing unexpected and unwanted forces into a structure and the certainty of adding cost to the bridge.

Combined Uplift and Lateral Load

Designing for combined uplift and lateral load is difficult. In pot and spherical bearings, providing restraint against uplift at the same time as allowing free rotation poses problems, and designs for these bearing types therefore tend to be expensive. If the rotation occurs about only one axis and the uplift forces are large, a traditional pin bearing might prove cost-effective. However, many bridges have some degree of skew, which induces rotation about more than one axis and renders this bearing type unsuitable. Furthermore, such bearings have a high profile and are more susceptible than are lower-profile bearings to overturning under seismic loads. Elastomeric bearings provide feasible and economical solutions under many conditions.

The detail shown in Figure II-3.4 for resisting lateral load will also resist uplift forces. It is simple to fabricate and install. The bolts should be installed at the axis of rotation so that they do not develop tension when the bearing rocks.

DESIGN FOR REPLACEMENT

Bearings are subjected to severe service conditions, which may lead to service lives that are shorter than for other bridge components. This is particularly true for systems such as mechanical bearings that require maintenance. Therefore the need for replacement of all or part of the bearing system must be considered in the design. It should be emphasized that designing for potential replacement should not, and normally does not, require the addition of expensive details.

The most important aspect of design for replacement is the provision of jacking locations at every girder. These points must be indicated on the plans. Modern flat jacks make this lifting quite easy because they have a low profile, do not require a large vertical movement, and can lift heavy loads. A typical flat jack and lift detail is shown in Figure II-3.7 There must be space on the piercap and a bearing point on the superstructure to jack up the girder. An alternative to the detail shown in Figure II-3.7 is to use hydraulic jacks under a temporary spreader beam that lifts adjacent girder top flanges simultaneously. If only some of the girders are to be lifted at any one time, the jacking force on each girder may be larger than the nominal load on an individual bearing because the lifting process may attract some load from the adjacent bearings. This process will also induce stress in some of the cross members or diaphragms, so using linked jacks to lift all the girders together should be considered.

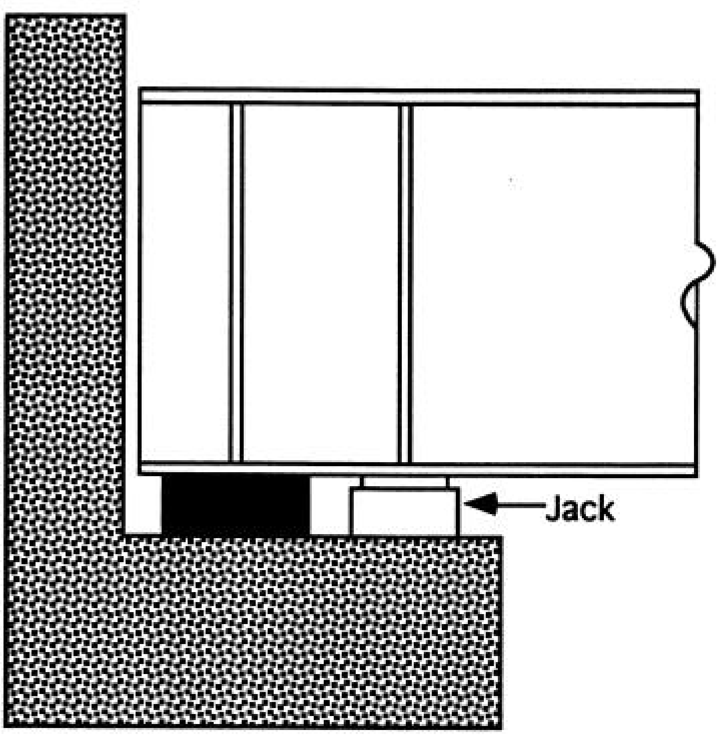
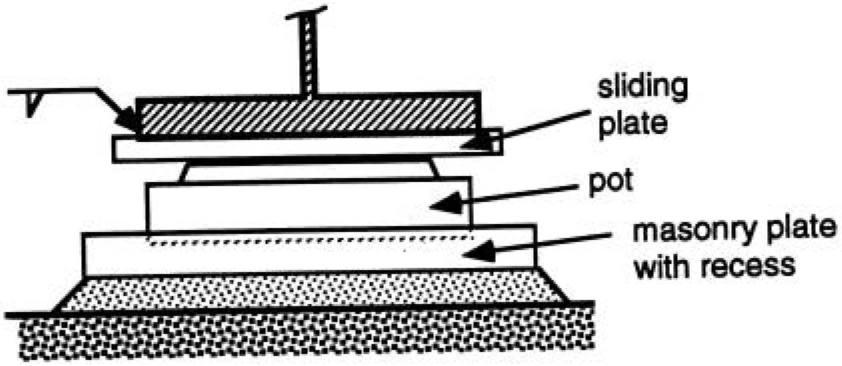
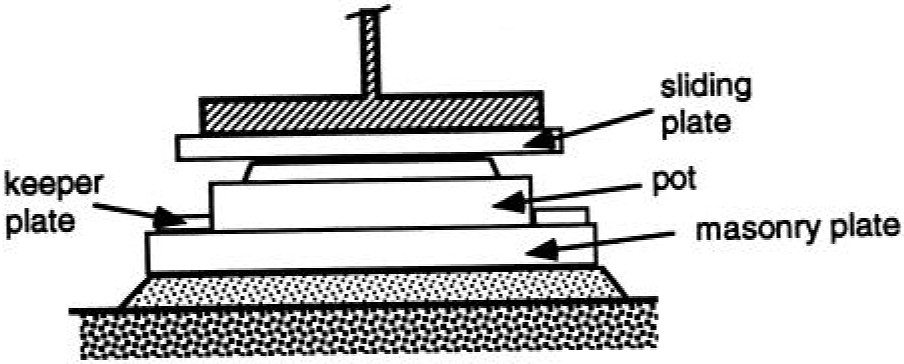


Figure II-3.7: Typical Jacking Point and Lift Details

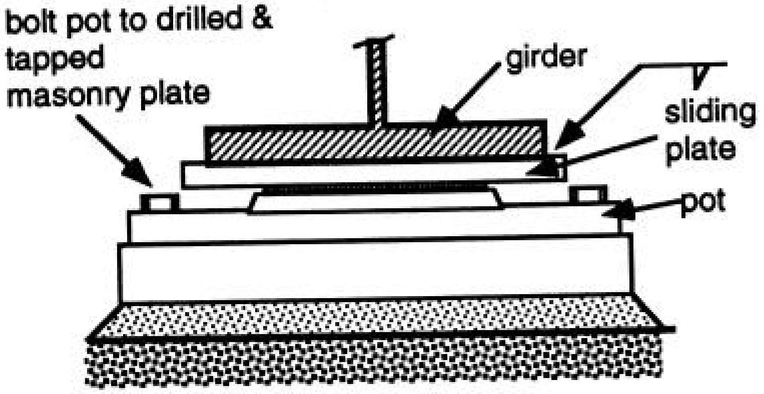
A second issue which affects the cost and ease of replacement is the attachment of the bearing and the space available for access. If the bearing is unattached, it can easily be pulled from its position when the load is removed. Any anchor bolts should be placed so that they do not impede the removal of the bearing. Welds can be cut but doing so requires oxyacetylene equipment that may be cumbersome in the space available. Grinding may also be needed in order to produce a flat enough surface for installing the new bearing. Careful monitoring of the girder centerlines is necessary regardless of the method of bearing removal and attachment. In the case of pot bearings, only some of the components, such as the seals and pad, may need replacing. Installing the new components may then be possible without cutting any welds or removing the bearing, provided the required lift height can be achieved.



a) Recess in masonry plate



b) Keeper plates bolted or welded to masonry plate.



c) Pot bolted directly to masonry plate

Figure II-3.8: Attachment Details to Facilitate Replacement

Last, the bearing and its attachments should also be designed so that the required lift height is minimized. For this reason the use of a masonry plate under a pot or spherical bearing is desirable, even if it is not needed for load spreading. A bearing that is connected directly to the piercap by anchor bolts without a masonry plate must be lifted over the bolts after the nuts have been removed. This arrangement significantly increases the required lift height and complicates the replacement. Three possible details that minimize the lift height by using masonry plates are illustrated in Figure II-3.8. A shallow recess may retain the bearing (Figure II-3.8a), a flat masonry plate may be used with bolted or welded keeper plates (Figure II-3.8b), or the bottom plate of the bearing may be bolted directly into holes that are drilled and tapped into the masonry plate (Figure II-3.8c). The height needed for removing and installing bolts should be accounted for.

BEARING ROTATIONS DURING CONSTRUCTION

Steel girders often have substantial camber before installation and this results in a large initial rotation on the bridge bearing while the compressive load on it is very small. The steel girder is quite flexible until the concrete deck develops composite action, and significant girder deflection and bearing rotation occur during placement of the deck. The bearings must clearly be designed so that they can tolerate these rotations, but the forces that are applied at the same time are usually much smaller than the maximum loads.

In elastomeric bearings, the load that can be carried is related to the rotation(10). However the combination of erection forces and rotations is unlikely to cause problems because it is applied only once during the life of the bridge and damage to elastomeric bearings generally arises from the accumulation of many cycles of stress. The elastomeric bearing design provisions in the AASHTO LRFD Specifications(10) were developed for repeated cycles of service load, so they are not applicable to a single application of a construction load combination.

In bearings such as pots or sphericals, the rotation capacity is limited by metal-to-metal contact and is not related to the accompanying load. These bearings must therefore be designed to accommodate the full rotation.

