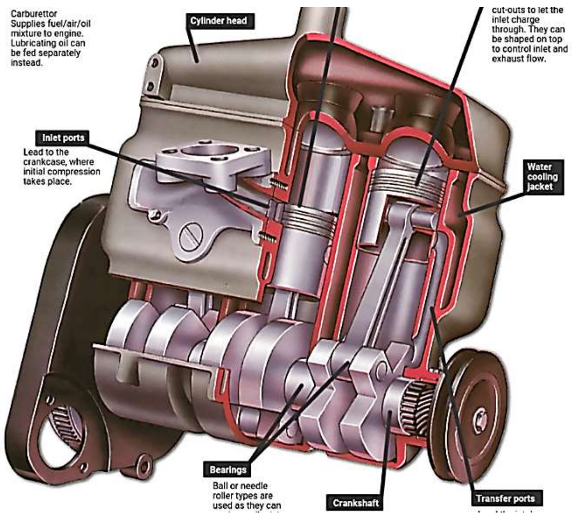
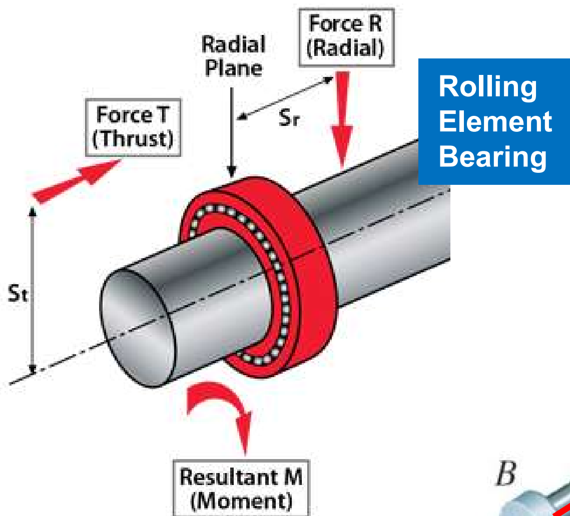
Two Bearing-Related Topics:

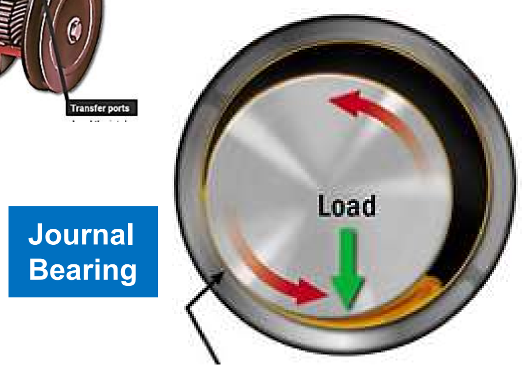
Ch. 11 Rolling-Contact Bearings
Ch. 12 Lubrication and Journal Bearings

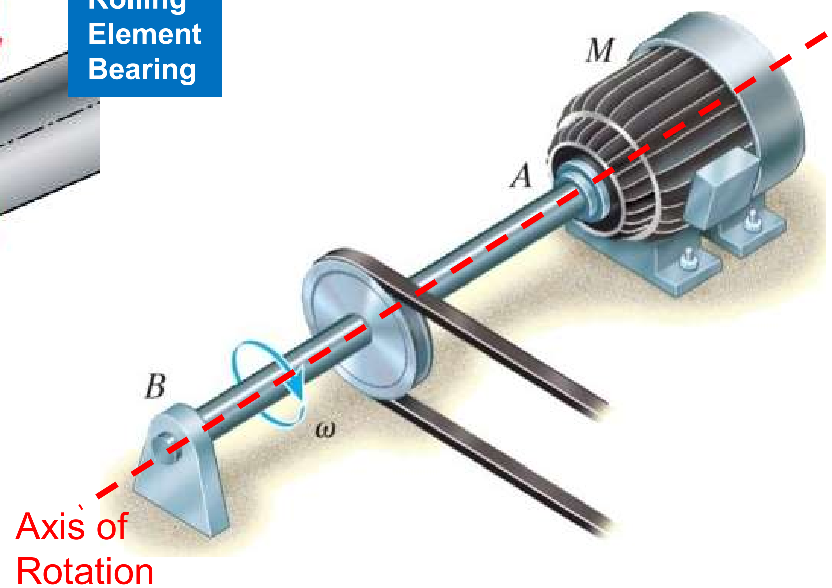
Bearing Functionality

The machine element introduced between two surfaces with relative motion to each other (moving vs. stationary or moving at different speed) while allowing load transmission through the motion interface.







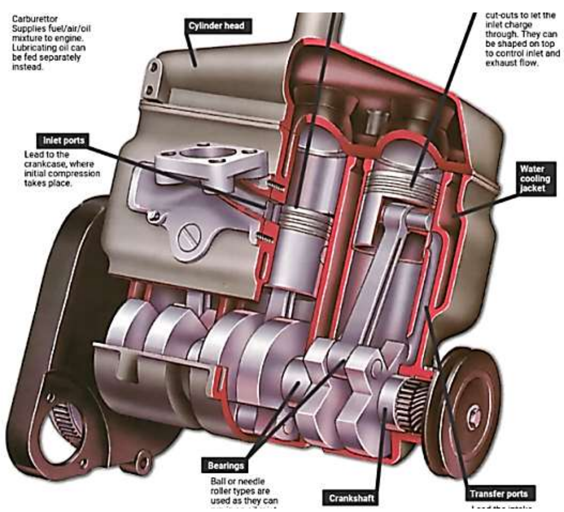


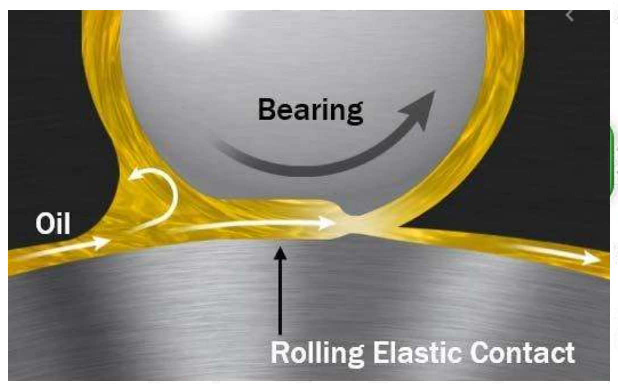
Bearing Terminology

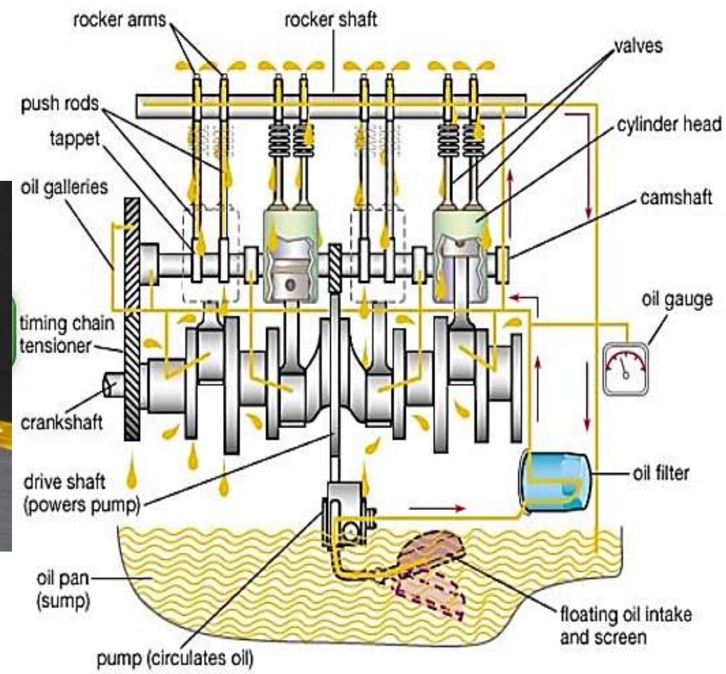
Lubrication: Any active or passive mean/mechanism delivering lubricant to load transmitting interface of a bearing.

Lubricant: Any interposed substance that reduces friction and wear of a load transmitting surface.

Purpose: The synergism of all of the above helps to lower friction, reduce material wear, prolong service life, and improve operation reliability of all mechanically driven equipment.

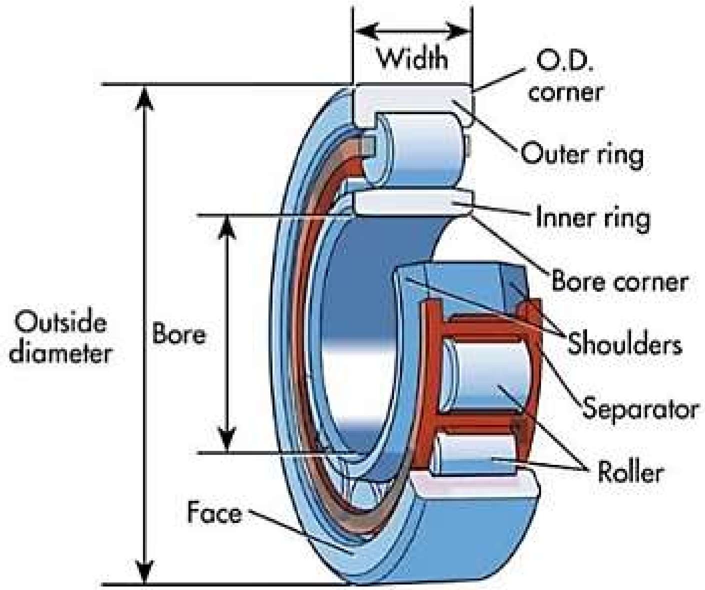




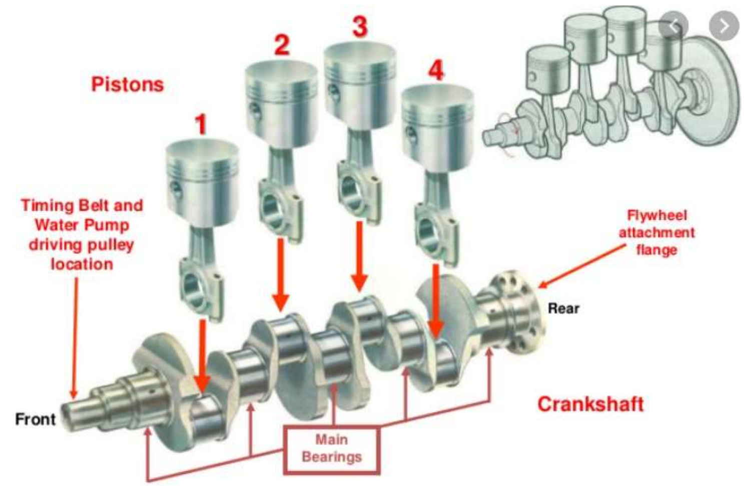


Examples of Bearing Configuration

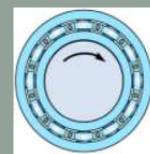
- Cylindrical Roller Bearings



- Crankshaft Radial Bearings



Comparison Between Journal vs Rolling Element Bearings Performance and Operation Characteristics

Characteristics	Rolling Element Bearing 	Journal Bearing 
Friction Torque, Start	**1**	28-80
Friction Torque, Running	**~0.5**	~1.4
Lubrication (Grease)	**Yes**	No
Lubrication (Oil)	**Yes**	**Yes**
Vertical Mounting	**Yes**	Special Design
High Speed	**Yes**	**Yes**
Low Speed	**Yes**	No
Shock Load Resistance	Weak	**Resilient**
Noise Level	High	**Low**
Space/Weight	High	**Low**
Assembly/Maintenance	Challenging	**Low-Moderate**
Cost	High	**Low**

Lecture Note 05A (Ch.11)
Rolling Contact Bearings: Ball Bearings

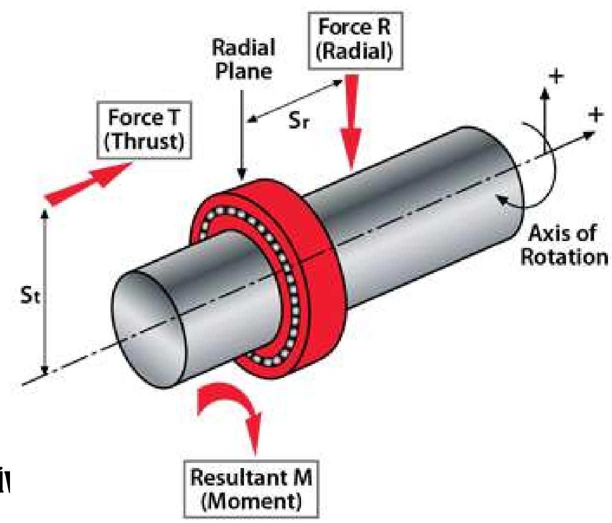
Instructor: Ping C. Sui, Ph.D.
ME 1029 Machine Design 2

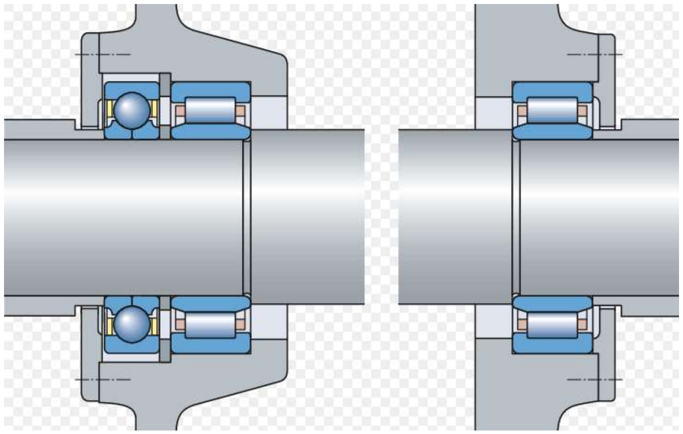
Fall 2021

Sichuan University - Pittsburgh Institute

Rolling Contact Bearings

- Common Names
  - Rolling contact bearing
  - antifriction bearing
  - rolling element bearing, etc.
- Primary advantages:
  - **Lower friction**: typical starting friction in a rolling bearing is negligible in comparison to a sleeve bearing
  - **Less heat generation**
- Primary disadvantage: cost, assembly, design envelope





Mechanical Designer's Responsibilities

- Mechanical designers working on system integration usually don't design rolling contact bearings.
- Specialty bearing suppliers (SKF, Timken, Schaffer, etc.) already designed and manufactured these bearings to fulfil specified load ratings, reliability life, etc. within prescribed space requirement.
- **Bearing specialists** must therefore consider such matters as fatigue loading, friction, heat, corrosion resistance, kinematic problems, material properties, lubrication, machining tolerances, assembly, use, and cost.
- Primary responsibilities of **mechanical development engineers** are to make decision on the proper bearing layout, type, and size within specified space limit, operating load, and lubricant/lubrication for bearings, etc.

