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"SPHERICAL ROLLER BEARING DESIGN AS USED ON MOVABLE BRIDGES"

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SPHERICAL ROLLER BEARING DESIGN AS USED ON MOVABLE BRIDGES

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INTRODUCTION

The design requirements for anti-friction, roller bearings used in movable bridge, trunnion and counterweight sheave positions, are subject to the American Association of State Highway and Transportation Officials (AASHTO) and the American Railway Engineering Association (AREA) specifications. The present AASHTO and AREA formulae for determining the maximum allowable bearing load is conservative and does not consider modern bearing design, materials, and the precision machined bearing components in use today.

The AASHTO and AREA requirements for anti-friction roller bearings will be explained. Several case studies will describe the method a bearing manufacturer must use to size the proper roller bearing choice for the given trunnion diameter, and how the AASHTO and AREA formulae could increase the bearing/trunnion size in several cases to meet the present, conservative specifications. A recommendation to increase the allowable AREA bearing load will be made.

ONE SENTENCE DESCRIPTOR

Modern anti-friction, roller bearing design, materials and precision machined bearing components, including computer analysis of the contact stress developed, suggests that AASHTO and AREA review their allowable load requirements.

DETERMINING TRUNNION BEARING REQUIREMENTS

The trunnion shaft size is determined by the bridge designer and is usually the limiting requirement with the bearing choices for that required diameter having sufficient capacity for the application use. We choose the bearing series to gain capacity and limit the Hertz contact stress developed to approximately 300,000 PSI (2070 MPa).

Torrington spherical roller bearings are available in 10 dimensional series and are graphically illustrated in Figure 1. These series conform to the American National Standards Institute (ANSI) and the American Bearing Manufacturers Association (ABMA) standards and meet the International Standards Organization (ISO) manufacturing parameters providing for the same basic bore, outside diameter, and width dimensions for interchangeable bearing installations.

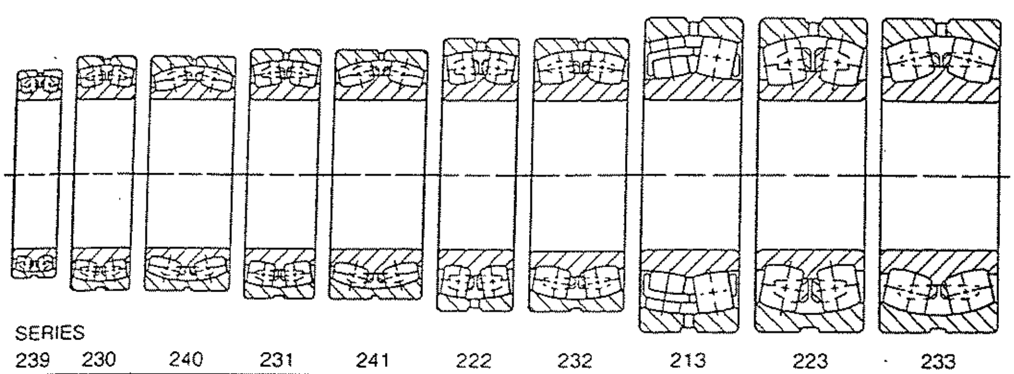

Figure 1: A graphical illustration of the ten dimensional series of spherical roller bearings available conforming to ISO and ANSI/ABMA standards