CONSTRUCTION ISSUES

Erection Methods

Steel bridge superstructures are fabricated in a shop and so they do not offer opportunities for large adjustments to the dimensions on site. Therefore methods of erecting steel bridges have evolved to allow for such adjustments. The primary problem is that the substructure contractor may not have placed the anchor bolts in the piers (or even the piers themselves) with sufficient accuracy to permit easy installation of the bearing, or masonry plate if one exists. Longitudinal location errors are more common than transverse ones. The problems are more severe with stiff systems such as pot, spherical or mechanical bearings than with elastomeric bearings, because they contain more anchor bolts and because the potential for damage by misalignment is greater. Where a bearing has no anchor bolts, the problems are vastly simplified. The real need for anchorage should therefore be carefully assessed.

The most satisfactory approach is to exert strict control over the work of the subcontractor so that the anchor bolts are correctly located, but this is not always easy or even possible. If this is not feasible, there are several possible adjustment locations for achieving the necessary longitudinal tolerance. The piers themselves may be jacked, or adjustments may be made at the interfaces between pier and masonry plate, bearing top plate and sole plate, or sole plate and girder. Each adjustment location has advantages and drawbacks.

Jacking the piers may damage the substructure. The possibility of moving the masonry plate relative to the pier depends on the anchor bolt installation technique. Many erectors like to run an accurate survey of the pier locations, then drill or core the piers so that the bolts can be correctly located for the girder and bearing. This approach solves the adjustment problem, but there is a risk of drilling through critical reinforcement, and in extreme cases, the bolts may be far from their intended location and the reinforcement in the concrete substructure may not be suited for the loading that results. This method may also provide insufficient tension capacity in the bolts in case of uplift if the sides of the holes are smooth. One alternative is to pre-form in the concrete oversize holes that are large enough to provide the necessary tolerance and, in cases where uplift may occur, to use a steel tube with a plate washer at the bottom, such as shown in Figure II-3.9. The holes are grouted after the bearing or masonry plate has been set. Another possibility is to use oversize holes in the bearing plate or masonry plate and to use plate washers over them. This arrangement requires adequate height and may not be feasible with low-profile bearings.

Adjustments may be made between the bearing top plate and the sole plate, if both exist. If the bearing has a top plate, it may be bolted to the sole plate using oversized or slotted holes. Again, vertical clearances for bolting should be verified. The adjustment that can be made by this method is somewhat limited unless the bearing top plate and the sole plate are large.

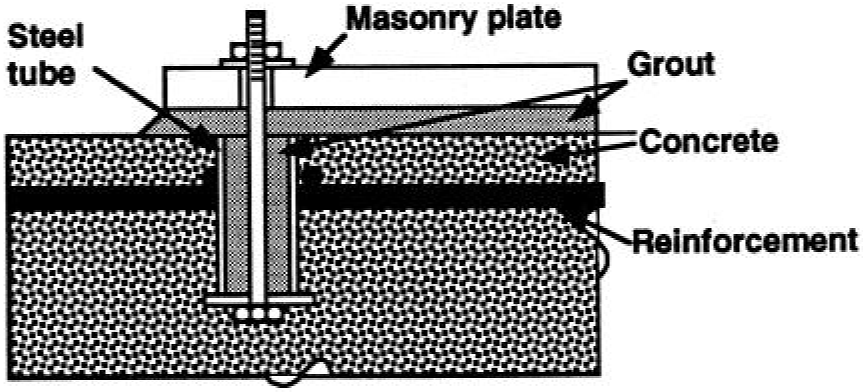


Figure II-3.9: Steel Tube Detail for Anchor Bolts

The sole plate may also be adjusted, at least longitudinally, relative to the girder flange provided that the two are then site welded. This is feasible, but requires site welding under conditions that might be difficult. If the bearing is elastomeric, it also risks heat damage from the welding. Temperature sensitive crayons or other means must be used to ensure that the elastomer is not overheated.

In all cases, dimensional control must be properly maintained. This requires at least that the centerline of the bearing be clearly marked so that discrepancies from the nominal bearing location can be properly identified and monitored.

Stability of Bearing and Girder During Erection

Steel bridges usually contain diaphragms or transverse bracing for lateral support of the girders. The structure is very stable in its complete configuration, but the girders may be relatively unstable during construction. This is particularly true for curved girders but is also true for individual girders on straight bridges. Multiple straight girders installed with diaphragms already in place should significantly reduce the potential for lateral instability for all bearing types, but they require heavier cranes.

The rotational flexibility of the bearings about the girder's longitudinal axis may aggravate this temporary instability, particularly for curved girders or single girders. In service, the girders are stabilized against such rotations by bracing, but it may not be installed until several girders are in place. It is more economical to provide stability by temporary locking the bearing against deformation or by temporary bracing the girder, rather than designing a permanent restraint of some sort. Contractors are capable of providing this bracing, but the need for temporary bracing should be shown on the plans.

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Appendix A:
Test Requirements

GENERAL

A number of tests are required to ensure satisfactory performance of bridge bearings. Most of these tests are described in detail in the AASHTO LRFD Specifications and other documents. These tests are normally used to achieve one of three objectives. First, material tests are used to assure that the properties are consistent with those used in the design. Second, quality control tests on the completed bearing are conducted to verify that the bearing was built to satisfactory quality standards and tolerances. Finally, tests are sometimes conducted to simulate service conditions in order to evaluate the service life of the bearing. These three major objectives are discussed separately, although there is clearly some overlap.

TESTS TO VERIFY DESIGN REQUIREMENTS

Most material tests are outlined in the appropriate ASTM and AASHTO Material Standards. However, PTFE and elastomers require special testing because their behavior can not be predicted by indirect measures or physical examination.

Friction Testing of PTFE

The coefficient of friction in PTFE depends on many variables such as contact pressure, sliding speed and temperature. Friction can have a large impact on the forces transmitted from the superstructure to the substructure, and these forces influence the economy of the entire bridge design.

The material for the test specimens must be identical to that in the manufactured bearing and the test specimens may be comprised of material taken from randomly selected bearings from the lot supplied by the manufacturer; complete bearings may also be used. The test pieces are loaded with a compressive stress corresponding to their maximum stress due to service dead plus live load, which is then held constant for one hour prior to, and throughout the duration of, the sliding test. At least 100 cycles of sliding, each consisting of at least ±25 mm (1 in.) of movement, are then applied at a temperature of 20^{o}C (68^{o}F). Additional low temperature tests may be required if the bridge site is located in a cold region. The tests are normally performed at a uniform sliding speed of 63 mm/min (2.5 in./min). The breakaway friction coefficient is computed for each direction of each cycle, and its mean and standard deviation are computed for the sixth through twelfth cycles.

The initial breakaway coefficient of friction for the first cycle can not exceed twice the design coefficient of friction, and the maximum value for all subsequent cycles can not exceed the design coefficient of friction. A multiplier of 2 is applicable for the first cycle because that criterion would otherwise dominate. It is justified by the low probability of finding the full gravity load on the bearing at the time of initial slip. The very first movement almost always occurs during transportation or bridge erection. Further, the normal margin of safety used in bridge design accommodates some one time overload. These tests assure that the bearing does not deliver a larger force to the superstructure or substructure than considered by the design engineer.

Shear Stiffness of Elastomeric Bearings

The shear modulus of the elastomer is the primary design requirement for steel reinforced elastomeric bearings or elastomeric bearing pads. The shear modulus test can be made from a specimen cut from a randomly selected bearing (an extra bearing must be manufactured to provide this specimen) or a comparable non-destructive stiffness test may be conducted on a pair of finished bearings. The test apparatus and procedure for small specimens are described in Annex A of ASTM D4014, *Standard Specification for Plain and Steel-Laminated Elastomeric Bearings for Bridges*. The shear modulus must fall within ±15 percent of the specified value, or within the range for its hardness given in the AASHTO LRFD Specifications if no shear modulus is specified.

If the test is conducted on finished bearings, the material shear modulus must be computed from the measured shear stiffness of the bearings taking due account of the influence on shear stiffness of bearing geometry and compressive load. There are considerable difficulties associated with predicting bearing shear stiffness from material modulus, or vice versa, because of the complex interaction of compressive and shear loads in an elastomeric bearing. For this reason, it is important not to specify both material modulus and bearing stiffness.

Elastomers stiffen at low temperatures. The extent depends upon the elastomer compound, the temperature and the duration of exposure. If an inappropriate elastomer compound is used the shear forces may be more than 100 times as large as those obtained at room temperature. They can cause severe damage to a bridge. The materials for bearings to be used in extremely cold climates must be subjected to the low temperature shear test. The three primary tests to be used are the Low Temperature Brittleness test (ASTM D746), the Instantaneous Low Temperature Stiffness test (ASTM D1043) and the Low Temperature Crystallization test (ASTM D4014). The test temperature depends upon the elastomer grade, and the required grade depends upon climatic conditions at the bridge site. For the low temperature crystallization and low temperature stiffness tests, the stiffness at the test temperature cannot exceed 4 times the stiffness noted at room temperature.

Low temperature testing is important only for bearings to be used in colder climates in the United States, so it is required only for elastomeric bearings made from low temperature grades 4 and 5. The low temperature tests are more expensive than the basic physical property tests, so the AASHTO LRFD Specifications require the manufacturer to provide certified test results conducted on the same compound within one year of the date of manufacture of the bearings, unless specific testing is required by the engineer.

TESTS TO ASSURE QUALITY OF THE MANUFACTURED PRODUCT

These tests are intended to assure that the bearings are manufactured to appropriate tolerances and clearances. Engineers are familiar with many tests of this type and little additional discussion is required. However, a few tests such as proof load tests on elastomeric bearings require some illustration.

Short Duration Proof Load Test of Elastomeric Bearings

Elastomeric bearings are different than most structural components. Satisfactory bearing behavior requires a well manufactured product. Appropriate curing is needed to obtain the correct elastomer material properties and scrupulous cleanliness is needed to achieve satisfactory bond.