Learning Objectives

- Learn to apply design parameters (load, speed, operation life, reliability, etc.) to calculate bearing equivalent load for
  - ball bearings;
  - cylindrical roller bearings; and
  - tapered roller bearings.
- Select bearings from manufacturer's catalog
- Assess selected bearing reliability

Topics Covered in Chapter 11

- 11–1 Bearing Types
- 11–2 Bearing Life
- 11–3 Bearing Load Life at Rated Reliability
- 11–4 Bearing Survival: Reliability versus Life
- 11–5 Relating Load, Life, and Reliability

Radial Bearings:
Deep Groove Ball Bearings
Cylindrical Roller Bearings

- 11–6 Combined Radial and Thrust Loading
- 11–8 Selection of Ball and Cylindrical Roller Bearings

Radial/Thrust Bearings:
Angular Contact Ball Bearings

- 11–9 Selection of Tapered Roller Bearings

Radial/Thrust Bearings:
Tapered Roller Bearings

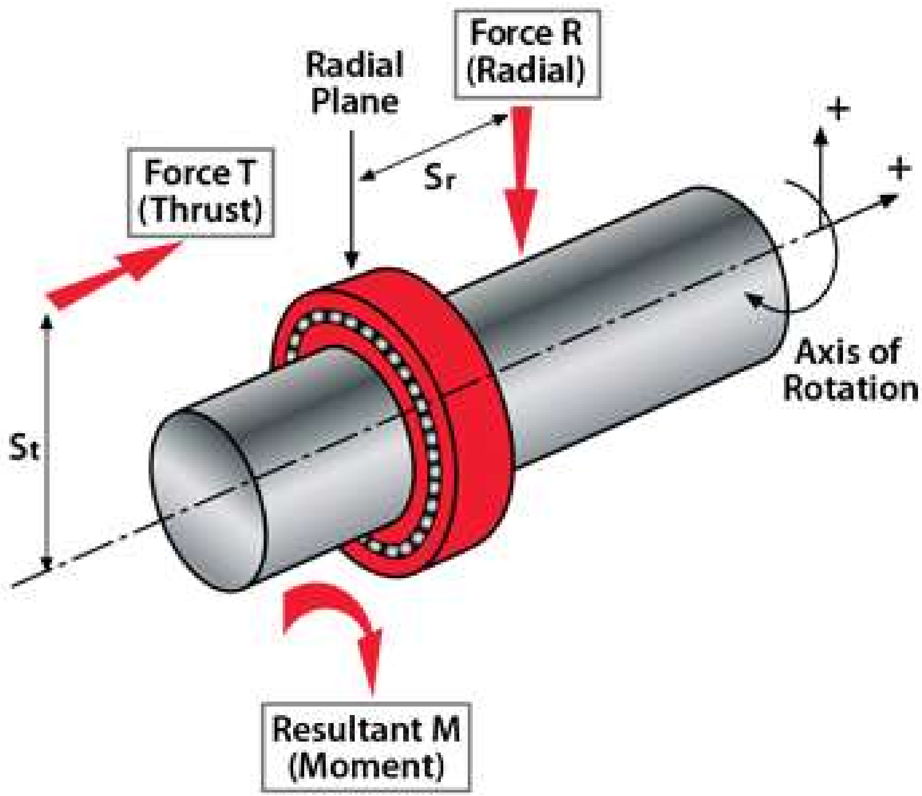
- 11–10 Design Assessment for Selected Rolling-Contact Bearings
- 11–11 Lubrication
- 11–12 Mounting and Enclosure
- 11–7 Variable Loading

11-1 Bearing Types

Bearing Types Based on Load-Carrying Capability

Bearing categories per load-carrying function:

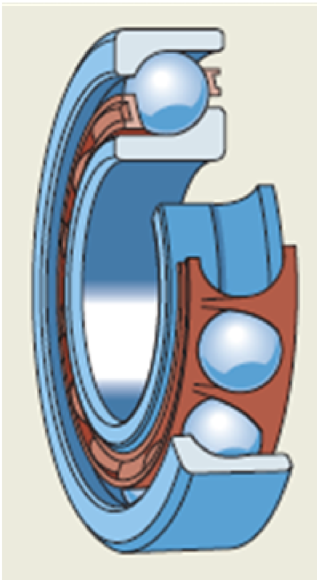
- **radial bearings**: carrying loads that are primarily radial
- **thrust bearings**: carrying loads that are primarily axial
- **angular contact bearings**: carrying combined radial and axial loads



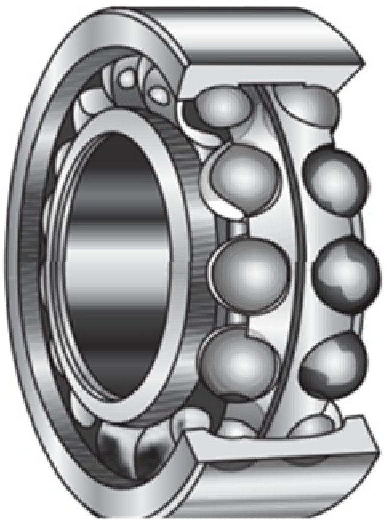
Bearing Types Based on Rolling Element

- Ball Bearings
- Roller Bearings

Single Row



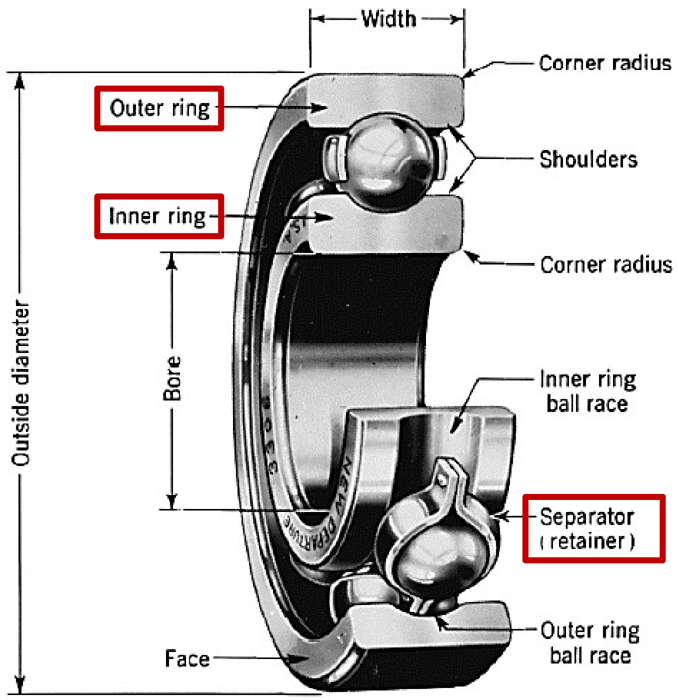
Double Row

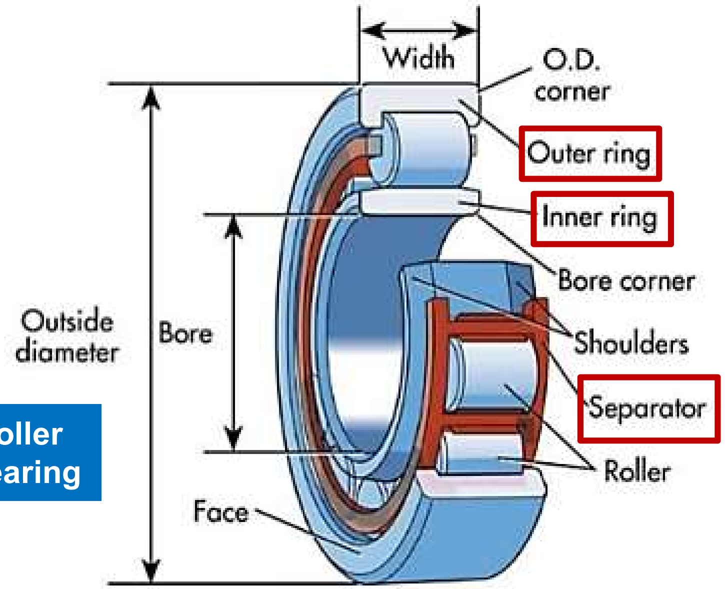


Ball/Roller Bearing Nomenclatures

- Four essential parts of a rolling element bearing:
  - outer ring (raceway),
  - inner ring (raceway),
  - rolling elements (balls or rollers); and
  - separator (or retainer)