BORE A mm	O.D. B mm	WIDTH C mm	CAPACITY: BASIC DYNAMIC newtons	CAPACITY: BASIC STATIC newtons	SHOULDER DIAMETER: SHAFT D mm	SHOULDER DIAMETER: HOUSING E mm	FILLET RADIUS max. r mm	WEIGHT Kg	LIMITING SPEED† (approx.): GREASE rpm	LIMITING SPEED† (approx.): OIL rpm	EQUIVALENT RADIAL LOAD (These factors apply for both metric and English calculations. See foldout on back cover for instructions on use.) DYNAMIC: e	DYNAMIC: $\frac{F_a}{F_r} \leq e$, $X=1$, Y	DYNAMIC: $\frac{F_a}{F_r} > e$, $X=.67$, Y	STATIC: In all cases, $X_0=1$, Y_0	BEARING NUMBER Series Number shown in bold type
400	540	106	1,670,000	3,670,000	438	514	3.0	64.4	320	640	0.17	3.88	5.78	3.80	23980
	600	148	2,760,000	5,600,000	452	547	4.1	140.2	300	600	0.22	3.04	4.52	2.97	23080
	600	200	3,600,000	7,560,000	444	553	4.1	189.6	300	600	0.32	2.14	3.19	2.09	24080
	650	200	3,970,000	7,610,000	456	591	5.1	251.3	285	570	0.31	2.21	3.28	2.16	23180
	650	250	4,940,000	9,740,000	451	591	5.1	308.4	285	570	0.38	1.76	2.62	1.72	24180
	720	256	5,070,000	9,560,000	477	636	5.1	444.5	270	540	0.37	1.82	2.71	1.78	23280
420	560	106	1,740,000	3,870,000	455	531	3.0	68.5	305	610	0.17	4.06	6.05	3.97	23984
	620	150	2,880,000	5,960,000	473	567	4.1	149.7	290	580	0.21	3.15	4.69	3.08	23084
	620	200	3,780,000	7,920,000	461	576	4.1	195.0	290	580	0.30	2.23	3.31	2.18	24084
	700	224	4,850,000	9,070,000	482	636	5.1	334.3	270	540	0.32	2.08	3.10	2.04	23184
	700	280	5,920,000	10,760,000	482	634	5.1	406.4	270	540	0.40	1.68	2.50	1.64	24184
	760	272	6,410,000	11,610,000	498	671	6.1	524.4	255	510	0.38	1.78	2.65	1.74	23284
440	600	118	2,080,000	4,540,000	482	567	3.0	91.6	290	580	0.18	3.85	5.74	3.77	23988
	650	157	3,180,000	6,540,000	496	598	5.1	172.8	275	550	0.21	3.15	4.69	3.08	23088
	650	212	4,090,000	8,850,000	486	601	5.1	230.4	275	550	0.31	2.21	3.29	2.16	24088
	720	226	4,980,000	9,650,000	490	652	5.1	353.4	260	520	0.31	2.14	3.19	2.10	23188
	720	280	6,090,000	12,190,000	501	658	5.1	428.2	260	520	0.39	1.74	2.58	1.70	24188
	790	280	6,140,000	11,430,000	519	701	6.1	629.6	245	490	0.37	1.82	2.71	1.78	23288
460	620	118	2,040,000	4,760,000	503	581	3.0	98.0	275	550	0.16	4.13	6.15	4.04	23992
	680	163	3,450,000	7,120,000	515	623	5.1	195.0	265	530	0.22	3.14	4.67	3.07	23092
	680	218	4,430,000	9,520,000	510	631	5.1	256.7	265	530	0.30	2.25	3.34	2.28	24092
	760	240	5,560,000	10,190,000	525	693	6.1	416.4	245	490	0.32	2.12	3.16	2.07	23192
	760	300	6,890,000	13,830,000	526	691	6.1	520.7	245	490	0.40	1.70	2.54	1.67	24192
	830	296	7,650,000	14,010,000	547	736	6.1	675.9	230	460	0.36	1.86	2.76	1.81	23292
480	650	128	2,470,000	5,470,000	521	627	4.1	116.1	265	530	0.17	3.86	5.75	3.78	23996
	700	165	3,580,000	7,430,000	540	647	5.1	206.8	255	510	0.21	3.22	4.79	3.15	23096
	700	218	4,540,000	9,870,000	528	647	5.1	269.4	255	510	0.29	2.33	3.47	2.28	24096
	790	248	6,000,000	11,560,000	556	712	6.1	465.4	235	470	0.32	2.14	3.19	2.09	23196
	790	308	7,380,000	14,810,000	547	718	6.1	575.2	235	470	0.39	1.73	2.57	1.69	24196
	870	310	7,960,000	14,630,000	563	774	6.1	782.9	220	440	0.37	1.84	2.74	1.80	23296
500	670	128	2,540,000	5,740,000	542	620	4.1	119.8	255	510	0.17	4.02	5.98	3.93	239/500
	720	167	3,590,000	7,520,000	543	663	5.1	213.2	245	490	0.21	3.23	4.80	3.16	230/500
	720	218	4,630,000	10,230,000	547	674	5.1	275.3	245	490	0.28	2.41	3.59	2.36	240/500
	830	264	6,760,000	12,850,000	574	756	6.1	550.2	245	490	0.32	2.10	3.13	2.05	231/500
	830	325	8,180,000	16,500,000	569	756	6.1	679.5	245	490	0.39	1.71	2.55	1.68	241/500
	920	336	9,560,000	17,170,000	604	809	6.1	954.4	210	420	0.37	1.82	2.71	1.78	232/500
530	710	136	2,880,000	6,540,000	578	676	4.1	146.1	240	480	0.17	4.00	5.96	3.92	239/530
	780	185	4,400,000	9,120,000	596	718	5.1	287.6	230	460	0.21	3.14	4.68	3.07	230/530
	780	250	5,870,000	12,720,000	586	725	5.1	386.5	230	460	0.30	2.25	3.35	2.20	240/530
	870	272	7,290,000	14,190,000	610	795	6.1	616.4	215	430	0.32	2.14	3.19	2.09	231/530
	870	325	8,360,000	16,640,000	604	795	6.1	728.9	215	430	0.37	1.80	2.69	1.76	241/530
	980	355	10,900,000	19,530,000	640	877	7.1	1152.6	200	400	0.37	1.84	2.74	1.80	232/530