Division II of the AASHTO *Standard Specifications for Highway Bridges* requires that every elastomeric bearing which is designed for high stress applications be subjected to a short duration load test. The bearing is loaded in compression to 150 percent of its rated service load. If the bearing is subjected in service to a rotation and compression, a tapered plate should be introduced in the load path so that the bearing sustains the load at the maximum simultaneous design rotation. The load shall be held for 5 minutes, removed, then reapplied for a second period of 5 minutes. The bearing should be examined visually while under the second loading. Any defect results in rejection of the bearing. A good bearing manufacturer can do this test very quickly and economically, since the press needed to manufacture the bearing can also be used to test it.

The test provides valuable information since any instances of poor dimensional tolerances and poor bond between the steel and elastomer will usually be visible. Further, it provides the owner a quick check of the manufacturer, since the test can be repeated on randomly selected bearings. No deflection data is required.

Long Duration Load Test for Elastomeric Bearings

Division II of the AASHTO *Standard Specifications for Highway Bridges* requires a long duration proof load test on a small number of bearings, randomly selected from any lot, which are designed for high stress applications. The test is conducted in the same way as the short-duration proof load test except that the second load is maintained for 15 hours. If the load drops below 90 percent of its target value during this time, the load must be increased to the target value and the test duration must be increased by the period of time for which the load was below the required value. Any splits, cracking, delamination, or improper placement of steel plates results in rejection of the lot of bearings. The long duration load test is important because it will reveal poor bond which is missed in the short duration load test.

Tests to Verify Manufacturing of Special Components

Tests may be required to verify that some special components have been manufactured properly. Examples are guides and their attachments for sliding pot bearings, and durability tests on elements such as seals in pot bearings. The intent is to ensure that the finished bearing will behave as specified by the designer. However, these tests differ from materials tests in that the item being verified is part of the manufacturing process rather than a material that is incorporated in it.

Criteria for such tests should be specified by the engineer, should be related as closely as possible to the service function of the component, and should be agreed upon with the manufacturer before production starts.

PROTOTYPE TESTS

Most bearing problems in the field arise from the accumulation of many cycles of load and movement. Tests that simulate field conditions are useful but are too expensive and time-consuming to be used as quality control tests. However, they provide an excellent basis for evaluating the suitability of a new bearing system or creating a performance specification.

To accelerate the testing, use a smaller number of cycles than would occur during the design life of the bearing along with larger loads and displacements. It is seldom possible to provide an exact equivalence between such a test and real field conditions. However, accelerated testing is valuable for ranking the behavior of different systems and for illuminating defects. Tests of this type can be used to explore the effects of factors such as debris accumulation and contamination. Care must be taken to avoid introducing new conditions in the test, such as elevated temperatures caused by high speed testing.

One such accelerated test program has been proposed for rotational elements. It was used on an extensive series of tests on pot and spherical bearings. This test consisted of 5000 cycles of ±0.02 radians rotation at a rate of approximately 1.5 cycles/min. The rotation limit was chosen because many bearing systems are designed for a rotation capacity of ±0.02 radians, so it represented a way of applying the most severe movements possible without exceeding the design limits. The best available evidence suggests that cyclic rotations in the order of ±0.005 radians are more common for traffic loading or temperature effects, but millions of cycles of rotation due to traffic loading and many thousands of temperature cycles are possible. As a result, this test procedure was applied for 5000 or 10 000 cycles to simulate a substantial service life.

Appendix B
Steel Reinforced Elastomeric Bearing Design Spreadsheet and Examples

INTRODUCTION

This Appendix contains instructions and examples that illustrate the use of the included spreadsheet titled AISIBRGS.XLS for designing rectangular steel-reinforced elastomeric bearings. The objective is to achieve a design that satisfies the constraints of the AASHTO LRFD Specifications with the least effort on the part of the engineer. The spreadsheet offers the advantages of allowing alternative designs to be assessed quickly to avoid tedious and potentially error-prone numerical calculations.

USE OF SPREADSHEET

This Microsoft Excel spreadsheet is largely self explanatory. Data must be entered in the outlined cells. The equations used by the spreadsheet can be seen in Figures B-1a and B-1b. Alphabetic entries (e.g. y or n) are not case-sensitive. The information given in this appendix is general in nature. Whenever possible the designer should consult with a bearing manufacturer who is likely to supply the bearings being designed to gather information on material properties and fabrication practices. This information will ensure the economy of the bearing design.

Input Data

In the section of the spreadsheet marked "INPUT DATA", the material properties and loads are defined by the user. Variables are defined in Table B-A.

Care must be taken with the co-ordinates. Rotation is assumed to take place about only one axis, which is defined as the *y* axis. In most bridges this will be the transverse axis. Buckling must eventually be checked for both directions, so the fixity against translation must be entered for both. In a bridge that is fixed against longitudinal and transverse movement at one end but free to expand at the other, the fixed end will have translation fixed for both the *x* and *y* directions. The expansion end will be fixed in the *x* direction and free to translate in the *y* direction (the *x*-fixity arises because the bridge is fixed against longitudinal translation at the other end and it does not stretch).

Variable	Unit	Description
Date		Cell is formatted to accept six digit numerical entry corresponding to ##/##/## for date.
Job Title		Cell is unformatted. Entry of any data is permissible.
G_{min} G_{max}	MPa	Minimum and maximum elastomer shear modulus. If the elastomer selected is specified by hardness, enter minimum and maximum shear modulus values into the appropriate cells. If the chosen elastomer is defined by shear modulus, enter that single value into both the minimum and maximum fields. Shear modulus values range from 0.55 to 1.25 MPa. A typical elastomer with a 55 Shore A Durometer hardness would have about a 0.7 to 0.9 MPa shear modulus range.
k_{bar}		Elastomer material property. This material property is used to calculate the effective modulus of the elastomer in compression. It is defined in NCHRP report 248 and varies from about 0.9 to 0.5 as the Shore A Durometer hardness varies from about 40 to 70. A value of **0.6** is suitable for most bridge bearing elastomers.
F_y	MPa	Yield strength of steel reinforcement. In general, bearing manufacturers do not use steel reinforcement grades other than AASHTO M270 Grade 250, F_y = **250** MPa.
$(\Delta F)_{TH}$	MPa	Fatigue limit stress of steel reinforcement. As defined in Table 6.6.1.2.5-3 of the AASHTO LRFD Specifications, $(\Delta F)_{TH}$ for steel reinforcement layers without holes or discontinuities is **165** MPa.
h_{cover}	mm	Thickness of elastomeric cover layer. This dimension is used to calculate the total height of the bearing. A typical cover of **3** mm is usually applied.
P_{DL}	kN	Service dead load.
P_{LL}	kN	Service live load.
rotn.	rad	Rotation of girder at bearing concurrent with specified loads.
Δ_s	mm	Shear displacement of bearing concurrent with specified loads.
Trans. fixed x?		Translation fixed in the *x* direction. The *x* direction is assumed along the longitudinal axis of the bridge. Enter y if the bearing is fixed against translation in this direction or n if the bearing is free to sway in this direction.
Trans. fixed y?		Translation fixed in the *y* direction. The *y* direction is assumed along the transverse axis of the bridge. Enter y if the bearing is fixed against translation in this direction or n if the bearing is free to sway in this direction.

Table B-A: Descriptions of Variables for "INPUT DATA"

Bearing Design

In the section of the spreadsheet marked "BEARING DESIGN" the user defines the geometric properties of the bearing through an interactive process. Variables are defined in Table B-B. The most efficient bearing design is likely to be achieved by balancing $N_{lay}(comp)$ and $N_{lay}(uplift)$. That is, using a bearing geometry that requires about the same number of internal elastomer layers to satisfy both the combined compression and rotation limits of Eq. 2-7 and the uplift requirements of either Eq. 2-10a or Eq. 2-10b.

Variable	Unit	Description
L	mm	Bearing dimension perpendicular to rotation axis. This is in the assumed *x* direction or along the longitudinal axis of the bridge.
W	mm	Bearing dimension parallel to rotation axis. The rotation axis is assumed to be in the *y* direction or along the transverse axis of the bridge. In general, this dimension should be as large as practical to permit rotation about the transverse axis and to stabilize the girder during erection. However, the bearing should be slightly narrower than the flange unless a stiff sole plate is used to insure uniform distribution of compressive stress and strain over the bearing area.
h_{ri}	mm	Thickness of a single internal elastomer layer. Although a minimum elastomer thickness of 3 mm is achievable by most manufacturers, typical bearings have a layer thickness in the range of 6 to 15 mm. In general, an initial trial of a **10** mm layer thickness is used.
N_{layers}		Number of internal elastomer layers. See discussion below.
h_s	mm	Thickness of steel reinforcement layer. Although a minimum steel reinforcement thickness of 2 mm is achievable by most bearing manufacturers, a **3** mm thickness or greater is preferred due to tolerance control limitations during the fabrication process.

Table B-B: Descriptions of Variables for "DESIGN BEARING"

Limiting values for each variable in question are reported on the left side of this spreadsheet section. In some cases, more than one behavioral characteristic influences the variable, so more than one limit exists. For example, the number of elastomer layers is influenced by uplift, combined compression shear and rotation, and stability in both the *x* and *y* directions. Some limits are upper bounds and some are lower bounds.

The entry boxes on the right side of this spreadsheet section are to be used by the designer to select a bearing parameter based on the reported limits. As each value is entered, the reported limits change appropriately. A check (OK or NG) appears on the extreme right side. If some of the multiple limits are mutually exclusive, the design is impossible and the user must select a different value for one of the earlier variables. For example, the number of layers may have to be less than 10 and greater than 20, in which case a different layer thickness or plan dimension should be tried.

The four variables related to the elastomer layers are interdependent, and should be selected first. The steel thickness is independent of other variables and may be selected last.