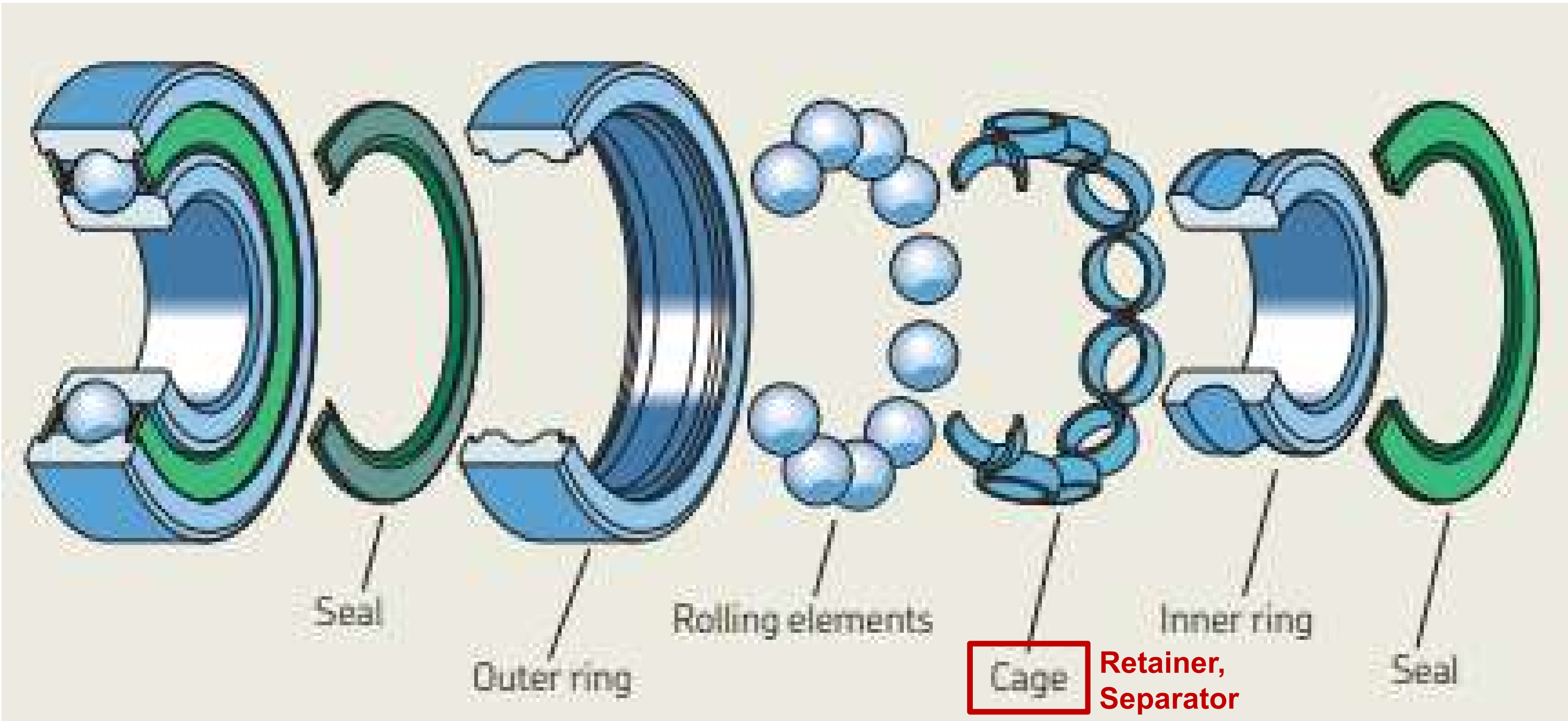
Figure 11–1
Ball Bearing

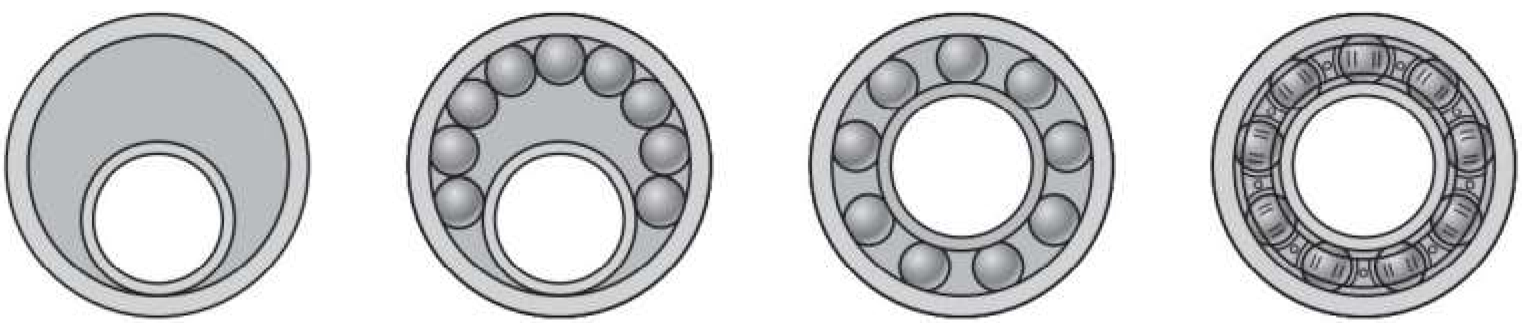




Roller Bearing

Construction of a Ball Bearing

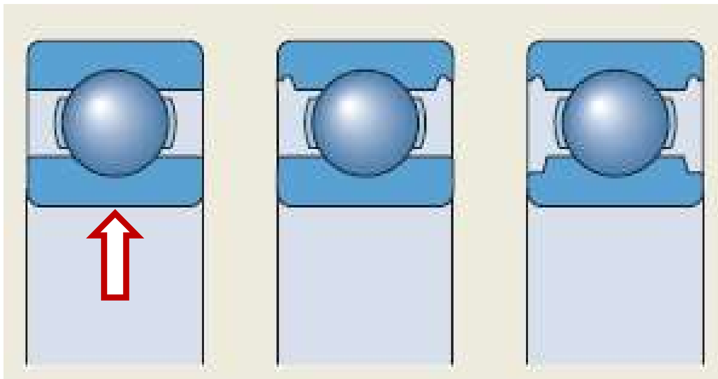


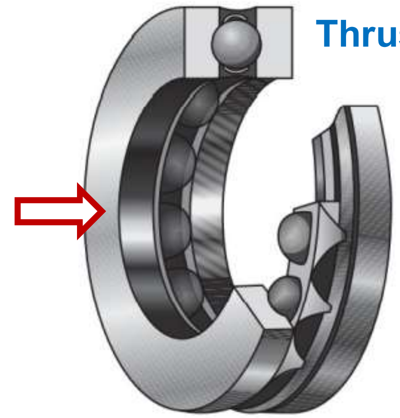


1 2 3 4

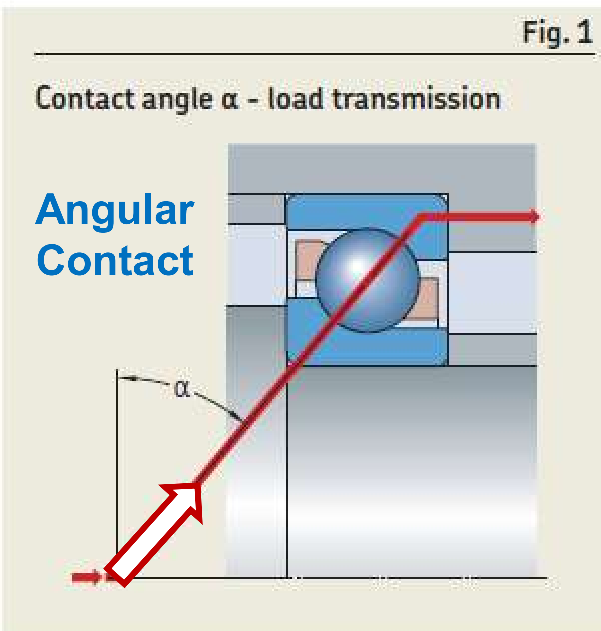
Ball Bearings: Capable of Higher Speed
Deep Groove vs. Angular Contact Ball Bearings

Deep Groove

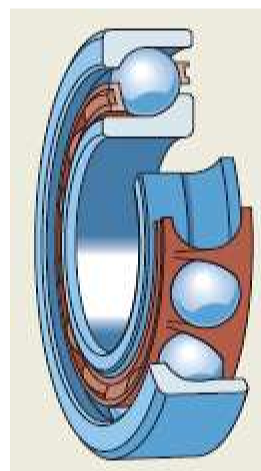




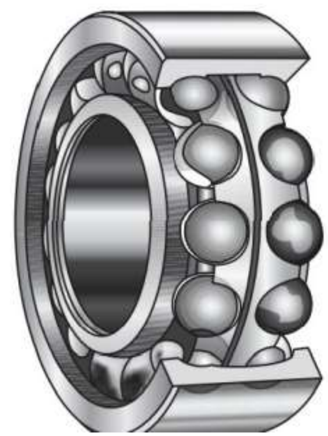
Thrust



Single Row

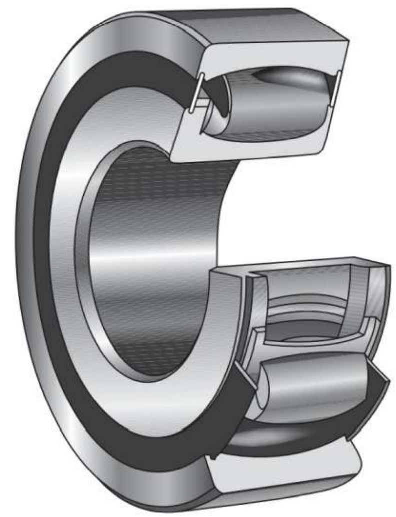


Double Row

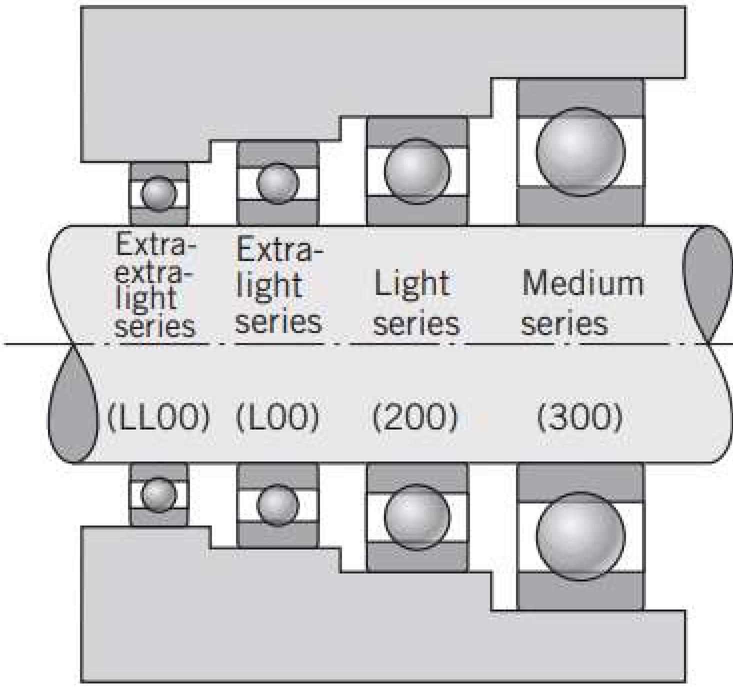


Roller Bearings: Carry Greater Loads

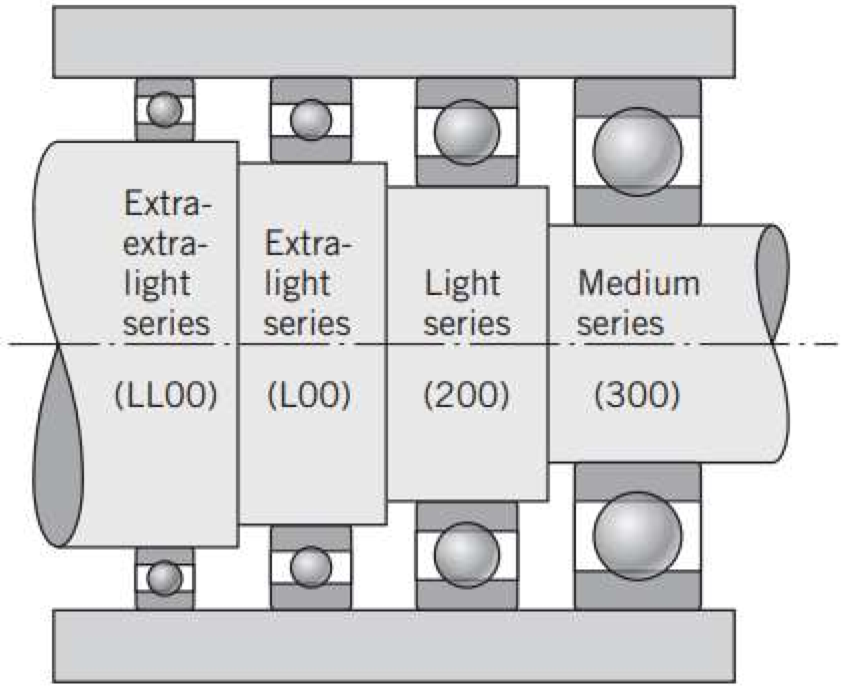
- Cylindrical roller bearing: radial load only, high load capacity but has less tolerance for misalignment
- Spherical roller bearing: useful where heavy loads and misalignment occur.
- Tapered roller bearing: combine advantages of ball and straight roller bearings; carries radial load as well as axial load.
- Needle roller bearing: useful where radial space is limited



Relative Proportions of Bearings of Different Series



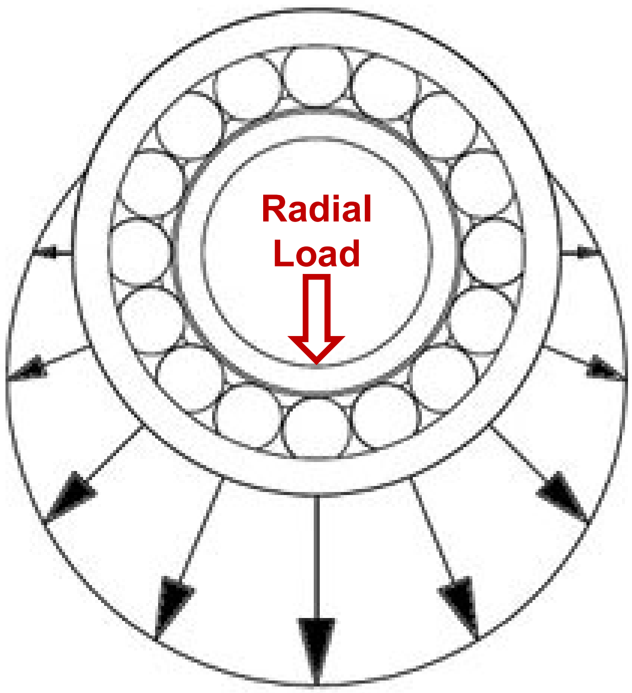
(a)
Relative proportions of bearings with same bore dimension



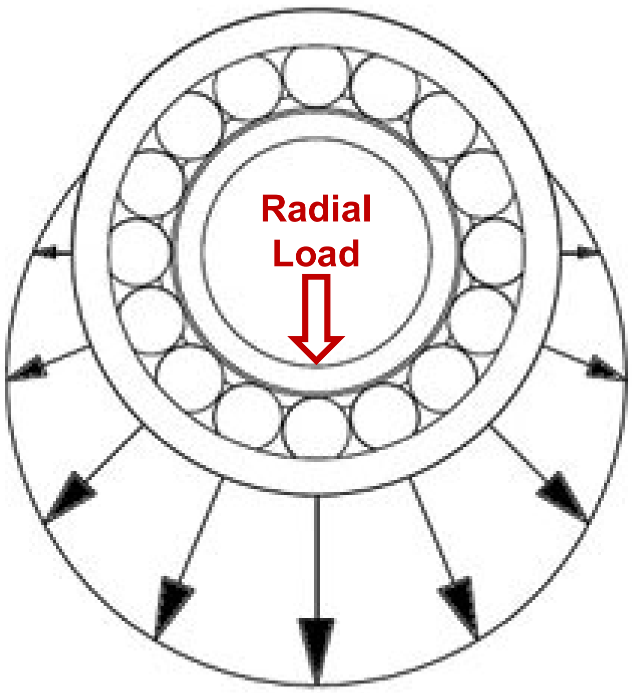
(b)
Relative proportions of bearings with same outside diameter

11-2 Definition of Bearing Life and Primary Failure Mode

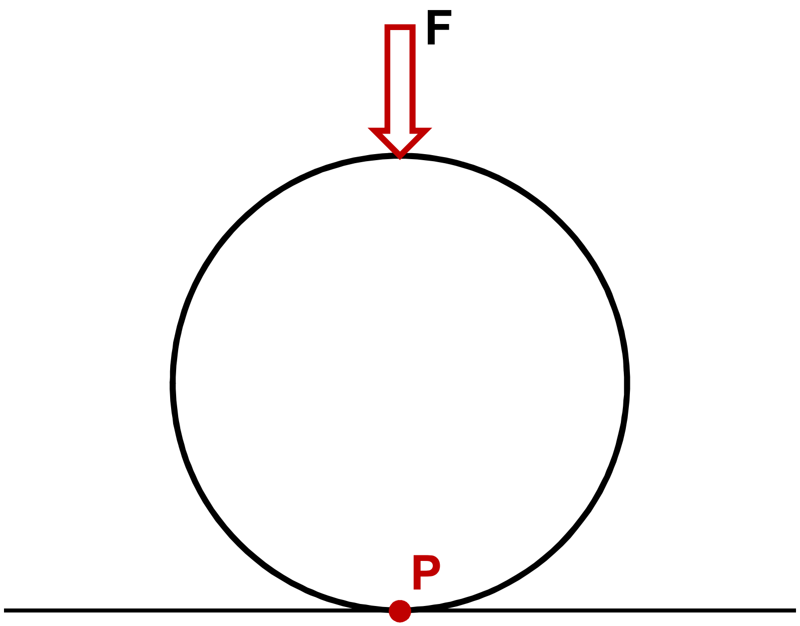
Load Distribution on Radial Ball Bearings



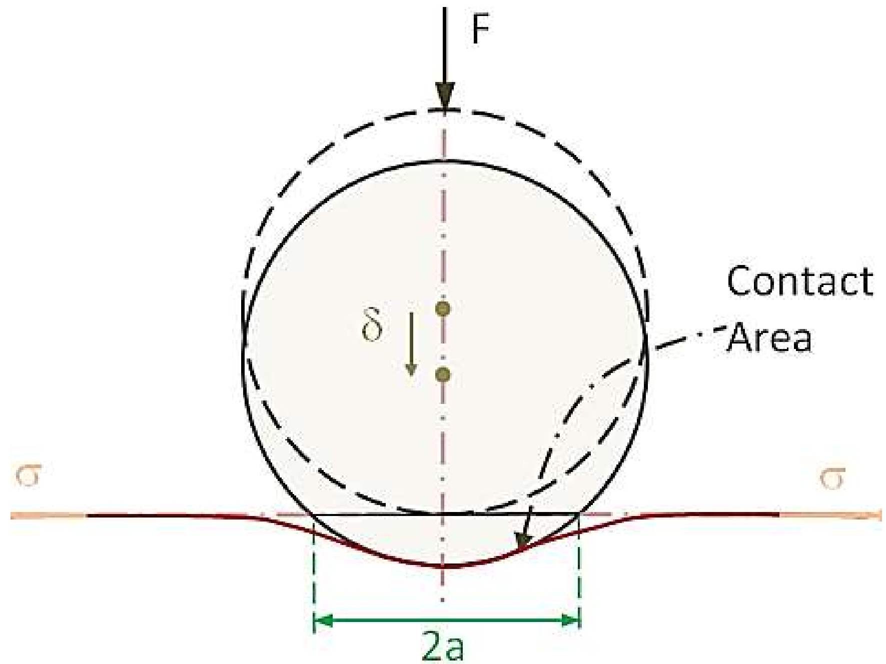
Load Distribution on Radial Ball Bearings