Figure 2. Catalog tables for equivalent radial load factors by bearing series number.

Example ... 23284 bearing P/N with given loading
Fr = 340 Kips and Fa = 15 % Fr = 51 Kips
then e > Fa/Fr = .15 and X = 1.0 , Y = 1.78

and Pe = Fr x (1.0) + Fa x (1.78) = 430.78 Kips

Note: AREA Allowable Load = 319.38 Kips
Torrington Allowable = 532.3 Kips.

In the figure, starting from the left and for a given bore diameter, the O.D. and width increases allow for internal geometry changes resulting in greater dynamic and static capacities. A typical bearing design scenario would be ... receive trunnion or counterweight sheave design data such as diameter and loading on the span or leaf, and the cycle times, angle of opening, and maybe a spec. sheet or two. This could be from a bridge designer or from the general or mechanical contractor requiring a bearing/block quote. We require the equivalent radial loading that the bearing is subjected to. We will use 15% of the given radial load (Fr) for the axial load (Fa) unless a thrust load for the fixed position bearing, greater than 15% of Fr, is provided. We then determine the equivalent radial loading on the bearing. The bearing catalog provides a method to calculate the equivalent radial load for the series chosen. Figure 2 is an example of the bearing series factors used to determine the equivalent radial load.

From tables, a spherical roller bearing series can be used to compare AREA versus the bearing manufacturers allowable loads. If the bearing bore and the trunnion shaft diameters agree, and the given loads do not exceed AREA allowable loading, we have a good match and the bearing choice is straight forward. A computer program determines the L10 life, the number of rollers in the load zone, and the Hertz contact stress developed for the radial and axial loads given. This is based on the actual internal geometry of the bearing series chosen. The housing or bearing pillow block can be determined for a straight or tapered bore, adapter mounted assembly. Typical shaft and block mounting sketches from the catalog pages help the designer to finalize his submittal drawings.

When the loading exceeds AREA allowable, another bearing series has to be determined from the look-up tables to satisfy the requirements. This usually increases the bearing bore diameter and also the supporting shaft diameter. As an example, Figure 3 shows a given trunnion diameter and radial loading for a bascule leaf. The bridge designer had to increase the trunnion diameter due to a revised loading. To meet AREA allowable loading a bearing diameter of 18.1102" and a series P/N 23292 bearing would be required.