Summary

The section of the spreadsheet marked “SUMMARY” reports the final bearing properties. The maximum shear force occurs at the design displacement. If the maximum shear force is unacceptably large, it can be reduced by making the bearing thicker or by adding a slider.

EXAMPLE 1: BEARING FOR TYPICAL LONG-SPAN BRIDGE

Same as example in Section 2.

Dead Load	2400 kN (540 kips)
Live Load	1200 kN (270 kips)
Longitudinal Translation	100 mm (4 in.)
Rotation	0.015 rad
Buckling	fixed longitudinally free transversely
Elastomer	55 Shore A Durometer $0.690 \text{ MPa} < G < 0.896 \text{ MPa}$
Steel	$F_y = 250$ MPa $(\Delta F)_{TH} = 165$ MPa

Referring to Figure B-2a, initial plan dimensions of 475 x 725 mm are selected to be slightly above the absolute minimums. It is usually beneficial to make the bearing as wide as possible (in the direction parallel to the axis of rotation) because this alleviates potential problems with uplift and combined stress constraints.

The elastomer layer thickness is initially assumed to be 10 mm in order to provide a high shape factor and good compressive strength. However, as shown in Figure B-2a, the assumed thickness leads to mutually exclusive limits on the number of layers, which must simultaneously be greater than 41.6 and less than 40.5. Comparison of the values for combined stress and uplift points out the problem. The elastomer layers are relatively thin for this application and produce a high rotational stiffness which induces uplift stresses and require a large number of layers to overcome. Since the resistance to combined stress is high, the need to minimize the rotational stress by using a large number of layers is not appropriate. Thus the number of layers is controlled by uplift.

Increasing the layer thickness to 15 mm (near the maximum permissible), as seen in Figure B-2b, reverses the situation making the combined stress limit control over the uplift limit. This occurs because the compressive stress limit is lower when the layers are thicker and the shape factor is smaller, and the uplift stresses induced by rotation are smaller. As stated earlier, the most efficient bearing is likely to be achieved by balancing $N_{lay}(comp)$ and $N_{lay}(uplift)$. This is done by selecting 14 mm thick layers (see Figure B-2c), in which case a total of 17 internal layers will be needed. This number is small enough that stability in both the x and y directions is also assured. Theoretically 16 layers at 13.78 mm each would be satisfactory, but controlling the layer thickness to ±0.01 mm is impractical.

The steel reinforcement thickness is subject only to lower bounds and so can be selected without trial and error.

It should be noted that the bearing was designed on the basis of elastomer hardness, in which case the AASHTO LRFD Specifications require that the least favorable value of G be used for each calculation. This provision exists because shear modulus and hardness are only loosely correlated, yet shear modulus is the property that controls design. If the material is defined by its hardness, and the bearing manufacturer provides the necessary test data, then economies can be realized. This is shown by the design in Figure B-2d.

EXAMPLE 2: BEARING FOR TYPICAL MEDIUM-SPAN BRIDGE

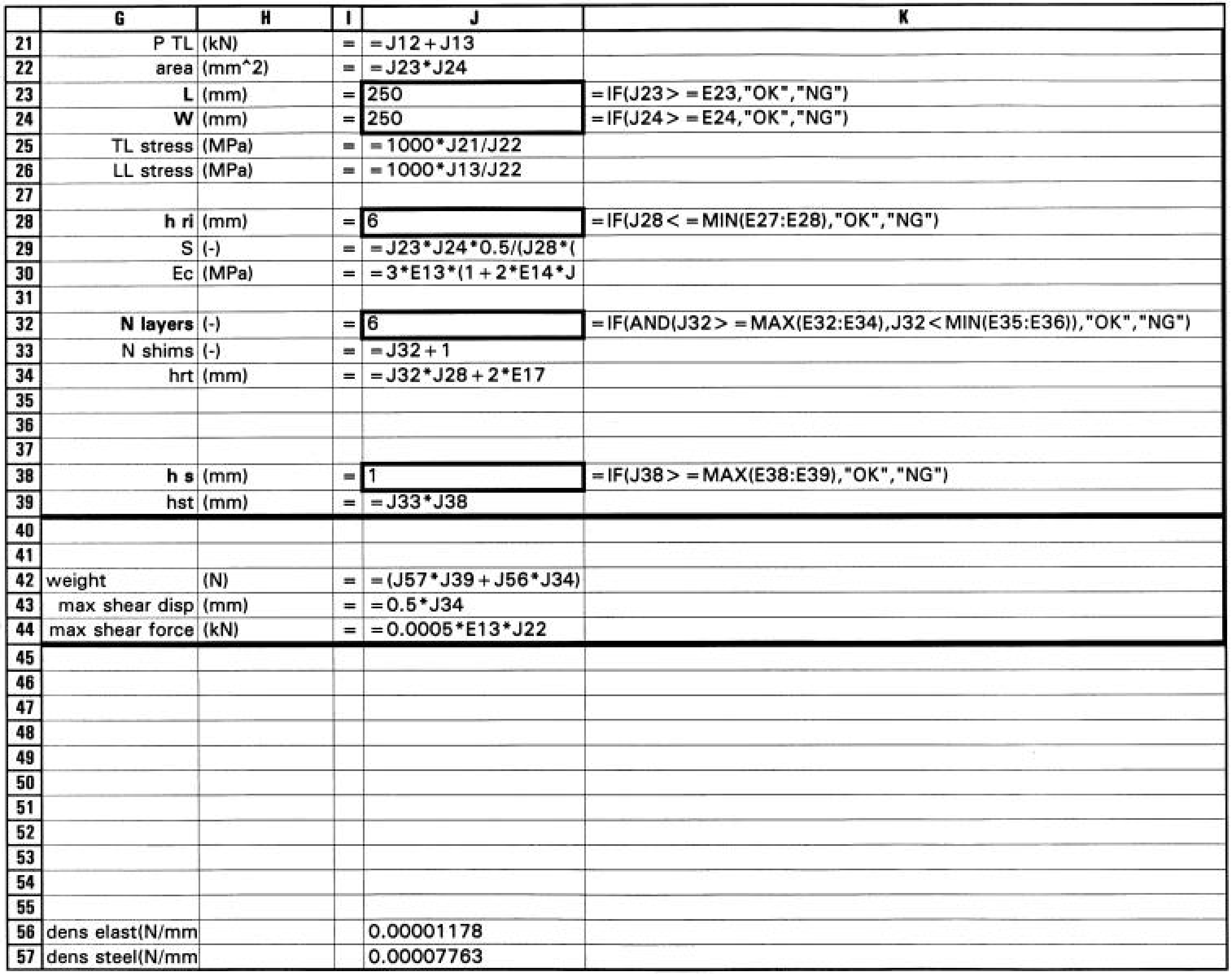
Dead Load	400 kN (90 kips)
Live Load	160 kN (36 kips)
Longitudinal Translation	15 mm (0.6 inches)
Rotation	0.01 rad
Buckling	fixed longitudinally free transversely
Elastomer:	55 Shore A Durometer $0.690 \text{ MPa} < G < 0.896 \text{ MPa}$
Steel	F_y= 250 MPa $(\Delta F)_{TH}$ = 165 MPa

Two solutions, one with a 500 mm bearing width and one with a 250 mm bearing width, are shown in Figures B-3a and B-3b respectively. In the first design, Figure B-3a, the engineer has a considerable design latitude. The selected geometry uses a plan area near to the minimum acceptable with 6 elastomer layers. A design with a larger plan area, lower stresses and fewer layers (and so fewer steel reinforcing layers) might prove more economical. If the length becomes too short, rollover due to longitudinal displacement becomes possible. In this case the length is still 9 times the estimated longitudinal displacement, so rollover is not a problem.

When the width is restricted to 250 mm, Figure B-3b, the bearing must become longer in order to provide the necessary area. Uplift and combined stress limits become active and rotation becomes critical in the design, forcing the use of more layers. The resulting bearing is about twice the height and weight of the 500 mm wide design.