Forming a Bearing Contact Area

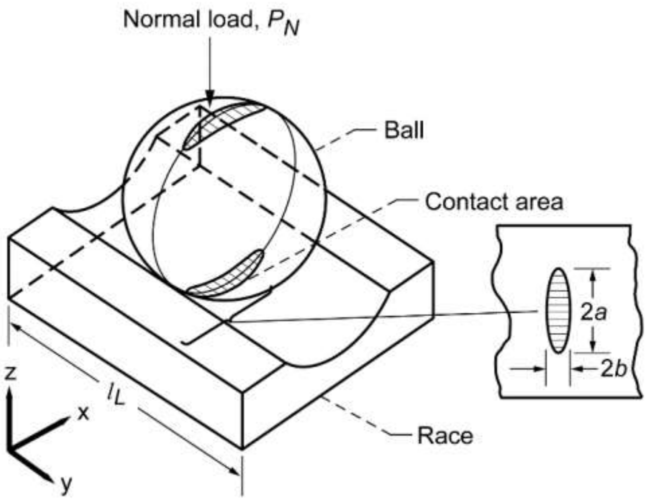


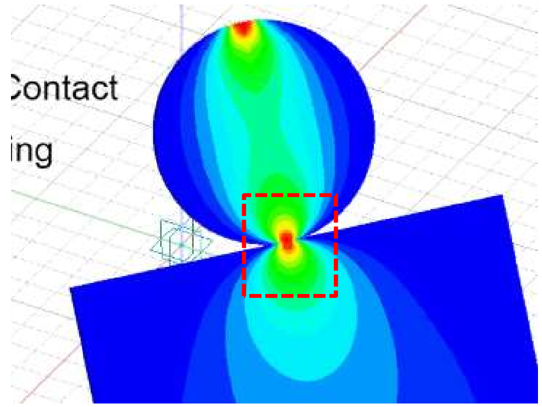
What happen at contact point P?
Contact Area: $A \rightarrow 0$
Nominal Contact Stress = $\frac{F}{A} = ??$

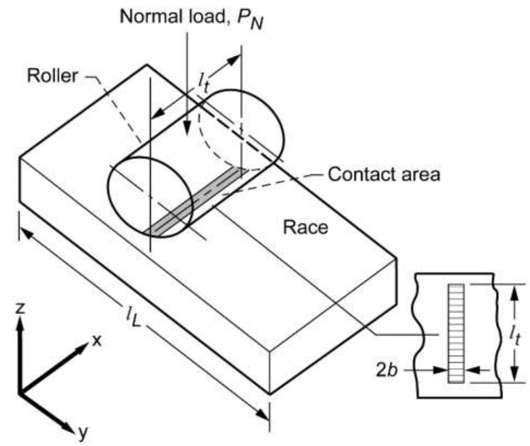


Elastic deformation yields a finite contact area.
Contact Stress is calculated by Hertz Theory (Ch.03-19)

Characteristics of Surface Contact Stress on Rolling Elements

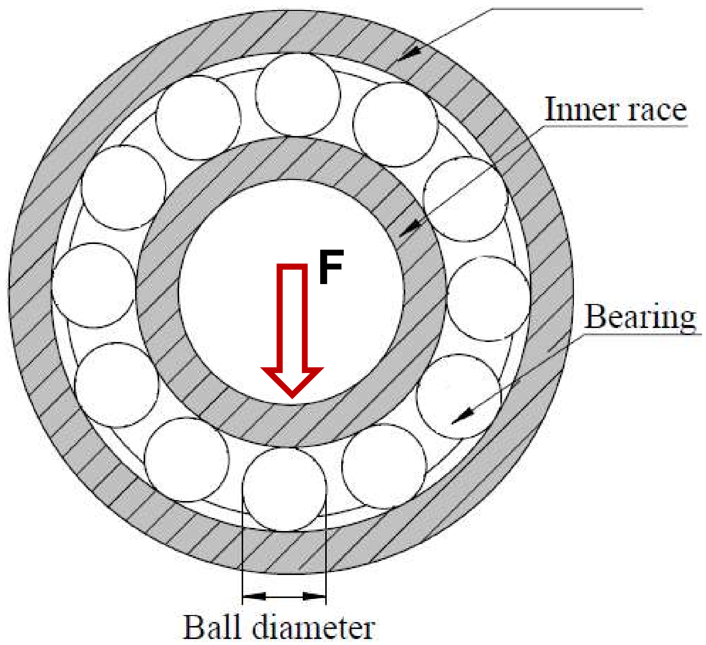






- Characteristics of Contact Stress (Hertz Theory, Ch.03):
  - Peak magnitude very high (> 1GPa)
  - Concentrated within small area (~100 μm)
  - Depth of max subsurface stress shallow (<100 μm)

Comparison of Contact Areas and Stresses



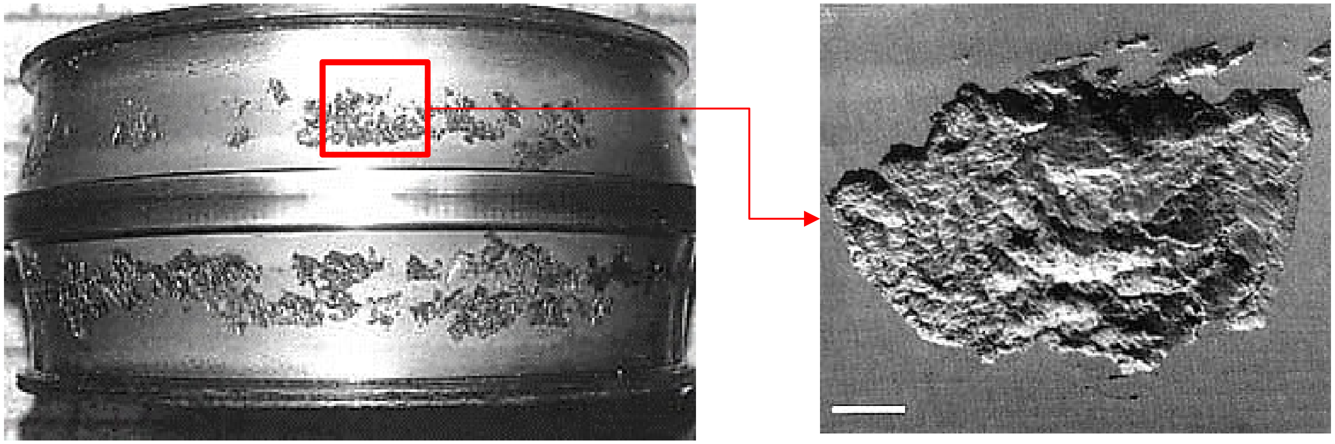
Which elements are seeing the load F?

Under loading, contact areas occur on (1) inner ring/rolling element interface, and (2) outer ring/rolling element interface.

Question: Which side has a smaller contact area (henceforth, higher stress)?

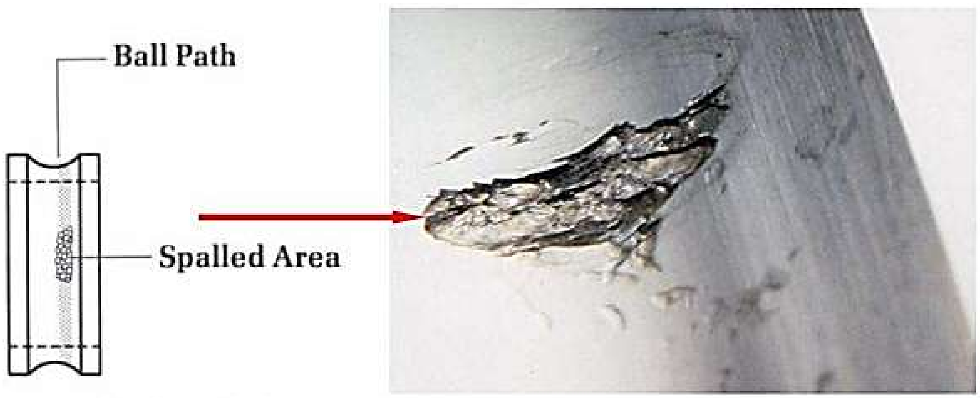
Bearing Life and Bearing Damaging Mechanisms

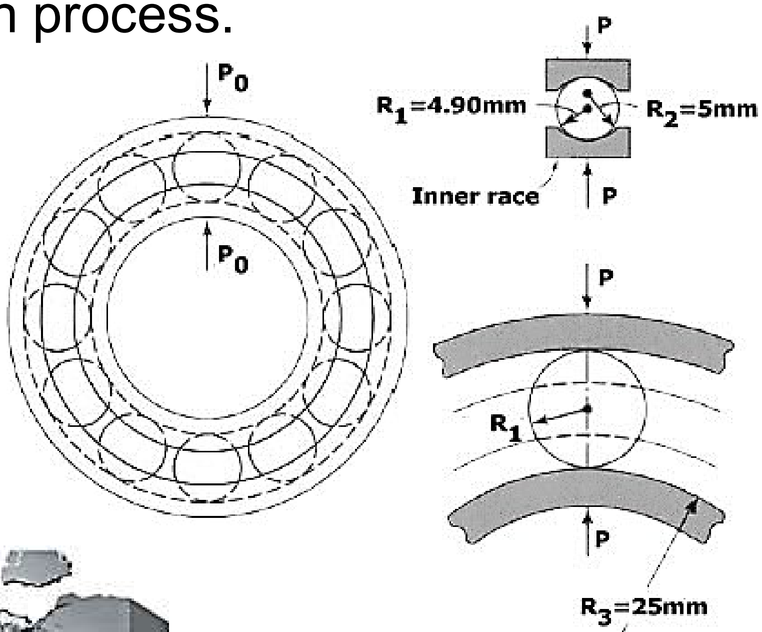
- When ball or roller of rolling-contact bearings rolls, contact stresses occur on inner ring, rolling element, and on outer ring
- Contact stresses are usually high (>1GPa) and metal fatigue is a common cause of failure.
- This failure type is known as **Rolling Contact Fatigue** (RCF).
- Typical phenomenon of RCF fatigue failure is <u>spalling</u> of the load carrying surfaces.

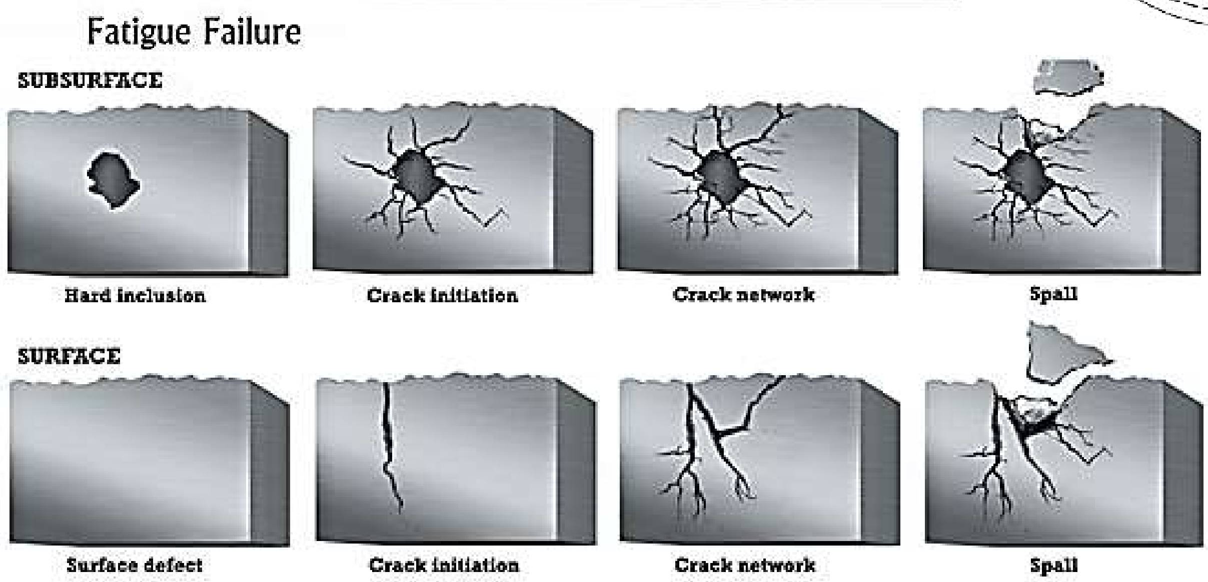


Bearing RCF: Spalling/Pitting/Surface Distress

RCF is a fatigue crack initiation/propagation process.