Given : Fr = 291,400 lbs. 15" dia. Trunnion Shaft
Then, Fa = 15 % Fr = 43,710 and Pe = 372,700 lbs. for 23280 series spherical roller brg.

AREA Spec. Allowable loading is ...

P/N	Brg. Bore	Allowable Loading AREA	Allowable Loading Torrington	HZ contact Stress PSI
23076	14.9606	123,290	205,480	
23176	14.9606	175,520	292,530	
23276	14.9606	242,170	403,620	278,000
Torrington Block P/N SDAFS23276KDV-111 X 13-15/16" (Too Small)				
23080	15.7480	147,010	245,020	
23180	15.7480	202,950	338,250	
23280	15.7480	258,750	431,250	270,000
Torrington Block P/N SDAFS23280DV-111 X 15"				
230/710	27.9528	374,330	623,880	
231/530	20.8661	377,840	629,740	
23292	18.1102	382,000	636,670	236,330
Torrington Block P/N SDAFS23292KDV-111 X 18.2" (Too large)				

Figure 3. AREA allowable loading versus Torrington for bearing bore diameters and series.

BRG. P/N & CAGE STYLE	LOADING in KIPS Fr	Fa	Pequiv.	ALLOWABLE CAPACITIES in KIPS AREA	TORRINGTON
232/630KYMB	900	135	1143	768.93	1281.55
232/800KYMB	900	135	1170	1145.1	1908.5
232/900KYMB	900	135	1183.5	1334.38	2223.96

Figure 4. The given bearing radial load of 900 Kips and AREA/AASHTO axial loading of 15 % Fr.

Our recommendation is a 23280 P/N, adapter mounted used in a SDAFS23280KDV-111 x 15" steel block. The Hertz contact stress is well below our design standards. Torrington's allowable loading is 1.7 times AREA, and is less than the allowable Hertz stress others would allow.[1]

We design for the operating static load not to exceed one-half the value of the bearing static capacity , and to limit the Hertz contact stress to 480,000 psi static (3310 MPa) and 380,000 psi dynamic (2620 MPa). These capacities are calculated per ANSI/ABMA standards and are accepted by ISO. It is important to note that Torrington design limits are conservative compared to those allowable by ANSI/ABMA.

Another example is seen in Figure 4 where the vertical lift span load revision increased the bearing series and trunnion sheave diameter. The span loading was increased from 687.5 to 846 Kips and then to 900 Kips resulting in a change in the sheave shaft diameter from 20" to 29.5" to comply with AASHTO and AREA.

AASHTO and AREA REQUIREMENTS

AREA and AASHTO are noted for being conservative with their design equations and allowable stresses; equations for shafts and gearing, and trunnion shafts are generally based on static stress conditions.[2]

The concern is whether static or dynamic capacities of a bearing should be used as the criteria for permissible load. If the static capacity is to be used as the criteria for permissible load, the relation between the permissible load and the static capacity should be considered

The AREA capacity is based on the roller contact pressure as stated: " ... for rollers of trunnion and counterweight sheave roller bearings, the permissible pressure in pounds per linear inch of roller shall be 3000d, where d is the diameter of the roller in inches. One-fifth of the roller shall be taken as effective in carrying the load." Mathematically stated, this is:

$5P/Nld$ greater or less than 3000.

Where P = Load
N = number of rollers
l = roller length
d = roller diameter

This AREA specification of 3000d results in a Hertz stress of 177,000 psi (1220 MPa). This conservative value has been exceeded in many bridge applications. Installations have been made where the permissible load has varied from 2280d to 4124d. Many of these have seen considerable service, the oldest being the Cape Cod Bridge at Buzzards Bay in Massachusetts.