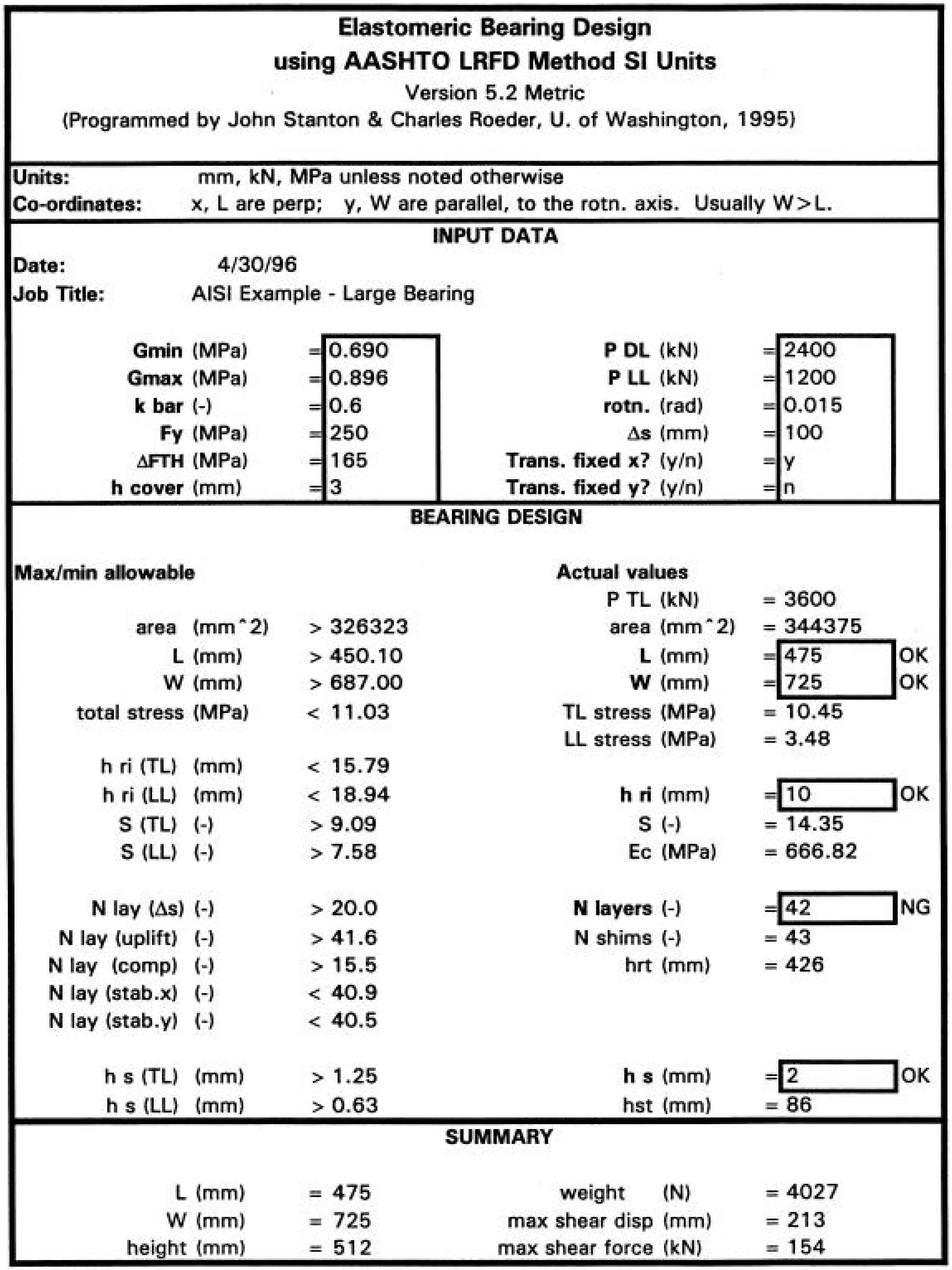
	B	C	D	E	F
22	area	(mm^2)	>	=1000*J21/E25	
23	L	(mm)	>	=E22/J24	
24	W	(mm)	>	=E22/J23	
25	total stress	(MPa)	<	11.032	
26					
27	h ri (TL)	(mm)	<	=J23*J24*0.5/(E29*(J23+J24))	
28	h ri (LL)	(mm)	<	=J23*J24*0.5/(E30*(J23+J24))	
29	S (TL)	(-)	>	=J25/(C54*E12)	
30	S (LL)	(-)	>	=J26/(C55*E12)	
31					
32	N lay (Δs)	(-)	>	=2*J15/J28	
33	lay (uplift)	(-)	>	=(E13*J29/J25)*J14*(J23/J28)^2	
34	lay (comp)	(-)	>	=C57*J14*(J23/J28)^2/(1-J25/(C56*E12*J29))	
35	lay (stab.x)	(-)	<	=($E$12/$J$25+E52)/(F52*C52)	
36	lay (stab.y)	(-)	<	=($E$12/$J$25+E53)/(F53*C53)	
37					
38	h s (TL)	(mm)	>	=3*J28*J25/E15	
39	h s (LL)	(mm)	>	=3*J28*J26/E16	
40					**SUMMARY**
41					
42	L	(mm)	=	=J23	
43	W	(mm)	=	=J24	
44	height	(mm)	=	=J34+J39	
45					
46					
47					
48					
49					
50	**Intermediate**	**calculations**			
51		c1		c2	k.eff
52	stability	=(3.84*$J$28/J23)/($J$29*SQRT(1+2*$J$23/$J$24))		=2.67/($J$29*($J$29+2)*(1+0.25*J23/J24))	=IF(OR(J16="Y",J16="y"),0.5,1)
53	stability	=(3.84*$J$28/J24)/($J$29*SQRT(1+2*$J$24/$J$23))		=2.67/($J$29*($J$29+2)*(1+0.25*J24/J23))	=IF(OR(J17="Y",J17="y"),0.5,1)
54	S.TL fac	=IF($J$15=0,2,1.66666666)			
55	S.LL fac	=IF($J$15=0,1,0.66666666)			
56	sig.comb fa	=IF($J$15=0,2.25,1.875)			
57	sig.comb fa	=IF($J$15=0,1/6,0.2)			

Figure B-1a: Spreadsheet Equations



	G	H	I	J	K
21	P TL	(kN)	=	=J12+J13	
22	area	(mm^2)	=	=J23*J24	
23	**L**	(mm)	=	250	=IF(J23>=E23,"OK","NG")
24	**W**	(mm)	=	250	=IF(J24>=E24,"OK","NG")
25	TL stress	(MPa)	=	=1000*J21/J22	
26	LL stress	(MPa)	=	=1000*J13/J22	
27					
28	**h ri**	(mm)	=	6	=IF(J28<=MIN(E27:E28),"OK","NG")
29	S	(-)	=	=J23*J24*0.5/(J28*(	
30	Ec	(MPa)	=	=3*E13*(1+2*E14*J	
31					
32	**N layers**	(-)	=	6	=IF(AND(J32>=MAX(E32:E34),J32<MIN(E35:E36)),"OK","NG")
33	N shims	(-)	=	=J32+1	
34	hrt	(mm)	=	=J32*J28+2*E17	
35					
36					
37					
38	**h s**	(mm)	=	1	=IF(J38>=MAX(E38:E39),"OK","NG")
39	hst	(mm)	=	=J33*J38	
40					
41					
42	weight	(N)	=	=(J57*J39+J56*J34)	
43	max shear disp	(mm)	=	=0.5*J34	
44	max shear force	(kN)	=	=0.0005*E13*J22	
45					
46					
47					
48					
49					
50					
51					
52					
53					
54					
55					
56	dens elast(N/mm			0.00001178	
57	dens steel(N/mm			0.00007763	

Figure B-1b: Spreadsheet Equations (Continued)



Elastomeric Bearing Design
using AASHTO LRFD Method SI Units
Version 5.2 Metric
(Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units: mm, kN, MPa unless noted otherwise
Co-ordinates: x, L are perp; y, W are parallel, to the rotn. axis. Usually W>L.

INPUT DATA

Date: 4/30/96
Job Title: AISI Example - Large Bearing

Gmin	(MPa)	= 0.690	**P DL**	(kN)	= 2400
Gmax	(MPa)	= 0.896	**P LL**	(kN)	= 1200
k bar	(-)	= 0.6	**rotn.**	(rad)	= 0.015
Fy	(MPa)	= 250	Δ**s**	(mm)	= 100
Δ**FTH**	(MPa)	= 165	**Trans. fixed x?**	(y/n)	= y
h cover	(mm)	= 3	**Trans. fixed y?**	(y/n)	= n