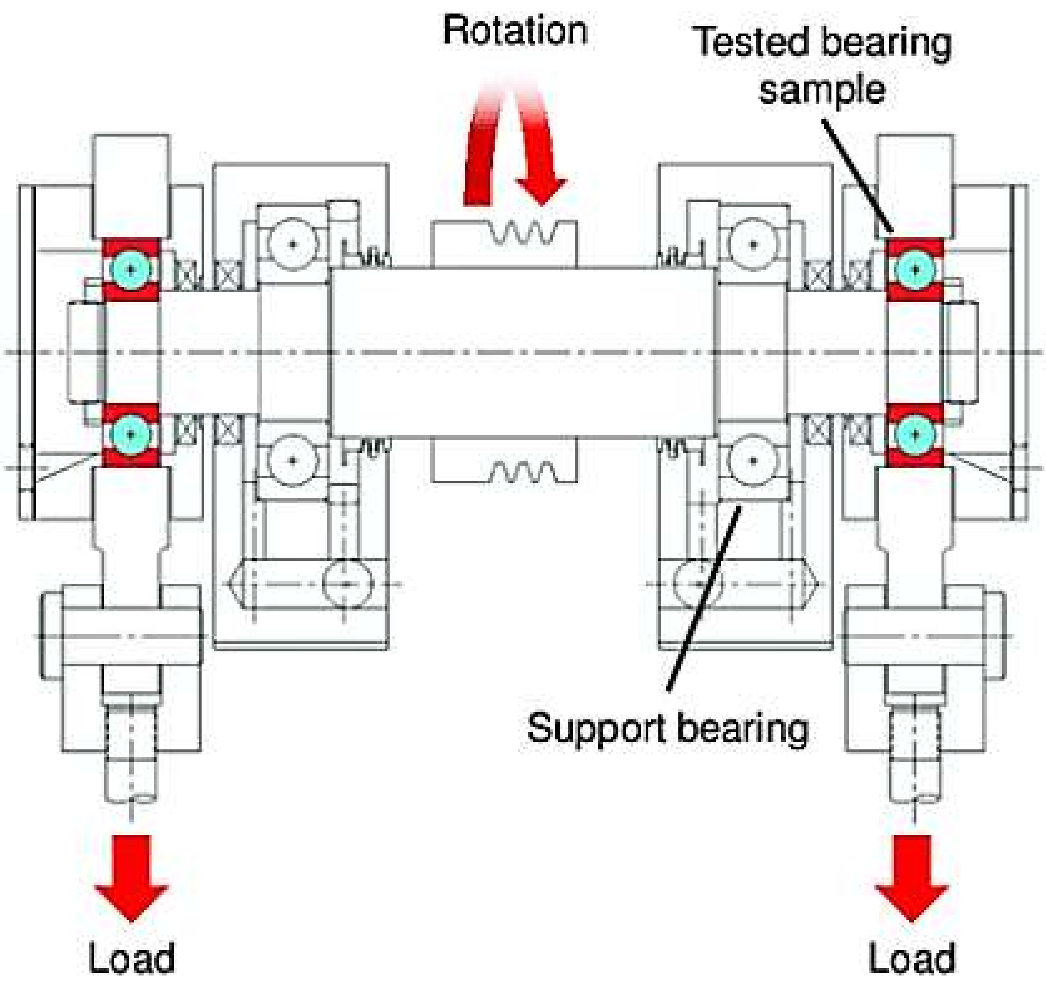






RCF failure usually initiates on inner ring.

Schematic of SKF R2 RCF Test Rig



Control Parameters

- Load
- Speed
- Bearing Types

Test continues until symptoms of failure detected or reaching benchmark of infinite life.

Failure criterion is the first evidence of fatigue with spalling or pitting of an area of 0.01 in^2.

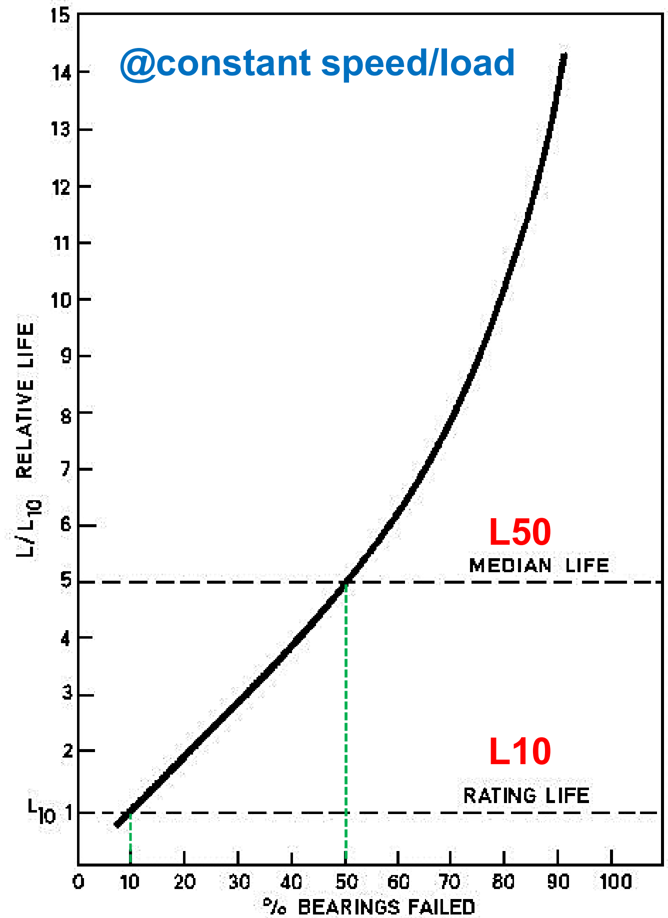
Bearing Life vs Testing

Multiple bearings were tested on RCF test rigs at constant speed/load.

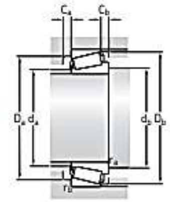
Bearing life defined as the total number of revolutions or hours from beginning to end of testing.

Terminology:

- **L10** (Minimum Life, Rating Life): fatigue life that 90 percent of the bearing population will endure
- **L50** (Median Life): life that 50 percent of the bearing population will endure
- Reported rating life (L10) by most bearing manufacturers is ~10^6 revolutions.
- Timken uses $90X10^6$ revolutions



Examples of SKF Bearing Manufacturer's Catalogue



Dimensions							Abutment and fillet dimensions									Calculation factors		
d	d_1 ≈	B	C	$r_{1,2}$ min.	$r_{3,4}$ min.	a	d_a max.	d_b min.	D_a min.	D_a max.	D_b min.	C_a min.	C_b min.	r_a max.	r_b max.	e	Y	Y_0
mm/in.							mm									–		
158,75 *6.25*	181	23,812 *0.9375*	18,258 *0.7188*	4,8 *0.19*	1,5 *0.06*	32	172	177	194	195	197	5	5,5	4,8	1,5	0,37	1,6	0,9
	181	23,812 *0.9375*	18,258 *0.7188*	1,5 *0.06*	1,5 *0.06*	32	172	170	194	195	197	5	5,5	1,5	1,5	0,37	1,6	0,9
165,1 *6.5*	242	95,25 *3.75*	69,85 *2.75*	3,3 *0.13*	6,4 *0.25*	69	203	182	280	315	308	14	22	3,3	6,4	0,37	1,6	0,9
177,8 *7*	203	30,162 *1.1875*	23,02 *0.9063*	1,5 *0.13*	1,5 *0.13*	42	190	190	212	216	220	5	7	1,5	1,5	0,44	1,35	0,8
	232	63,5 *2.5*	47,625 *1.875*	7 *0.28*	3,3 *0.13*	62	201	201	247	274	270	10	15,5	7	3,3	0,46	1,3	0,7
178,595 *7.0313*	216	57,15 *2.25*	38,895 *1.5313*	3,3 *0.13*	3,3 *0.13*	46	196	195	240	250	251	9	12,5	3,3	3,3	0,33	1,8	1
179,934 *7.084*	216	57,15 *2.25*	38,895 *1.5313*	3,3 *0.13*	3,3 *0.13*	46	196	196	240	250	251	9	12,5	3,3	3,3	0,33	1,8	1
187,325 *7.375*	232	47,625 *1.875*	36,512 *1.4375*	3,5 *0.14*	3,3 *0.13*	54	213	204	253	267	267	6	14	3,5	3,3	0,43	1,4	0,8
189,738 *7.47*	232	57,15 *2.25*	41,275 *1.625*	3,3 *0.13*	3,3 *0.13*	48	211	206	254	264	266	9	11	3,3	3,3	0,33	1,8	1
190,5 *7.5*	232	47,625 *1.875*	36,512 *1.4375*	3,5 *0.14*	3,3 *0.13*	54	213	207	253	267	267	6	14	3,5	3,3	0,43	1,4	0,8
196,85 *7.75*	217	23,017 *0.9062*	17,462 *0.6875*	1,5 *0.06*	1,5 *0.06*	40	207	209	232	230	235	5	6	1,5	1,5	0,43	1,4	0,8
	229	39,688 *1.5625*	30,162 *1.1875*	3,5 *0.14*	3,3 *0.13*	50	210	213	236	242	247	8	9,5	3,5	3,3	0,44	1,35	0,8
198,298 *7.807*	246	49,212 *1.9375*	36,512 *1.4375*	3,5 *0.14*	3,3 *0.13*	60	223	215	254	264	272	8	9,5	3,5	3,3	0,5	1,2	0,7
199,949 *7.872*	246	49,212 *1.9375*	36,512 *1.4375*	3,5 *0.14*	3,3 *0.13*	60	223	217	254	264	272	8	9,5	3,5	3,3	0,5	1,2	0,7
200,025 *7.875*	236	46,038 *1.8125*	34,133 *1.3438*	3,5 *0.14*	3,3 *0.13*	44	220	217	257	261	265	7	8,5	3,5	3,3	0,31	1,9	1,1
203,2 *8*	246	46,038 *1.8125*	36,512 *1.4375*	3,5 *0.14*	3,3 *0.13*	60	222	220	254	267	272	8	9,5	3,5	3,3	0,5	1,2	0,7

https://www.skf.com/binary/77-121486/SKF-rolling-bearings-catalogue.pdf

Manufacturer's Bearing Load Rating

- Catalog load rating (**C10**) is defined as the radial load of L10 life at the bearing manufacturer's rating life.
- C10 is often referred to as a <u>Basic Dynamic Load Rating</u>, or sometimes just Basic Load Rating

SKF Bearing Catalog

Dimensions							Basic load ratings dynamic	static	Fatigue load limit	Limiting speed with shaft tolerance h6	Mass	Designation
d	D	B	C	d_1 ≈	s_1	$r_{1,2}$ min.	C	C_0	P_u			
mm							kN		kN	r/min	kg	–
40	80	36	21	51,8	25,3	1	30,7	19	0,8	4 800	0,5	▸ **YAT 208**
	80	49,2	21	51,8	30,2	1	24,7	19	0,8	2 800	0,6	▸ **YAR 208-2RF/HV**
	80	49,2	21	51,8	30,2	1	24,7	19	0,8	2 800	0,6	**YAR 208-2RFGR/HV**
	80	49,2	21	51,8	30,2	1	30,7	19	0,8	950	0,59	▸ **YARAG 208**
	80	49,2	21	51,8	30,2	1	30,7	19	0,8	2 800	0,6	▸ **YAR 208-2RF**
	80	49,2	21	51,8	30,2	1	30,7	19	0,8	2 800	0,61	**YAR 208-2RF/VE495**
	80	49,2	21	51,8	30,2	1	30,7	19	0,8	4 800	0,6	▸ **YAR 208-2F**
45	85	37	22	56,8	25,8	1	33,2	21,6	0,915	4 300	0,56	▸ **YAT 209**
	85	49,2	22	56,8	30,2	1	33,2	21,6	0,915	850	0,66	**YARAG 209**
	85	49,2	22	56,8	30,2	1	33,2	21,6	0,915	2 400	0,67	▸ **YAR 209-2RF**
	85	49,2	22	56,8	30,2	1	33,2	21,6	0,915	4 300	0,67	▸ **YAR 209-2F**
50	90	38,8	22	62,5	27,6	1	35,1	23,2	0,98	4 000	0,63	▸ **YAT 210**
	90	51,6	22	62,5	32,6	1	29,6	23,2	0,98	2 200	0,76	▸ **YAR 210-2RF/HV**
	90	51,6	22	62,5	32,6	1	29,6	23,2	0,98	2 200	0,76	▸ **YAR 210-2RFGR/HV**
	90	51,6	22	62,5	32,6	1	35,1	23,2	0,98	800	0,75	▸ **YARAG 210**
	90	51,6	22	62,5	32,6	1	35,1	23,2	0,98	2 200	0,77	▸ **YAR 210-2RF**
	90	51,6	22	62,5	32,6	1	35,1	23,2	0,98	2 200	0,77	▸ **YAR 210-2RF/VE495**

Bearing Load Rating

- **Dynamic Load Rating (C_{10} or C)**
  - The first evidence of fatigue with spalling or pitting of an area of 0.01 in^2.
  - Used to estimate the life of a rotating bearing.

- **Static Load Ratings (C_0)**
  - The load that will produce a total permanent deformation in the raceway and rolling element at any contact point of 0.0001 times the diameter of the rolling element
  - Used to determine the maximum permissible load that can be applied to a non-rotating bearing or estimate thrust load of a rotating/non-rotating bearing.

Bearing Dimensions and Basic Load Ratings

Table 11-2 Single-Row 02-Series Deep-Groove and Angular-Contact Ball Bearings

Bore, mm	OD, mm	Width, mm	Fillet Radius, mm	Shoulder Diameter, mm d_S	d_H	Load Ratings, kN Deep Groove C_{10}	C_0	Angular Contact C_{10}	C_0
10	30	9	0.6	12.5	27	5.07	2.24	4.94	2.12
12	32	10	0.6	14.5	28	6.89	3.10	7.02	3.05
15	35	11	0.6	17.5	31	7.80	3.55	8.06	3.65
17	40	12	0.6	19.5	34	9.56	4.50	9.95	4.75
20	47	14	1.0	25	41	12.7	6.20	13.3	6.55
25	52	15	1.0	30	47	14.0	6.95	14.8	7.65
30	62	16	1.0	35	55	19.5	10.0	20.3	11.0
35	72	17	1.0	41	65	25.5	13.7	27.0	15.0
40	80	18	1.0	46	72	30.7	16.6	31.9	18.6
45	85	19	1.0	52	77	33.2	18.6	35.8	21.2
50	90	20	1.0	56	82	35.1	19.6	37.7	22.8
55	100	21	1.5	63	90	43.6	25.0	46.2	28.5
60	110	22	1.5	70	99	47.5	28.0	55.9	35.5
65	120	23	1.5	74	109	55.9	34.0	63.7	41.5
70	125	24	1.5	79	114	61.8	37.5	68.9	45.5
75	130	25	1.5	86	119	66.3	40.5	71.5	49.0
80	140	26	2.0	93	127	70.2	45.0	80.6	55.0
85	150	28	2.0	99	136	83.2	53.0	90.4	63.0
90	160	30	2.0	104	146	95.6	62.0	106	73.5
95	170	32	2.0	110	156	108	69.5	121	85.0