Originally the permissible pressure allowable by AREA was 2650d. This was increased to 3000d 35 years ago. The first movable highway bridge specification adopted by AASHTO was published in 1938, revised & updated by the editions of 1953 & 1970. The 14th edition is dated 1989 and includes much of the 1975 AREA specification revisions.[3]

ROLLER LOAD DISTRIBUTION

A bearing supplier can provide the roller load distribution for your analysis; so that you do not use a point loading for the bearing. You know the resultant force and location, and given the roller distribution of forces will make your analysis more meaningful and accurate. Figure 5 is a sketch of the roller load distribution for the 23284KYMBW33W45A spherical roller bearing used in a trunnion position for a bascule bridge. There are 36 rollers, 18 per race path, with 20 degrees between each roller. Nine rollers are in the load zone.

Designers have been provided with similar roller load distributions for their housing deflection analysis. Two major programs are used in the analysis. One program performs the bearing analysis which determines the roller load distribution, contact stress, and life, and the other program provides the finite element analysis which determines the bearing inner and outer ring distortions. The analysis flow chart is shown in Figure 6.[4] An iterative procedure is used where the bearing analysis program calculates the roller loads which are input as nodal forces into the finite element program. The finite element program calculates the inner and outer ring distortions at the roller locations which are then input back into the bearing analysis program as out-of-roundness. The bearing analysis program is run with the distorted shape and a new roller load distribution is determined. The new roller load distribution is input back into the finite element program. This procedure is continued until the life of the bearing does not change by more than one percent from iteration to iteration.

ROLLER/RACE PROFILE ENHANCEMENT

Conformity of roller/raceway surface is given considerable analysis in the design and manufacture of present bearing internal geometry to reduce edge loading in the contact area reducing stress. Manufacturers profile the rolling contact surfaces with multiple contours. In one geometry, the central region of the roller and races is shaped to optimize contact length, while the ends are rounded to eliminate stress concentration. Another technique is to improve the surface finish which enhances lubricant film thickness effectiveness reducing the likelihood of inter-asperity contact to develop. This enhances geometric uniformity and improves component roundness, thereby improving fatigue life.

There has been a steady tightening of dimensional tolerances since the 1940's with even tighter tolerancing requirements for the future. The limit of best practice in normal production machining was 0.000300" in 1980. The required accuracy in the year 2000 will be 0.000040".[5]

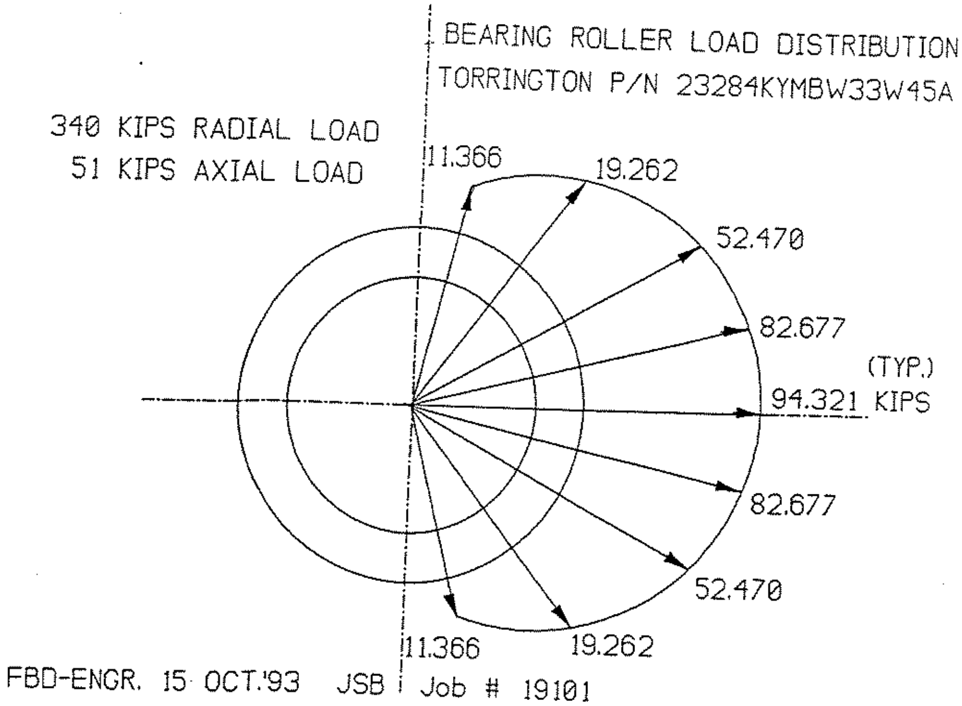

Figure 5. Bearing roller load distribution for 340 Kips radial and 51 Kips axial loading.