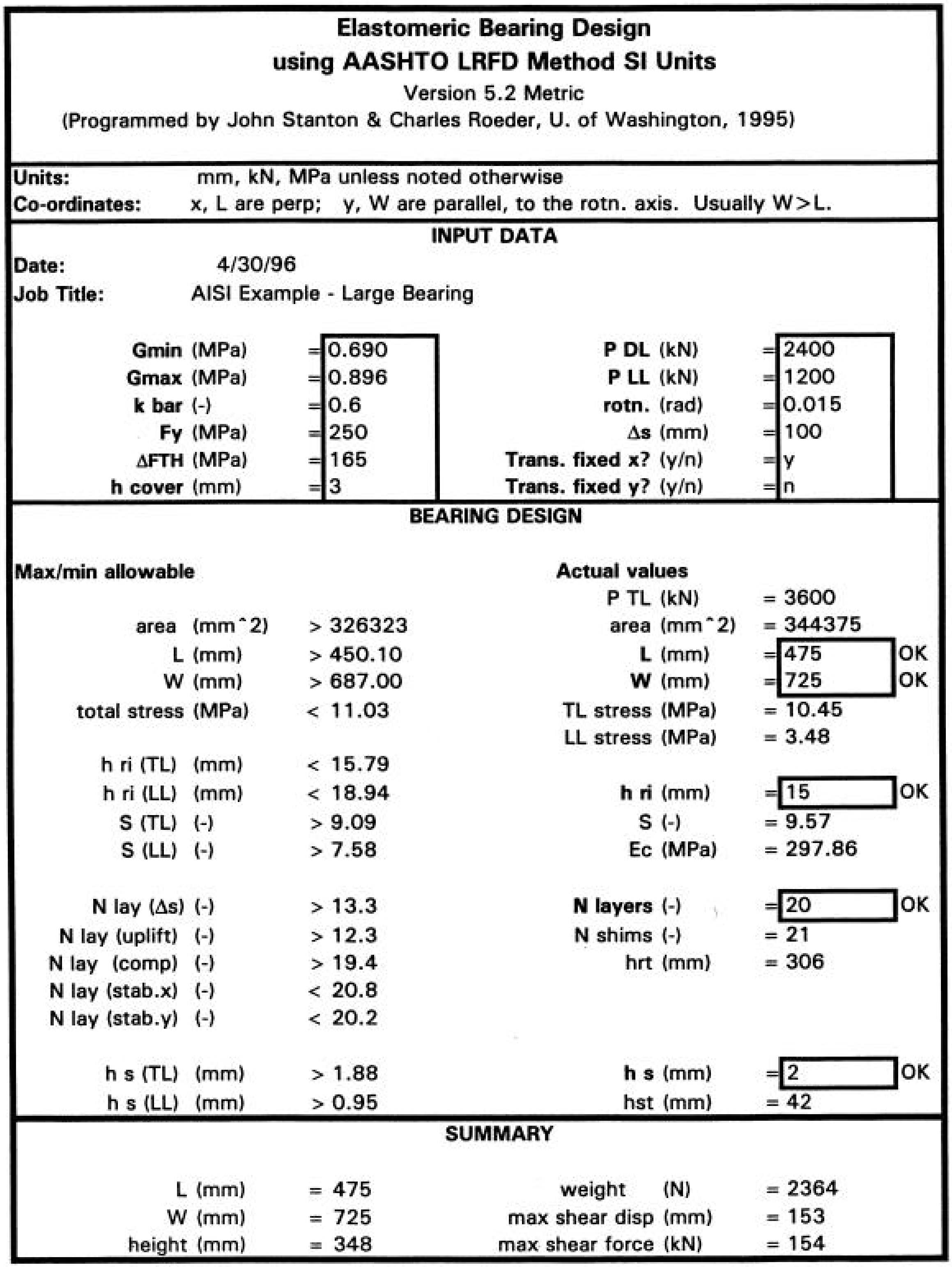
BEARING DESIGN

Max/min allowable			**Actual values**			
			P TL	(kN)	= 3600	
area	(mm^2)	> 326323	area	(mm^2)	= 344375	
L	(mm)	> 450.10	**L**	(mm)	= 475	OK
W	(mm)	> 687.00	**W**	(mm)	= 725	OK
total stress	(MPa)	< 11.03	TL stress	(MPa)	= 10.45	
			LL stress	(MPa)	= 3.48	
h ri (TL)	(mm)	< 15.79				
h ri (LL)	(mm)	< 18.94	**h ri**	(mm)	= 10	OK
S (TL)	(-)	> 9.09	S	(-)	= 14.35	
S (LL)	(-)	> 7.58	Ec	(MPa)	= 666.82	
N lay (Δs)	(-)	> 20.0	**N layers**	(-)	= 42	NG
N lay (uplift)	(-)	> 41.6	N shims	(-)	= 43	
N lay (comp)	(-)	> 15.5	hrt	(mm)	= 426	
N lay (stab.x)	(-)	< 40.9				
N lay (stab.y)	(-)	< 40.5				
h s (TL)	(mm)	> 1.25	**h s**	(mm)	= 2	OK
h s (LL)	(mm)	> 0.63	hst	(mm)	= 86	

SUMMARY

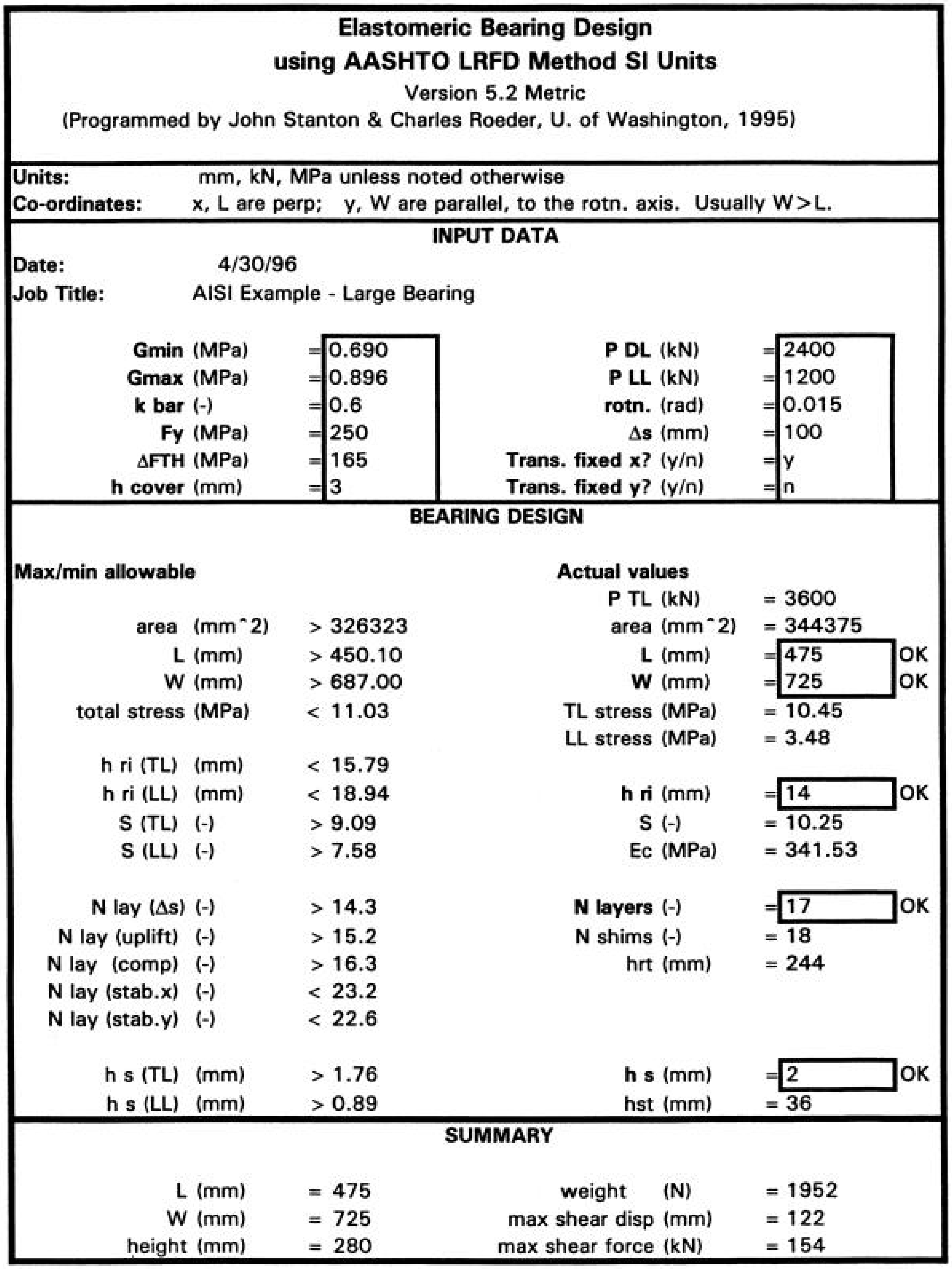
L	(mm)	= 475	weight	(N)	= 4027
W	(mm)	= 725	max shear disp	(mm)	= 213
height	(mm)	= 512	max shear force	(kN)	= 154

Figure B-2a: Large Bearing: Trial Design with 10 mm Elastometer Layers



```
                         Elastomeric Bearing Design
                    using AASHTO LRFD Method SI Units
                           Version 5.2 Metric
    (Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units:              mm, kN, MPa unless noted otherwise
Co-ordinates:       x, L are perp;   y, W are parallel, to the rotn. axis.  Usually W>L.
                                   INPUT DATA
Date:                 4/30/96
Job Title:          AISI Example - Large Bearing

           Gmin (MPa)        =0.690                    P DL (kN)         =2400
           Gmax (MPa)        =0.896                    P LL (kN)         =1200
          k bar (-)          =0.6                      rotn. (rad)       =0.015
             Fy (MPa)        =250                        Δs (mm)         =100
           ΔFTH (MPa)        =165            Trans. fixed x? (y/n)       =y
        h cover (mm)         =3              Trans. fixed y? (y/n)       =n
                                  BEARING DESIGN

Max/min allowable                                Actual values
                                                      P TL (kN)         = 3600
           area  (mm^2)      > 326323                 area (mm^2)       = 344375
              L  (mm)        > 450.10                    L (mm)         =475        OK
              W  (mm)        > 687.00                    W (mm)         =725        OK
   total stress  (MPa)       <  11.03            TL stress (MPa)        = 10.45
                                                 LL stress (MPa)        = 3.48
        h ri (TL)  (mm)      <  15.79
        h ri (LL)  (mm)      <  18.94                 h ri (mm)         =15         OK
           S (TL)  (-)       > 9.09                      S (-)          = 9.57
           S (LL)  (-)       > 7.58                     Ec (MPa)        = 297.86

       N lay (Δs)  (-)       > 13.3               N layers (-)          =20         OK
     N lay (uplift) (-)      > 12.3                N shims (-)          = 21
     N lay  (comp)  (-)      > 19.4                    hrt (mm)         = 306
     N lay (stab.x) (-)      <  20.8
     N lay (stab.y) (-)      <  20.2

         h s (TL)  (mm)      > 1.88                    h s (mm)         =2          OK
         h s (LL)  (mm)      > 0.95                    hst (mm)         = 42
                                   SUMMARY

              L (mm)         = 475                 weight      (N)      = 2364
              W (mm)         = 725          max shear disp (mm)         = 153
         height (mm)         = 348          max shear force (kN)        = 154
```

Figure B-2b: Large Bearing: Trial Design with 15mm Elastomer Layers



Elastomeric Bearing Design
using AASHTO LRFD Method SI Units
Version 5.2 Metric
(Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units:	mm, kN, MPa unless noted otherwise
Co-ordinates:	x, L are perp; y, W are parallel, to the rotn. axis. Usually W>L.