Table 11-3 for Cylindrical Roller Bearings

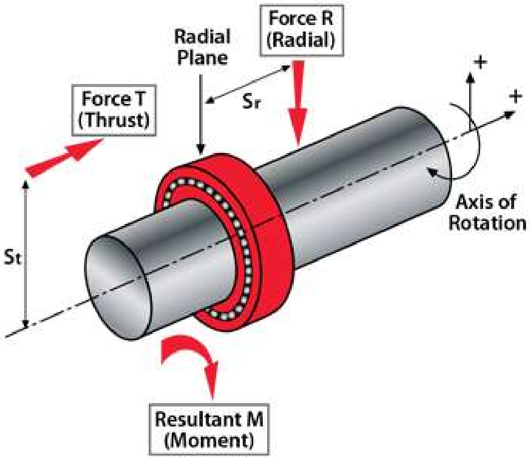
Bore, mm	02-Series OD, mm	Width, mm	Load Rating, kN C_{10}	C_0	03-Series OD, mm	Width, mm	Load Rating, kN C_{10}	C_0
25	52	15	16.8	8.8	62	17	28.6	15.0
30	62	16	22.4	12.0	72	19	36.9	20.0
35	72	17	31.9	17.6	80	21	44.6	27.1
40	80	18	41.8	24.0	90	23	56.1	32.5
45	85	19	44.0	25.5	100	25	72.1	45.4
50	90	20	45.7	27.5	110	27	88.0	52.0
55	100	21	56.1	34.0	120	29	102	67.2
60	110	22	64.4	43.1	130	31	123	76.5
65	120	23	76.5	51.2	140	33	138	85.0
70	125	24	79.2	51.2	150	35	151	102
75	130	25	93.1	63.2	160	37	183	125
80	140	26	106	69.4	170	39	190	125
85	150	28	119	78.3	180	41	212	149
90	160	30	142	100	190	43	242	160
95	170	32	165	112	200	45	264	189
100	180	34	183	125	215	47	303	220
110	200	38	229	167	240	50	391	304
120	215	40	260	183	260	55	457	340
130	230	40	270	193	280	58	539	408
140	250	42	319	240	300	62	682	454
150	270	45	446	260	320	65	781	502

Relating Catalogue Info to Design Data

Bore, mm	OD, mm	Width, mm	Fillet Radius, mm	Shoulder Diameter, mm d_S	Shoulder Diameter, mm d_H	Load Ratings, kN Deep Groove C_{10}	Deep Groove C_0	Angular Contact C_{10}	Angular Contact C_0
10	30	9	0.6	12.5	27	5.07	2.24	4.94	2.12
12	32	10	0.6	14.5	28	6.89	3.10	7.02	3.05
15	35	11	0.6	17.5	31	7.80	3.55	8.06	3.65

Bearing Catalogue Info
- Bore Diameter
- Load Ratings (C10)
- 1 MM cycles Life
- 90 percent reliability

Design Parameters
- Load: 2500 N
- Speed: 3000 rpm
- Duration: 5000 hours
- 3000rpmx5000hr = 15 MM cycles
- Reliability: 95 percent



11-3 Bearing Load-Life Relationship at Rated Reliability

- Bearing Load vs. Bearing Life (Same Reliability)

Bearing Load vs. Life Relationship

- Nominally identical bearing groups are tested at different loads to the life-failure criterion.
- Load vs. L10 life (90 percent endured) data are plotted on a log-log graph as shown in Fig. 11-4

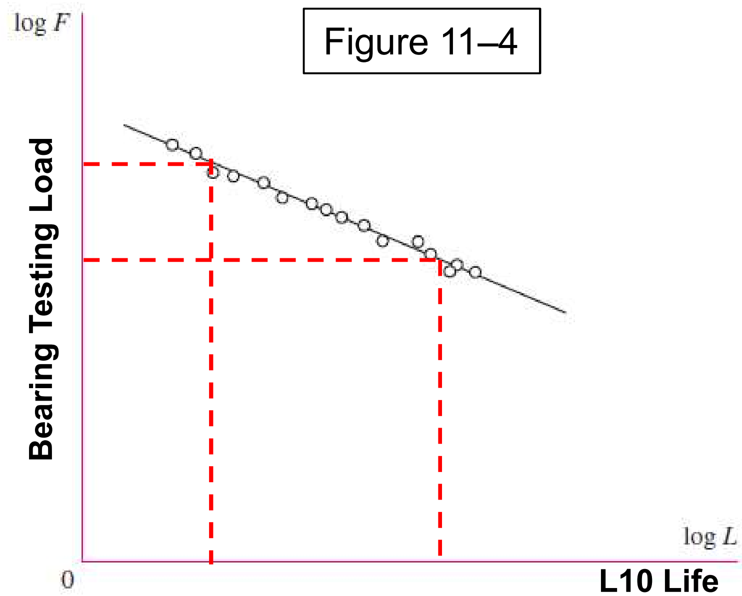


Figure 11–4

- Bearing load-life function
  $FL^{1/a} = constant$
  - ball bearings: $a = 3$
  - roller bearings: $a = \frac{10}{3}$
- Addressed Question:
  - Impact on bearing life while increasing/decreasing the bearing load under <u>90 percent reliability</u>

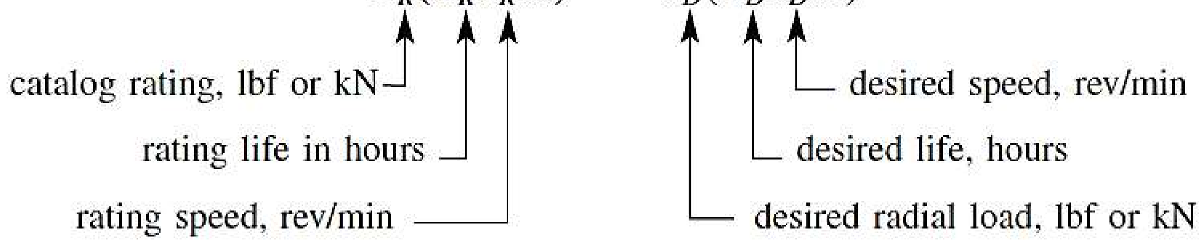
Bearing Load vs. Life Relationship

Relate desired load/life to catalog load rating life

$$F_R L_R^{1/a} = F_D L_D^{1/a}$$ (**R**: Rated; and **D**: Designed)

- Life (L) in revolutions: $L = 60 \cdot \mathcal{L} \cdot n$ ($\mathcal{L}$: hours; and n: rev/min)

$$F_R(\mathcal{L}_R n_R 60)^{1/a} = F_D(\mathcal{L}_D n_D 60)^{1/a}$$



Solving for F_R, we obtain an expression for a catalog load rating as a function of the desired load, desired life, and catalog rating life.

$$C_{10} = F_R = F_D \left(\frac{L_D}{L_R}\right)^{1/a} = F_D \left(\frac{\mathcal{L}_D n_D}{\mathcal{L}_R n_R}\right)^{1/a}$$

Example 11-1

Consider SKF rates its bearings for 1-million revolutions.

If life of 5000 h @1725 rev/min with a load of 400 lbf and reliability of 90 percent is desired, for which catalog rating would you search in a catalog?

Solution:

Decoding design requirement information :

- Assume a ball bearing will be used
- 90 percent reliability
- $F_D = 400\ lbf$
- $\mathcal{L}_D = 5000\ h$
- $n_D = 1725\ rpm$

Design target: 517.5×10^6 revolutions

SKF information: $L_{10} = L_R = 60\mathcal{L}_R n_R = 10^6$ revolutions

$$C_{10} = F_D \left(\frac{\mathcal{L}_D n_D}{\mathcal{L}_R n_R}\right)^{1/a} = 400 \left(\frac{5000 \cdot 1725 \cdot 60}{10^6}\right)^{1/3} = 3211\ lbf = 14.3\ kN$$

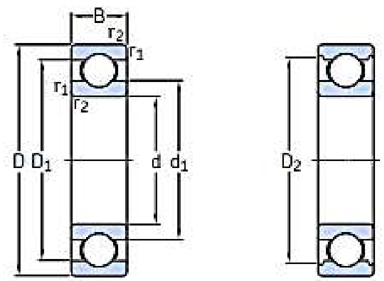
Will have to pick a bearing with minimum load rating of 14.3 kN from catalogue.

Example 11-1 (Cont'd)

Consider SKF rates its bearings for 1 million revolutions. If you desire a life of 5000 h at 1725 rev/min with a load of 400 lbf with a reliability of 90 percent, for which catalog rating would you search in an SKF catalog?

1.1 Single row deep groove ball bearings
d 17 – 22 mm

$$C_{10} = 14.3\ kN$$



A 6300-series SKF single row deep groove ball bearing can be used for this application.

Principal dimensions			Basic load ratings dynamic	static	Fatigue load limit	Speed ratings Reference speed	Limiting speed[1]	Mass	Designations Bearing open or capped on both sides	capped on one side[1]
d	D	B	C	C_0	P_u					
mm			kN		kN	r/min		kg	–	
17 cont.	47	14	14,3	6,55	0,275	34 000	22 000	0,11	▸ 6303	–
	47	14	14,3	6,55	0,275	–	11 000	0,12	▸ 6303-2RSH	6303-RSH
	47	14	14,3	6,55	0,275	34 000	17 000	0,12	6303-2RSL	6303-RSL
	47	14	14,3	6,55	0,275	34 000	17 000	0,12	▸ 6303-2Z	6303-Z
	47	19	13,5	6,55	0,275	–	11 000	0,16	62303-2RS1	–
	62	17	22,9	10,8	0,455	28 000	18 000	0,27	6403	–
20	32	7	4,03	2,32	0,104	–	13 000	0,018	▸ 61804-2RS1	–
	32	7	4,03	2,32	0,104	45 000	22 000	0,018	▸ 61804-2RZ	–
	32	7	4,03	2,32	0,104	45 000	28 000	0,018	▸ 61804	–

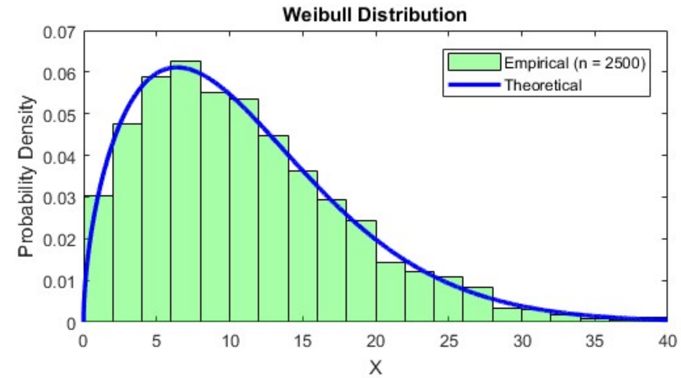
11-4 Bearing Reliability-Life Relationship
11-5 Bearing Load-Life-Reliability Relationship

- Scenario 1: Bearing Life vs. Reliability
- Scenario 2: How to relate bearing manufacturer's reported test load, test speed, and reliability to designer's application load, speed, and reliability conditions?

Bearing Survival: Reliability versus Life

At constant load, relationship between bearing reliability and life:

$$R = exp\left[-\left(\frac{x-x_0}{\theta-x_0}\right)^b\right]$$



- R = reliability
- x = life measure dimensionless variate, $\frac{L}{L_{10}}$
- x_o = "minimum," value of the variate
- θ = characteristic parameter corresponding to the 63.2121 percentile value of the variate
- b = shape parameter that controls the skewness

Parameters x_0, θ and b <u>need to be provided by bearing manufacturers</u>; however, manufacturers usually consider these to be highly proprietary information. Henceforth, there is not much mechanical designers can do.

Assumed values in textbook are what usually used by designers:

- x_0= 0.02, $(\theta- x_0)$ = 4.439, and b = 1.483

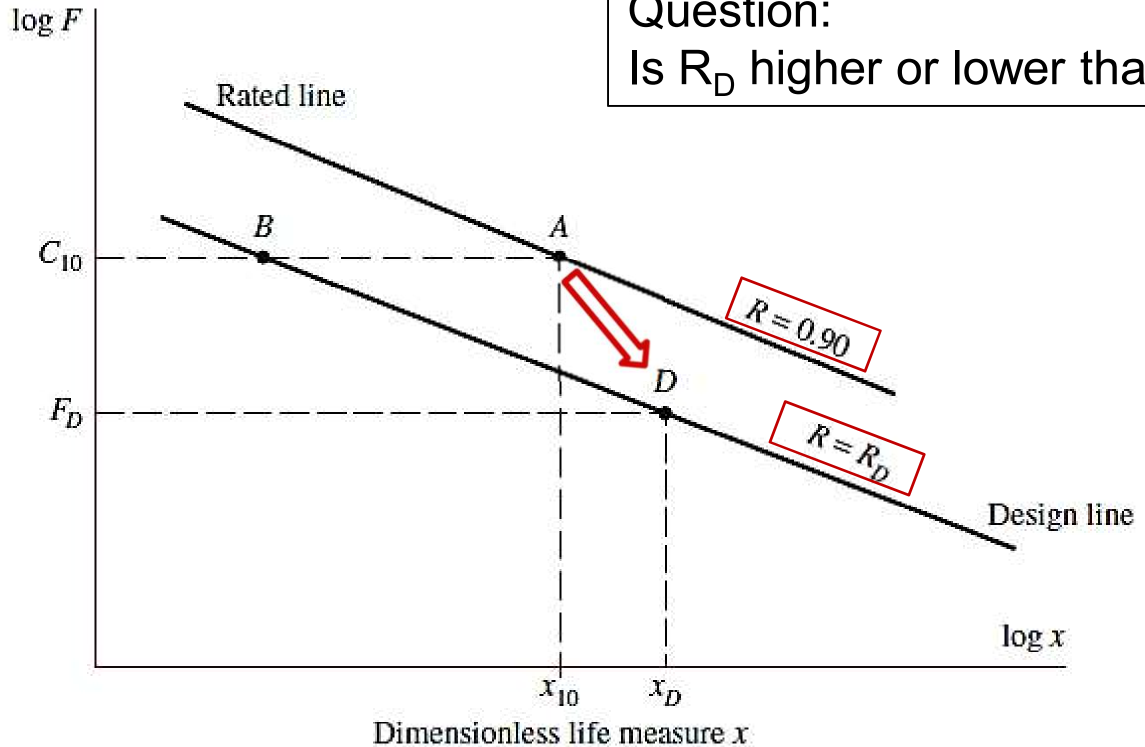
Constant Reliability Contours

Point A: catalog rating C_{10} at x = $\frac{L}{L_{10}}$ = 1 $\left(x_{10} = \frac{L_{10}}{L_{10}} = 1\right)$

Point D: desired reliability R_D with design life $x_D = \frac{L_D}{L_{10}}$ at design load F_D

Addressed Question: Given a bearing (known C10,), what is its reliability under design x_D and F_D?