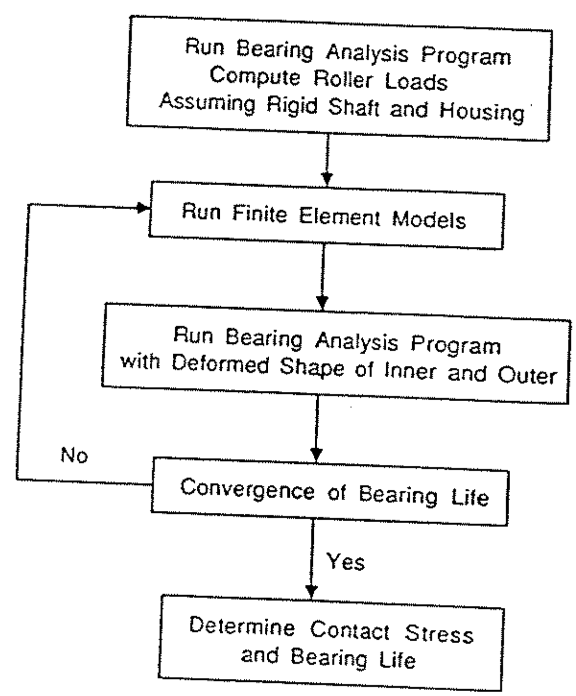

Figure 6. Analysis Flowchart

MATERIAL AND MANUFACTURING IMPROVEMENTS

Improved casting techniques are providing "cleaner steels", free of inclusions, casting voids, and forging seams. These improvements have provided the bearing manufacturer with dependable materials to produce bearing components; rings, rollers and retainers. Metallurgical and heat treatment process advancements have allowed quantitative assessment of cleanness for improved performance of bearing steels over the past 15 years. Improved cleanness has allowed manufacturers to increase bearing life-prediction ratings.[1]

Bearing manufacturers are certified ISO 9000 or have programs in place at their plants to become certified in the near future. Plants and offices have TQM, SPC, CAE/CAD/CAM in use along with better machine tools and better tool bits, grinding wheel abrasives plus added control of vendor items and materials used. This produces better finishes and with improved quality assurance procedures in place, a better product is assembled, inspected, and shipped.

Improved surface finishes, roundness and geometric tolerancing provide better bearing component control; presently roller diameters are matched within 0.000200" with roundness of 0.000050" readily achieved. Precision bearings are available with 1/4 the allowable RBEC 1 tolerance requirement (Roller Bearing Engineering Council).

Better machine tools and SPC provide for the control of raceway concentricity to be matched in the same angular quadrant for each race path adding to the improvement in rolling bearing performance.

Manufacturing improvements have greatly reduced true and false brinell marks and scratches on the contact surfaces; with no corrosion pitting from in-process-time; providing the correct cage to roller clearance for proper guiding without wiping the lube from the roller surface; with the correct bore, O.D. and width dimensions within tolerances; with no subsurface defects on the bearing component contact surfaces; made to the correct unmounted radial internal clearance for the application; having an applied protective coating, properly packaged for shipment in a container that supports the bearing and not the bearing supporting the shipping container.

Seal manufactures have modified existing materials and developed new ones. These materials enable seals to be made today in profiles and configurations unheard of twenty years ago.