INPUT DATA

Date:	4/30/96
Job Title:	AISI Example - Large Bearing

Gmin (MPa)	=	0.690	**P DL** (kN)	=	2400
Gmax (MPa)	=	0.896	**P LL** (kN)	=	1200
k bar (-)	=	0.6	**rotn.** (rad)	=	0.015
Fy (MPa)	=	250	Δs (mm)	=	100
ΔFTH (MPa)	=	165	**Trans. fixed x?** (y/n)	=	y
h cover (mm)	=	3	**Trans. fixed y?** (y/n)	=	n

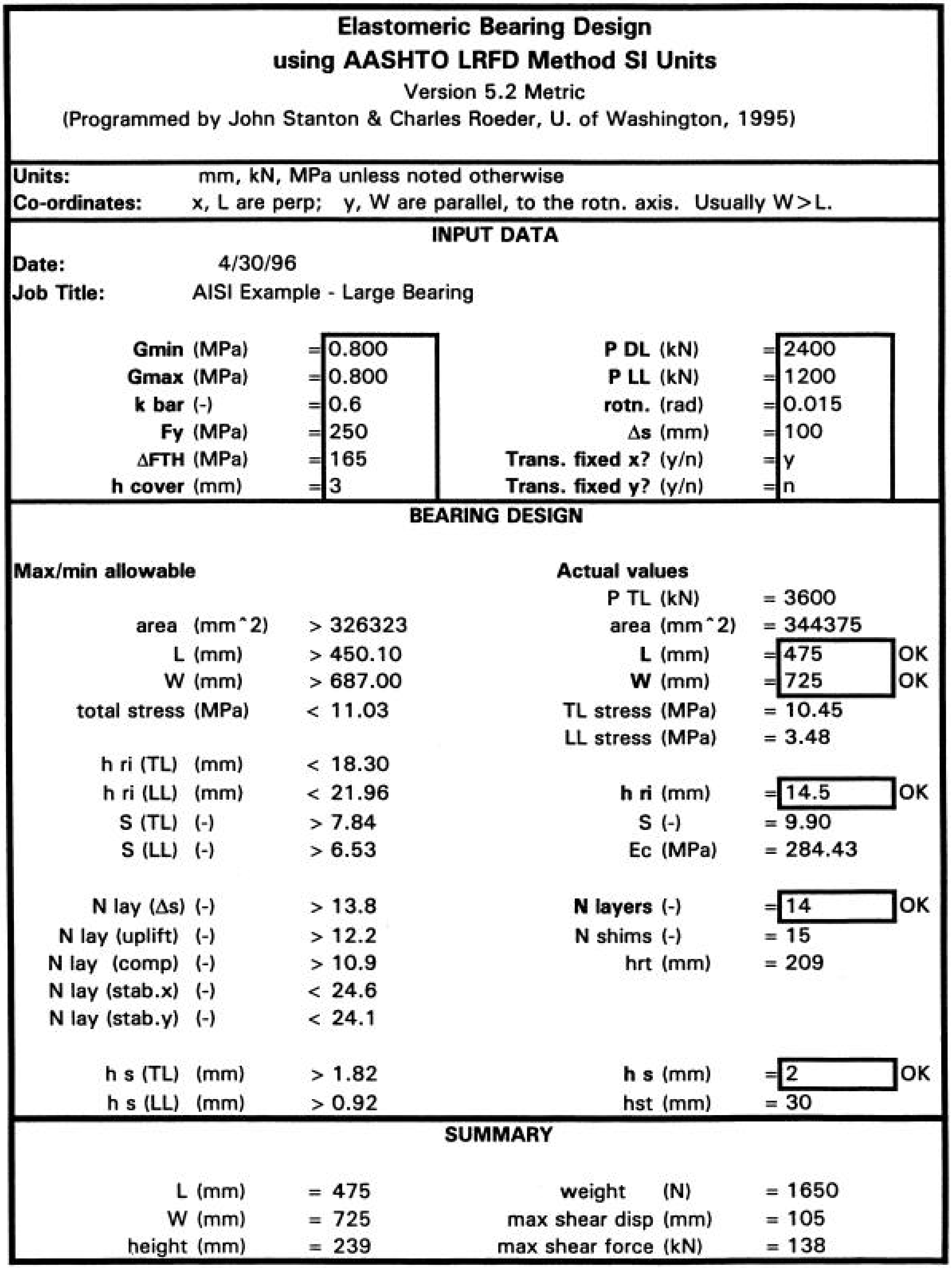
BEARING DESIGN

Max/min allowable		**Actual values**		
		P TL (kN)	= 3600	
area (mm^2)	> 326323	area (mm^2)	= 344375	
L (mm)	> 450.10	**L** (mm)	= 475	OK
W (mm)	> 687.00	**W** (mm)	= 725	OK
total stress (MPa)	< 11.03	TL stress (MPa)	= 10.45	
		LL stress (MPa)	= 3.48	
h ri (TL) (mm)	< 15.79			
h ri (LL) (mm)	< 18.94	**h ri** (mm)	= 14	OK
S (TL) (-)	> 9.09	S (-)	= 10.25	
S (LL) (-)	> 7.58	Ec (MPa)	= 341.53	
N lay (Δs) (-)	> 14.3	**N layers** (-)	= 17	OK
N lay (uplift) (-)	> 15.2	N shims (-)	= 18	
N lay (comp) (-)	> 16.3	hrt (mm)	= 244	
N lay (stab.x) (-)	< 23.2			
N lay (stab.y) (-)	< 22.6			
h s (TL) (mm)	> 1.76	**h s** (mm)	= 2	OK
h s (LL) (mm)	> 0.89	hst (mm)	= 36	

SUMMARY

L (mm)	= 475	weight (N)	= 1952
W (mm)	= 725	max shear disp (mm)	= 122
height (mm)	= 280	max shear force (kN)	= 154

Figure B-2c: Large Bearing: Final Design with 14mm Elastomer Layers



Elastomeric Bearing Design
using AASHTO LRFD Method SI Units
Version 5.2 Metric
(Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units: mm, kN, MPa unless noted otherwise
Co-ordinates: x, L are perp; y, W are parallel, to the rotn. axis. Usually W>L.

INPUT DATA

Date: 4/30/96
Job Title: AISI Example - Large Bearing

Gmin (MPa)	=	0.800	**P DL** (kN)	=	2400
Gmax (MPa)	=	0.800	**P LL** (kN)	=	1200
k bar (-)	=	0.6	**rotn.** (rad)	=	0.015
Fy (MPa)	=	250	Δs (mm)	=	100
ΔFTH (MPa)	=	165	**Trans. fixed x?** (y/n)	=	y
h cover (mm)	=	3	**Trans. fixed y?** (y/n)	=	n

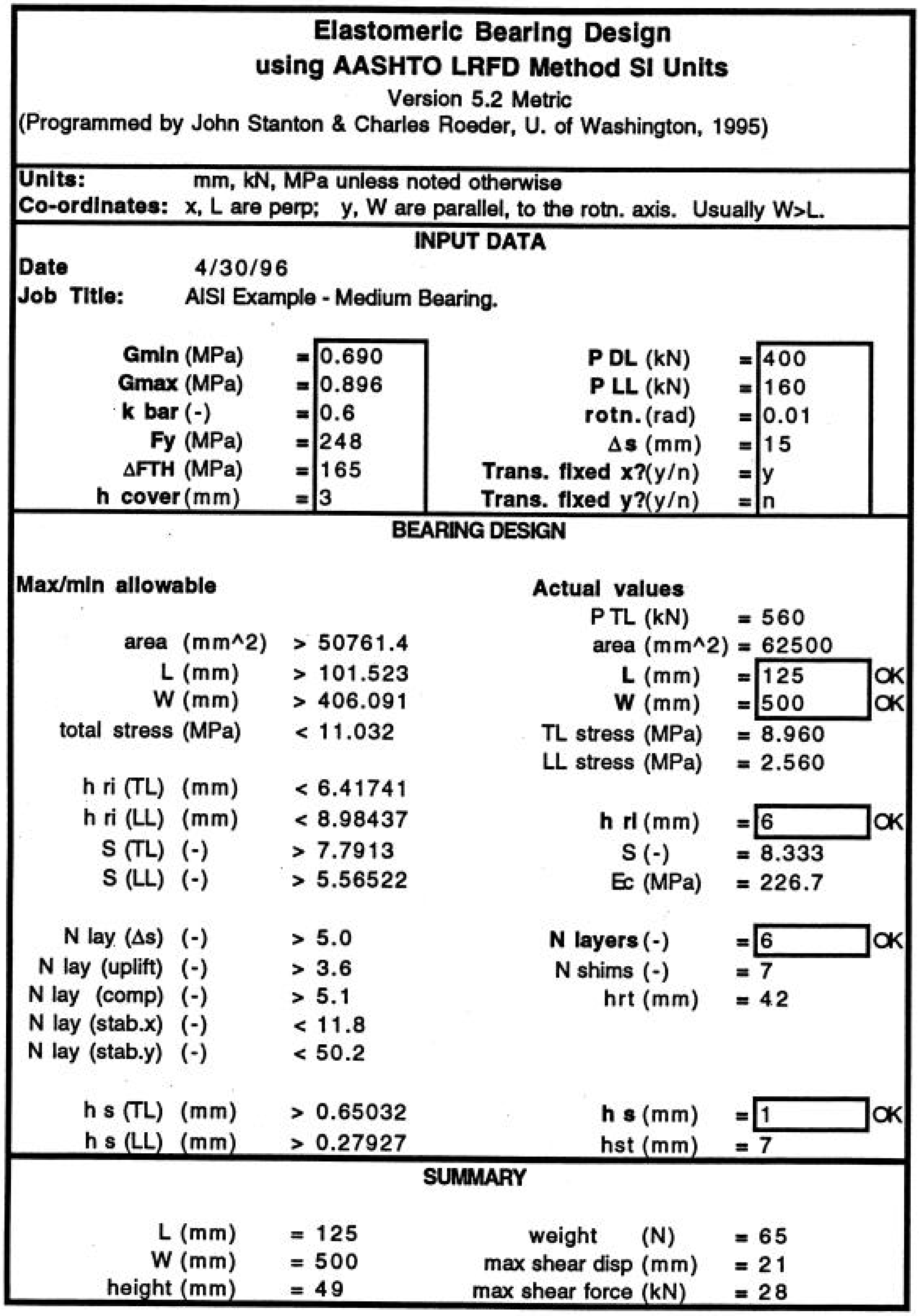
BEARING DESIGN

Max/min allowable		**Actual values**		
		P TL (kN)	= 3600	
area (mm^2)	> 326323	area (mm^2)	= 344375	
L (mm)	> 450.10	**L** (mm)	= 475	OK
W (mm)	> 687.00	**W** (mm)	= 725	OK
total stress (MPa)	< 11.03	TL stress (MPa)	= 10.45	
		LL stress (MPa)	= 3.48	
h ri (TL) (mm)	< 18.30			
h ri (LL) (mm)	< 21.96	**h ri** (mm)	= 14.5	OK
S (TL) (-)	> 7.84	S (-)	= 9.90	
S (LL) (-)	> 6.53	Ec (MPa)	= 284.43	
N lay (Δs) (-)	> 13.8	**N layers** (-)	= 14	OK
N lay (uplift) (-)	> 12.2	N shims (-)	= 15	
N lay (comp) (-)	> 10.9	hrt (mm)	= 209	
N lay (stab.x) (-)	< 24.6			
N lay (stab.y) (-)	< 24.1			
h s (TL) (mm)	> 1.82	**h s** (mm)	= 2	OK
h s (LL) (mm)	> 0.92	hst (mm)	= 30	