Question:
Is R_D higher or lower than 90%?



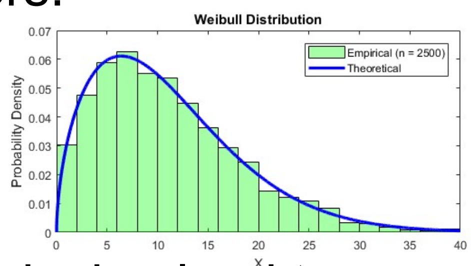
Load-Life-Reliability Relation

$$C_{10} = a_f F_D \left[\frac{x_D}{x_0 + (\theta - x_0)(1 - R_D)^{1/b}} \right]^{1/a}$$

Convert from a design load, life, and reliability to a catalog load rating based on a rating life at 90 percent reliability.

Or in the following form with standard **Weibull** parameters:

$$C_{10} = a_f F_D \left[\frac{x_D}{0.02 + 4.439(1 - R_D)^{0.674}} \right]^{1/a}$$



Application Factor: $a_f \geq 1.0$

- which serves as a factor of safety to increase the design load to take into account overload, dynamic loading, and uncertainty.

Type of Application	Load Factor
Precision gearing	1.0–1.1
Commercial gearing	1.1–1.3
Applications with poor bearing seals	1.2
Machinery with no impact	1.0–1.2
Machinery with light impact	1.2–1.5
Machinery with moderate impact	1.5–3.0

Table 11-5
Recommended Load-Application Factors

EXAMPLE 11-3

The design load on a ball bearing is 413 lbf and an application factor of 1.2 is appropriate. The speed of the shaft is to be 300 rev/min, the life to be 30 kh with a reliability of 0.99.

What is the C10 catalog entry to be sought (or exceeded) when searching for a deep-groove bearing in a manufacturer's catalog on the basis of 10^6 evolutions for rating life?

[The Weibull parameters are x_0=0.02, (θ- x_0)=4.439, and b=1.483.]

<u>Solution:</u>

$$x_D = \frac{L_D}{L_R} = \frac{60 \cdot 30000 \cdot 300}{10^6} = 540$$

So the equivalent catalog load rating is

$$C_{10} = a_f F_D \left[\frac{x_D}{0.02 + 4.439(1 - R_D)^{0.674}}\right]^{1/a} = 1.2 \cdot 413 \left[\frac{540}{0.02 + 4.439(1 - 0.99)^{0.674}}\right]^{1/3} = 6696\ lbf$$

C_{10} = 6696 lbf (= 29.8 kN)

Table 11-2 Single-Row 02-Series Deep-Groove and Angular-Contact Ball Bearings

Bore, mm	OD, mm	Width, mm	Fillet Radius, mm	Shoulder Diameter, mm d_S	d_H	Load Ratings, kN Deep Groove C_{10}	C_0	Angular Contact C_{10}	C_0
10	30	9	0.6	12.5	27	5.07	2.24	4.94	2.12
12	32	10	0.6	14.5	28	6.89	3.10	7.02	3.05
15	35	11	0.6	17.5	31	7.80	3.55	8.06	3.65
17	40	12	0.6	19.5	34	9.56	4.50	9.95	4.75
20	47	14	1.0	25	41	12.7	6.20	13.3	6.55
25	52	15	1.0	30	47	14.0	6.95	14.8	7.65
30	62	16	1.0	35	55	19.5	10.0	20.3	11.0
35	72	17	1.0	41	65	25.5	13.7	27.0	15.0
40	80	18	1.0	46	72	30.7	16.6	31.9	18.6
45	85	19	1.0	52	77	33.2	18.6	35.8	21.2
50	90	20	1.0	56	82	35.1	19.6	37.7	22.8
55	100	21	1.5	63	90	43.6	25.0	46.2	28.5
60	110	22	1.5	70	99	47.5	28.0	55.9	35.5
65	120	23	1.5	74	109	55.9	34.0	63.7	41.5
70	125	24	1.5	79	114	61.8	37.5	68.9	45.5
75	130	25	1.5	86	119	66.3	40.5	71.5	49.0
80	140	26	2.0	93	127	70.2	45.0	80.6	55.0
85	150	28	2.0	99	136	83.2	53.0	90.4	63.0
90	160	30	2.0	104	146	95.6	62.0	106	73.5
95	170	32	2.0	110	156	108	69.5	121	85.0

Load-Life-Reliability Relation

$$C_{10} = a_f F_D \left[\frac{x_D}{x_0 + (\theta - x_0)(1 - R_D)^{1/b}} \right]^{1/a}$$

It can be re-arranged to get:

$$R = exp\left\{ - \left[\frac{x_D \left(\frac{a_f F_D}{C_{10}} \right)^a - x_0}{\theta - x_0} \right]^b \right\}$$

, or approximate by:

$$R \approx 1 - \left[\frac{x_D \left(\frac{a_f F_D}{C_{10}} \right)^a - x_0}{\theta - x_0} \right]^b \qquad R \geq 0.90$$

EXAMPLE 11-9

In Ex.11–3, the minimum required load rating for 99 percent reliability, at x_D = 540, is C_{10} = 6696 lbf (= 29.8 kN). From Table 11–2, a 02-40 mm deep groove ball bearing would satisfy the requirement.

40	80	18	1.0	46	72	1	30.7	16.6	31.9	18.6

If the bore in the application had to be 70 mm or larger (selecting a 02-70 mm deep-groove ball bearing), what is the resulting reliability?

[The Weibull parameters are x_0=0.02, $(\theta- x_0)$=4.439, and b=1.483.]

Solution:

Table 11-2, for a 02-70 mm deep-groove ball bearing

70	125	24	1.5	79	114	61.8	37.5	68.9	45.5

C_{10}=61.8 kN=13888 lbf

$$R \approx 1 - \left[\frac{x_D\left(\frac{a_f F_D}{C_{10}}\right)^a - x_0}{\theta - x_0}\right]^b = 1 - \left\{\left[\frac{540\left(\frac{1.2\cdot 413}{13888}\right)^3 - 0.02}{4.439}\right]^{1.483}\right\} = 0.999963$$

which, as expected, is much higher than 0.99.

Table 11–2

Dimensions and Load Ratings for Single-Row 02-Series Deep-Groove and Angular-Contact Ball Bearings

Bore, mm	OD, mm	Width, mm	Fillet Radius, mm	Shoulder Diameter, mm d_S	Shoulder Diameter, mm d_H	Load Ratings, kN Deep Groove C_{10}	Load Ratings, kN Deep Groove C_0	Load Ratings, kN Angular Contact C_{10}	Load Ratings, kN Angular Contact C_0
10	30	9	0.6	12.5	27	5.07	2.24	4.94	2.12
12	32	10	0.6	14.5	28	6.89	3.10	7.02	3.05
15	35	11	0.6	17.5	31	7.80	3.55	8.06	3.65
17	40	12	0.6	19.5	34	9.56	4.50	9.95	4.75
20	47	14	1.0	25	41	12.7	6.20	13.3	6.55
25	52	15	1.0	30	47	14.0	6.95	14.8	7.65
30	62	16	1.0	35	55	19.5	10.0	20.3	11.0
35	72	17	1.0	41	65	25.5	13.7	27.0	15.0
40	80	18	1.0	46	72	30.7	16.6	31.9	18.6
45	85	19	1.0	52	77	33.2	18.6	35.8	21.2
50	90	20	1.0	56	82	35.1	19.6	37.7	22.8
55	100	21	1.5	63	90	43.6	25.0	46.2	28.5
60	110	22	1.5	70	99	47.5	28.0	55.9	35.5
65	120	23	1.5	74	109	55.9	34.0	63.7	41.5
70	125	24	1.5	79	114	61.8	37.5	68.9	45.5
75	130	25	1.5	86	119	66.3	40.5	71.5	49.0
80	140	26	2.0	93	127	70.2	45.0	80.6	55.0
85	150	28	2.0	99	136	83.2	53.0	90.4	63.0
90	160	30	2.0	104	146	95.6	62.0	106	73.5
95	170	32	2.0	110	156	108	69.5	121	85.0

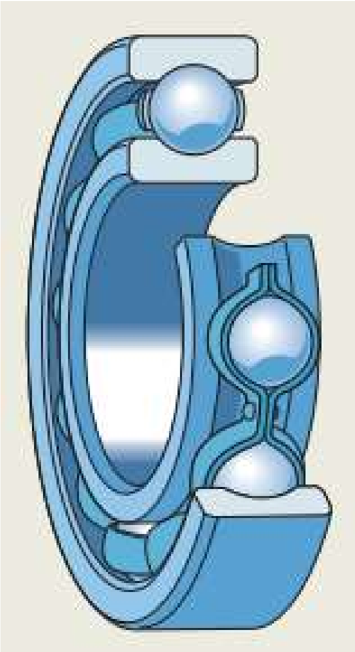
System and Individual Bearing Reliability

Shafts generally have two bearings (A and B). Often these bearings are different. If the bearing reliability of the shaft with its pair of bearings is to be R, then R is related to the individual bearing by:

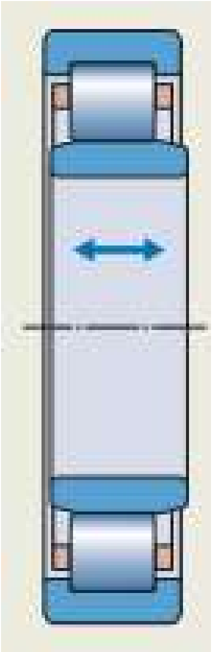
- Bearing reliability of the shaft: $R = R_A \cdot R_B$
- For initial sizing, assume $R_A = R_B = \sqrt{R}$
- Another possibility is to use the reliability of one bearing, say R_A. Then set the reliability goal of the second as $R_B = \frac{R}{R_A}$ or vice versa.
- Design-wise, it is possible and acceptable to round down $R_A < \sqrt{R}$ or $R_B < \sqrt{R}$ as long as maintaining $R_A \cdot R_B \geq R$.

Bearings Without Axial Loading

- Up to this point, bearings under discussions are without capacity for axial loading.
- Bearing selections are from **Table 11-2** (Deep-Groove Ball Bearing) and **Table 11-3** (Cylindrical Roller Bearing)



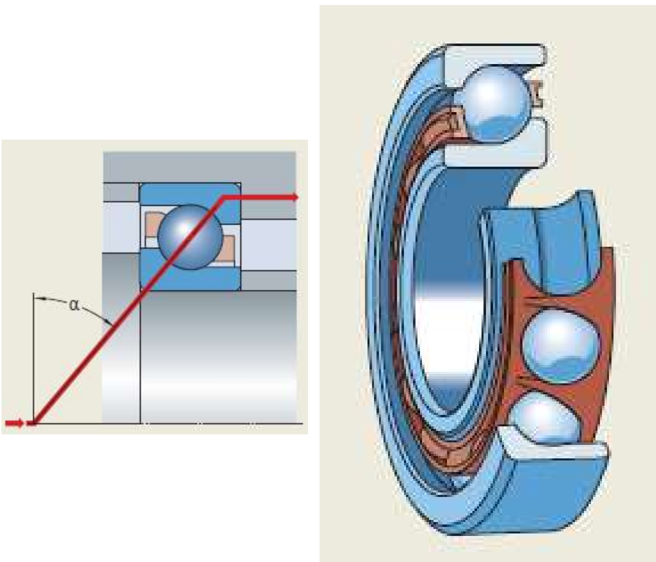
Deep-Groove
Ball Bearing



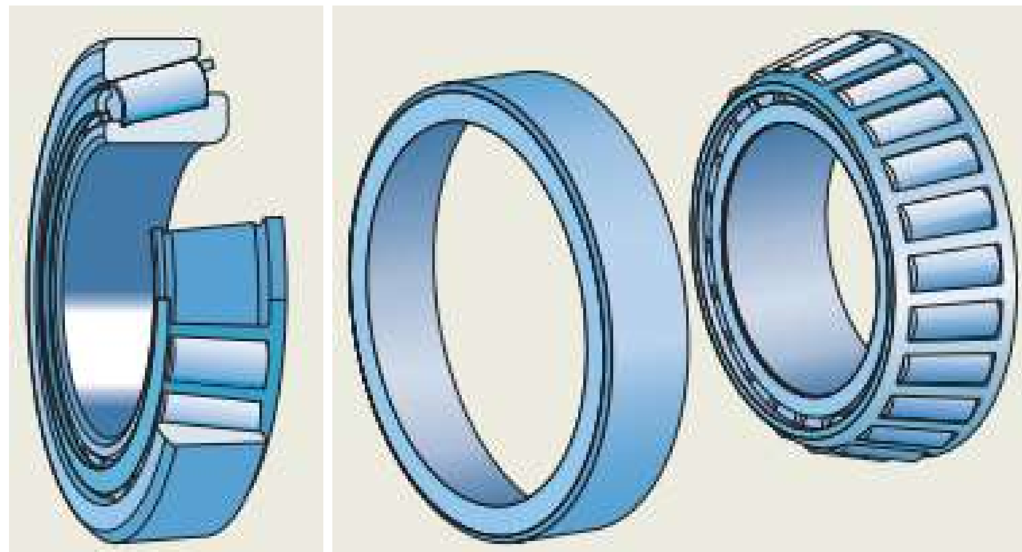
Cylindrical
Roller Bearing

Bearings With Axial Loading

- Bearing selections are from **Table 11-2** (Angular Contact Ball Bearing) and **Figure 11-15** (Tapered Roller Bearing)



Angular Contact Ball Bearing



Tapered Roller Bearing

11-6 Combined Radial and Thrust Loading

- Manufacturer’s load rating is based on radial load only
- Design condition frequently with existence of both radial and thrust loads

Bearing Equivalent Load

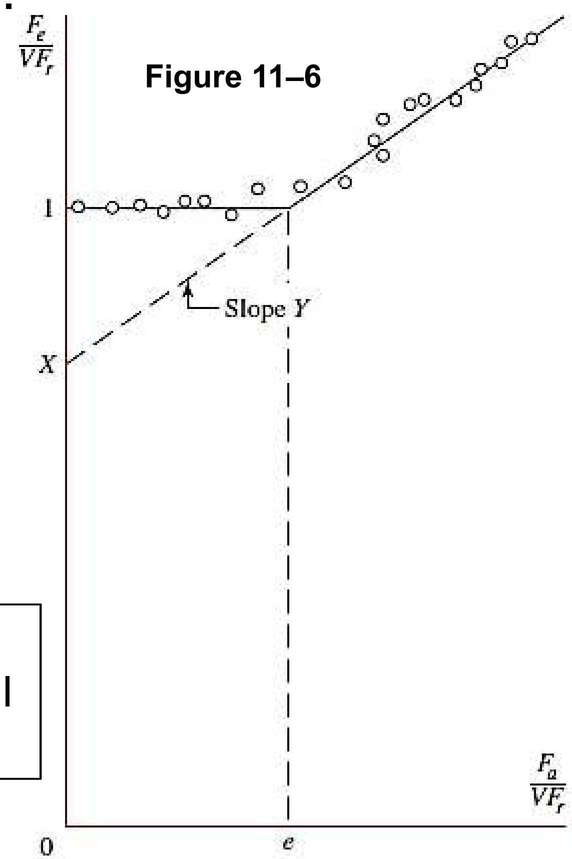
- F_r : radial loads
- F_a : axial thrust loads
- F_e : equivalent radial load that does the same damage as the combined radial and thrust loads together.
- Rotation factor V
  - V = 1 when <u>inner</u> ring rotates
  - V = 1.2 when <u>outer</u> ring rotates

$$\frac{F_e}{VF_r} = 1 \qquad \text{when } \frac{F_a}{VF_r} \le e$$

$$\frac{F_e}{VF_r} = X + Y\frac{F_a}{VF_r} \qquad \text{when } \frac{F_a}{VF_r} > e$$

Observation:
- Axial load can be neglected for bearing selection until it exceeds 20~30% of the radial load.