We are concerned with preventing tramp dirt from entering the housing/bearing cavity and contaminating the lubricant. And we are all equally concerned with the lube egress contaminating our environment. The traditional mineral oil based lubricants and the modern lithium complex synthetic greases are allowed to perform to meet the application expectations. Grease developments have been in the areas of water resistance, non-metallic compatibility, base oil release, and quiet greases.

The Movable Bridge Industry has benefited from the improvements in bearing manufacturing which was necessary to meet Industry demands such as the paper industry; as paper machine speeds and widths increased, bearing requirements changed significantly.

Laser-alignment and dial-indicator systems provide for better installations and provide a "foot print" of the as-built conditions; a bench mark for predictive maintenance. Bearings with sensors provide feed back during operation for control and predictive maintenance purposes. Lubrication-oil analysis in the field by maintenance mechanics can be done using analyzers which can determine oil degradation and contamination.

RECOMMENDATIONS

We feel that the trunnion shaft diameter, as sized by the design engineer, should also set the bore diameter of the spherical roller bearing and not have the bearing set the shaft diameter.

AASHTO/AREA should consider increasing the allowable loading/capacity from 3000d to 5000d; an increase of 1.7 times. And leave the 15 % factor for the axial load as a minimum if the actual axial/thrust loading is not given for the fixed position; that is, use $Fa = 15\% Fr$.

AASHTO/AREA should consider the effective length of the roller and not the complete roller length. All rollers have radii and some have relief lengths for reducing the contact stress; edge loading at the roller ends.

AASHTO/AREA should provide a method for "... written approval of the Engineer option" which can be used when a bearing choice does not comply with the allowable loading but satisfies sound engineering practices and is supported by analysis.

In view of our past experience with bridge installations and similarly loaded heavy movable structures/applications, the increase to 5000d is still conservative. We do not feel that this should be substantially greater than this because of the reliability factor and long life requirement peculiar to this type of installation. The present specification of 3000d results in a Hertz stress of 177,000 psi (1220 MPa). The value of 5000d results in a Hertz contact stress of 228,000 psi (1570 MPa) and is well within the stresses normally associated with the deformation of races.

The American National Standard for load ratings and fatigue life for roller bearings have established bearing manufacturing practices and are sponsored by The American National Standards Institute, Inc. (ANSI), and the American Bearing Manufacturers Association (ABMA). ANSI/ABMA publish load ratings and fatigue life specifications for the manufacture of roller bearings allowing for 580,000 psi (4000 MPa) calculated contact stress for a static load condition. Experience shows that a total permanent deformation of 0.0001 of the rolling element diameter, at the center of the most heavily loaded roller/raceway contact, can be tolerated in most bearing applications without the subsequent bearing operation being impaired. Tests indicate that a load of the magnitude in question may be considered to correspond to a calculated contact stress of 580,000 psi (4000 MPa) to be developed for all roller bearings.[1]

We must note that although the present AREA formula of 3000d is conservative we can not agree that it should be as high as 15,000d as others have suggested. Most bearing materials harden in the range of Rc 58-62 and would become brittle under this loading. A bearing using a 2" diameter roller loaded to a value of 15,000d would result in .0002" permanent deformation at the race/roller contact. Ball and roller bearing formulae have been developed on the basis of test data on small bearings and the results extrapolated to apply to larger diameter bearings of all types. It is not practical or economically feasible to test large diameter bearings in the size range used on movable bridge applications.

The Burlington Northern Railroad vertical lift bridge, over the Willamette River in Portland Oregon, has 900 MM bore (35.4331") bearings with a 62.2" O.D. The weight of this bearing is 9100 pounds.

The capacity formulae developed through ABMA, the Roller Bearing Engineers Committee, does not have complete agreement by the members on certain internal bearing geometry factors and the allowable life adjustment factors which can be used in the published capacity ratings. Published catalog capacity ratings are subject to competitive pressures and can be misunderstood.

We recommend the AREA criteria for roller bearing selection be used and based on allowable stress as in its present form, but that the allowable unit stress be increased from 3000d to 5000d.

ACKNOWLEDGMENT

We wish to express our thanks to The Torrington Company for permission to present and publish this paper.

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