SUMMARY

L (mm)	= 475	weight (N)	= 1650
W (mm)	= 725	max shear disp (mm)	= 105
height (mm)	= 239	max shear force (kN)	= 138

Figure B-2d: Large Bearing: Design Based on Specified Shear Modulus



Elastomeric Bearing Design
using AASHTO LRFD Method SI Units
Version 5.2 Metric
(Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units: mm, kN, MPa unless noted otherwise
Co-ordinates: x, L are perp; y, W are parallel, to the rotn. axis. Usually W>L.

INPUT DATA

Date 4/30/96
Job Title: AISI Example - Medium Bearing.

Gmin (MPa)	= 0.690		**P DL** (kN)	= 400	
Gmax (MPa)	= 0.896		**P LL** (kN)	= 160	
k bar (-)	= 0.6		**rotn.** (rad)	= 0.01	
Fy (MPa)	= 248		**Δs** (mm)	= 15	
ΔFTH (MPa)	= 165		**Trans. fixed x?**(y/n)	= y	
h cover (mm)	= 3		**Trans. fixed y?**(y/n)	= n	

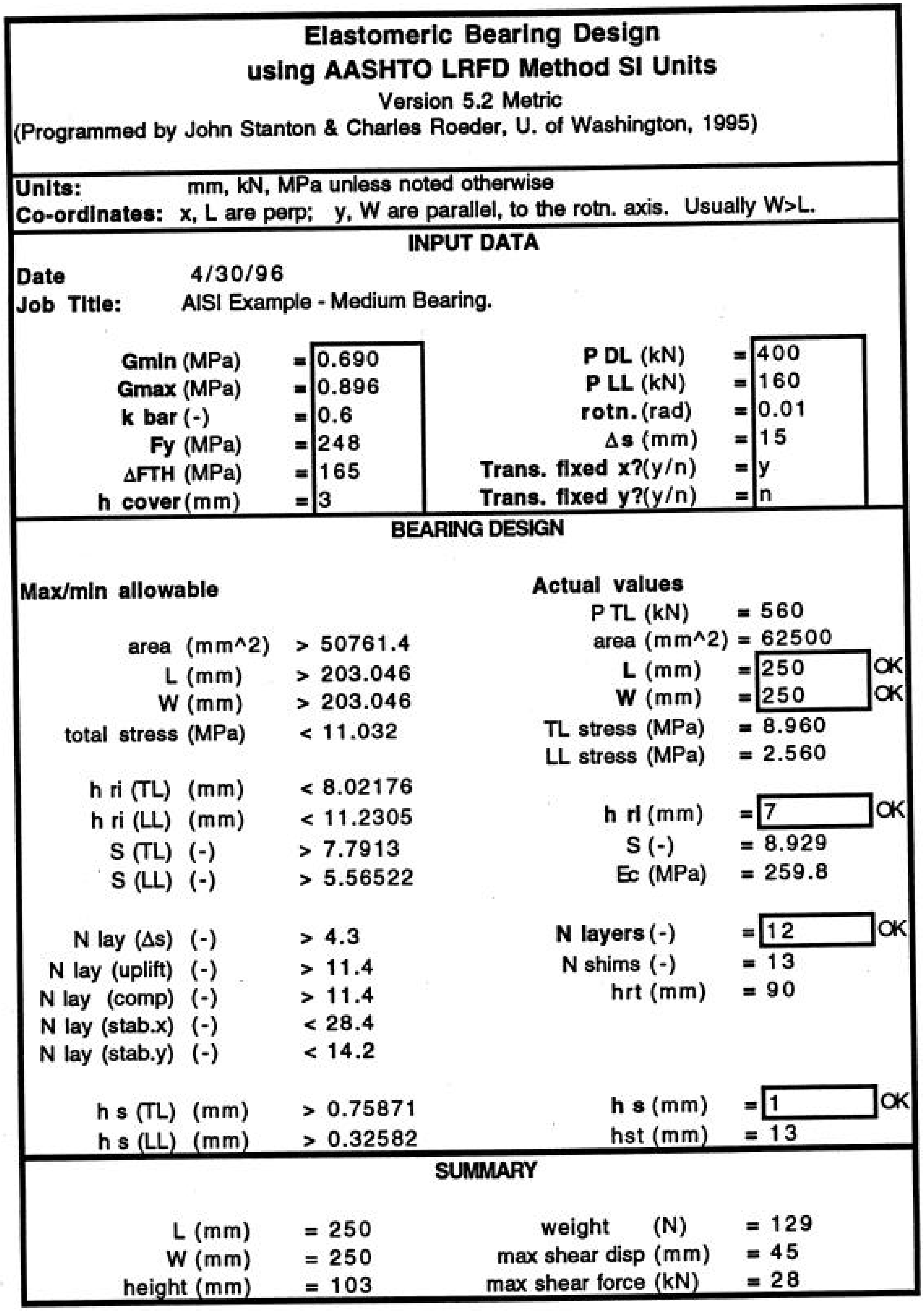
BEARING DESIGN

Max/min allowable		**Actual values**		
		P TL (kN)	= 560	
area (mm^2)	> 50761.4	area (mm^2)	= 62500	
L (mm)	> 101.523	**L** (mm)	= 125	OK
W (mm)	> 406.091	**W** (mm)	= 500	OK
total stress (MPa)	< 11.032	TL stress (MPa)	= 8.960	
		LL stress (MPa)	= 2.560	
h ri (TL) (mm)	< 6.41741			
h ri (LL) (mm)	< 8.98437	**h ri** (mm)	= 6	OK
S (TL) (-)	> 7.7913	S (-)	= 8.333	
S (LL) (-)	> 5.56522	Ec (MPa)	= 226.7	
N lay (Δs) (-)	> 5.0	**N layers** (-)	= 6	OK
N lay (uplift) (-)	> 3.6	N shims (-)	= 7	
N lay (comp) (-)	> 5.1	hrt (mm)	= 42	
N lay (stab.x) (-)	< 11.8			
N lay (stab.y) (-)	< 50.2			
h s (TL) (mm)	> 0.65032	**h s** (mm)	= 1	OK
h s (LL) (mm)	> 0.27927	hst (mm)	= 7	

SUMMARY

L (mm)	= 125	weight (N)	= 65
W (mm)	= 500	max shear disp (mm)	= 21
height (mm)	= 49	max shear force (kN)	= 28

Figure B-3a: Medium Bearing: Final Design, Width = 500 mm



Elastomeric Bearing Design
using AASHTO LRFD Method SI Units
Version 5.2 Metric
(Programmed by John Stanton & Charles Roeder, U. of Washington, 1995)

Units: mm, kN, MPa unless noted otherwise
Co-ordinates: x, L are perp; y, W are parallel, to the rotn. axis. Usually W>L.

INPUT DATA

Date 4/30/96
Job Title: AISI Example - Medium Bearing.

Gmin (MPa)	=	0.690	**P DL** (kN)	=	400
Gmax (MPa)	=	0.896	**P LL** (kN)	=	160
k bar (-)	=	0.6	**rotn.** (rad)	=	0.01
Fy (MPa)	=	248	**Δs** (mm)	=	15
ΔFTH (MPa)	=	165	**Trans. fixed x?**(y/n)	=	y
h cover (mm)	=	3	**Trans. fixed y?**(y/n)	=	n

BEARING DESIGN

Max/min allowable		**Actual values**		
		P TL (kN)	= 560	
area (mm^2)	> 50761.4	area (mm^2)	= 62500	
L (mm)	> 203.046	**L** (mm)	= 250	OK
W (mm)	> 203.046	**W** (mm)	= 250	OK
total stress (MPa)	< 11.032	TL stress (MPa)	= 8.960	
		LL stress (MPa)	= 2.560	
h ri (TL) (mm)	< 8.02176			
h ri (LL) (mm)	< 11.2305	**h ri** (mm)	= 7	OK
S (TL) (-)	> 7.7913	S (-)	= 8.929	
S (LL) (-)	> 5.56522	Ec (MPa)	= 259.8	
N lay (Δs) (-)	> 4.3	**N layers** (-)	= 12	OK
N lay (uplift) (-)	> 11.4	N shims (-)	= 13	
N lay (comp) (-)	> 11.4	hrt (mm)	= 90	
N lay (stab.x) (-)	< 28.4			
N lay (stab.y) (-)	< 14.2			
h s (TL) (mm)	> 0.75871	**h s** (mm)	= 1	OK
h s (LL) (mm)	> 0.32582	hst (mm)	= 13	

SUMMARY

L (mm)	= 250	weight (N)	= 129
W (mm)	= 250	max shear disp (mm)	= 45
height (mm)	= 103	max shear force (kN)	= 28

Figure B-3b: Medium Bearing: Final Design, Width = 250 mm