Figure 11–6



Bearing Equivalent Load

Generalized form for equivalent load:

$$F_e = X_i V F_r + Y_i F_a$$

- Rotation factor
  - V=1 inner ring rotates; V=1.2 outer ring rotates

C_o: basic static load rating

Basic load ratings dynamic C	static C_0
kN	
14,3	6,55
14,3	6,55
14,3	6,55
14,3	6,55
13,5	6,55
22,9	10,8

Table 11–1

		$F_a/(VF_r) \le e$		$F_a/(VF_r) > e$	
F_a/C_0	e	X_1	Y_1	X_2	Y_2
0.014*	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0	0.56	1.99
0.042	0.24	1.00	0	0.56	1.85
0.056	0.26	1.00	0	0.56	1.71
0.070	0.27	1.00	0	0.56	1.63
0.084	0.28	1.00	0	0.56	1.55
0.110	0.30	1.00	0	0.56	1.45
0.17	0.34	1.00	0	0.56	1.31
0.28	0.38	1.00	0	0.56	1.15
0.42	0.42	1.00	0	0.56	1.04
0.56	0.44	1.00	0	0.56	1.00

*Use 0.014 if $F_a/C_0 < 0.014$.

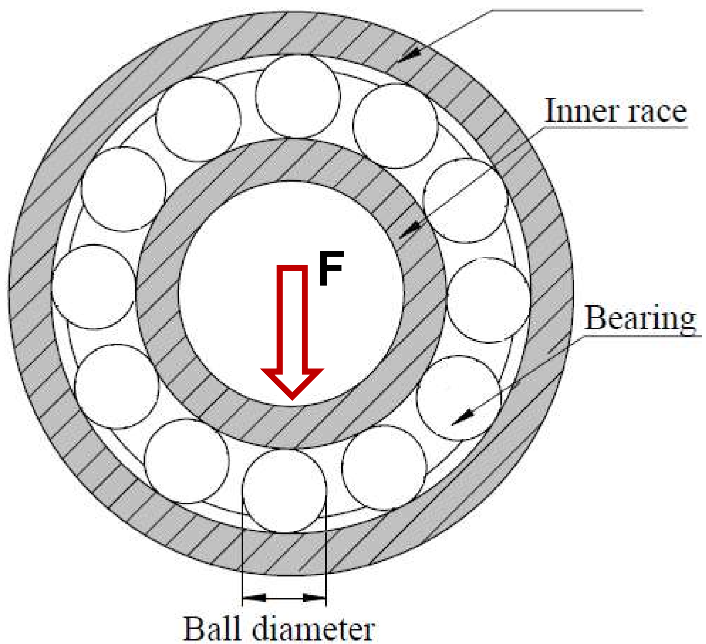
Bearing Equivalent Load

Generalized form for equivalent load:

$$F_e = X_i V F_r + Y_i F_a$$

Rotation factor (V=1 inner ring rotates; V=1.2 outer ring rotates)

Question: When outer ring rotates and inner ring is stationary, V=1.2 ► F_e increases ►a bigger bearing is needed for the same life ►Why?



EXAMPLE 11-4

An SKF 6210 angular-contact ball bearing has an axial load F_a of 400 lbf and a radial load F_r of 500 lbf applied with the outer ring stationary.

The basic static load rating C_0 is 4450 lbf and the basic load rating C_{10} is 7900 lbf.

Estimate the $\mathcal{L}_{10}$ life at a speed of 720 rev/min.

F_a/C_0	e	$F_a/(VF_r) \le e$ X_1	Y_1	$F_a/(VF_r) > e$ X_2	Y_2
0.014*	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0	0.56	1.99
0.042	0.24	1.00	0	0.56	1.85
0.056	0.26	1.00	0	0.56	1.71
0.070	0.27	1.00	0	0.56	1.63
0.084	0.28	1.00	0	0.56	1.55
0.110	0.30	1.00	0	0.56	1.45
0.17	0.34	1.00	0	0.56	1.31
0.28	0.38	1.00	0	0.56	1.15
0.42	0.42	1.00	0	0.56	1.04
0.56	0.44	1.00	0	0.56	1.00

*Use 0.014 if $F_a/C_0 < 0.014$.

Solution:

Rotation Factor V=1 (outer ring stationary)

$\frac{F_a}{C_0} = \frac{400}{4450} = 0.09$ ► e=0.285 from Table 11-1

$\frac{F_a}{VF_r} = \frac{400}{1\cdot500} = 0.8 > e$ ► $Y_i = 1.527$ from Table 11-1

Equivalent radial load: $F_e = X_2 V F_r + Y_2 F_a = 0.56 \cdot 1 \cdot 500 + 1.527 \cdot 400 = 890.8\ lbf$

Thus, estimated $\mathcal{L}_{10}$ life at 720 rpm with 90% reliability:

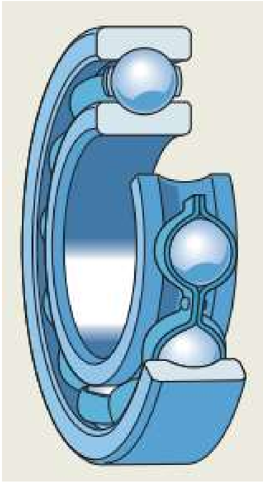
$$\mathcal{L}_{10} = \frac{60 \cdot \mathcal{L}_R n_R}{60 \cdot n_D}\left(\frac{C_{10}}{F_e}\right)^a = \frac{10^6}{60 \cdot 720}\left(\frac{7900}{890.8}\right)^3 = 16146\ h$$

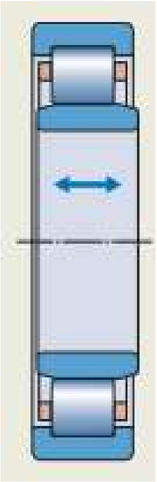
$$C_{10} = F_R = F_D\left(\frac{L_D}{L_R}\right)^{1/a} = F_D\left(\frac{\mathcal{L}_D n_D}{\mathcal{L}_R n_R}\right)^{1/a}$$

If Rotation Vector V=1.2 (inner ring stationary)

$\frac{F_a}{VF_r} = \frac{400}{1.2\cdot500} = 0.67 > 0.285$ ► $Y_i = 1.527$ from Table 11-1 ► F_e = 946.8 lbf

11-8 Selection of Ball and Cylindrical Roller Bearings





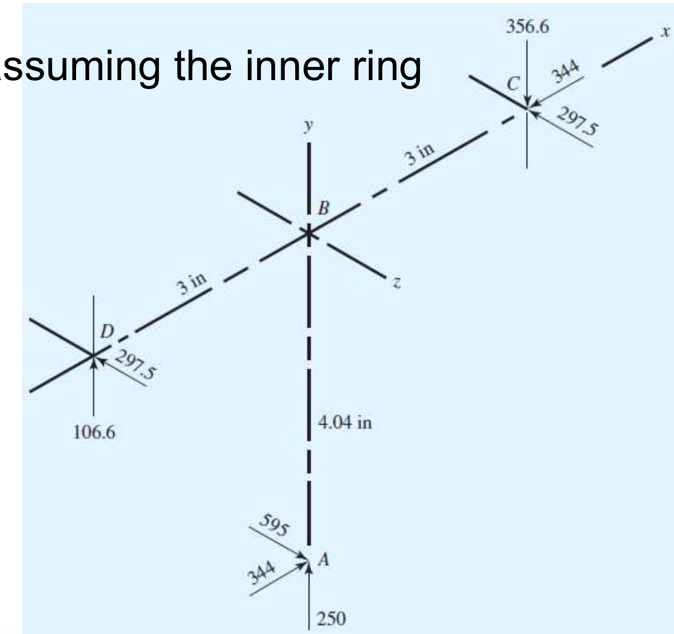
EXAMPLE 11–7

The second shaft on a parallel-shaft 25-hp foundry crane speed reducer contains a helical gear with a pitch diameter of 8.08 in.

- The components of the gear force transmitted to the second shaft are shown in Fig. 11–12, at point A.
- Location C: A ball bearing is to be selected to accept the thrust, and
- Location D: a cylindrical roller bearing is to be utilized
- The life goal of the speed reducer is 10 kh, with a reliability factor for the ensemble of all four bearings (both shafts) to equal or exceed 0.96 for the Weibull parameters of Ex. 11–3.
- The application factor is to be 1.2.

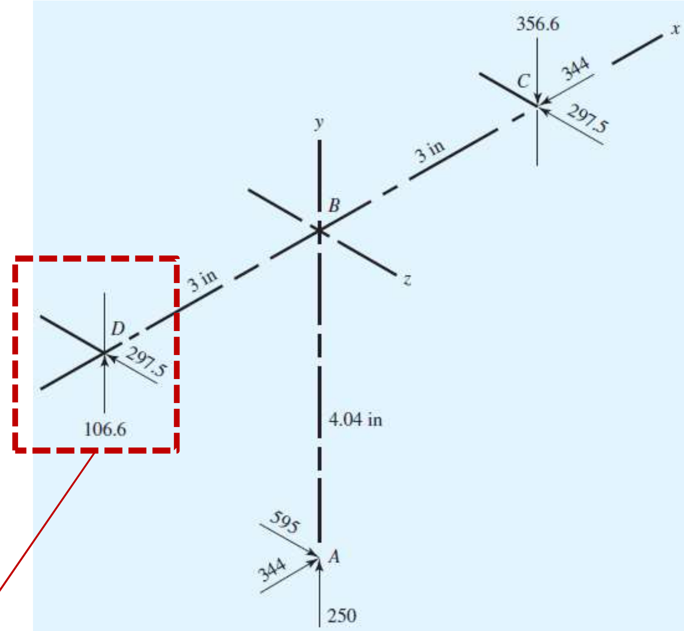
(a) Select the roller bearing for location D.

(b) Select the ball bearing (angular contact) for location C, assuming the inner ring rotates.



EXAMPLE 11–7

Transmitted Power	$HP := 25 \cdot hp$
Transmitted Torque to Shaft CD from Tangential Force @A	$Trq := 595\ lbf \cdot 4.04\ in = \left(2.404 \cdot 10^{3}\right)\ in \cdot lbf$
	$n_D := \dfrac{HP}{Trq}\ \dfrac{1}{2 \cdot \pi} = 655.476\ \dfrac{1}{min}$
Total Number of Beaings	$NB := 4$
Design Bearing Life	$L_{hr} := 10000 \cdot hr$
Individual Bearing Reliability	$R := (0.96)^{\left(\frac{1}{NB}\right)} = 0.9898$
Designed Bearing Life (Cycles)	$L_D := L_{hr} \cdot n_D = 3.933 \cdot 10^{8}$
Dimensionless Design Life	$x_D := \dfrac{L_D}{L_{10}} = 393.286$



Bearing D Selection

Bearing Type: Cylindrical Roller Bearing

$a := \dfrac{10}{3}$ $\quad R_D := R$

Application Factor	$a_f := 1.2$
Radial Force @D	$F_D := \sqrt{297.5^2 + 106.6^2} \cdot lbf = 316.022\ lbf$
Catalogue Rating Load	$C_{10} := a_f \cdot F_D \cdot \left(\dfrac{x_D}{\left(x_0 + \theta_1 \cdot (1 - R_D)\right)^{\frac{1}{b}}} \right)^{\frac{1}{a}} = 3581.05\ lbf$
	$C_{10} = 15.93\ kN$

Use Table 11.3 (P.575) to pick a Cylindrical Roller Bearing

	02-Series				03-Series			
Bore, mm	OD, mm	Width, mm	Load Rating, kN C_{10}	C_0	OD, mm	Width, mm	Load Rating, kN C_{10}	C_0
25	52	15	16.8	8.8	62	17	28.6	15.0
30	62	16	22.4	12.0	72	19	36.9	20.0
35	72	17	31.9	17.6	80	21	44.6	27.1

EXAMPLE 11–7

Bearing C Selection

Bearing Type: Angular Contact Ball Bearing $\quad a := 3 \quad R_D := R$

Radial Force @C $\quad F_C := \sqrt{356.6^2 + 297.6^2} \cdot lbf = 464.467\ lbf$

Axial Force @C $\quad F_{CA} := 344 \cdot lbf$

Radial Load $\quad F_r := F_C = 464.467\ lbf \quad$ Axial Load $\quad F_a := F_{CA} = 344\ lbf$

Rotation Factor $\quad V := 1 \quad$ (Input: Assume outer ring stationary)

$$f2 := \frac{F_a}{V \cdot F_r} = 0.741$$

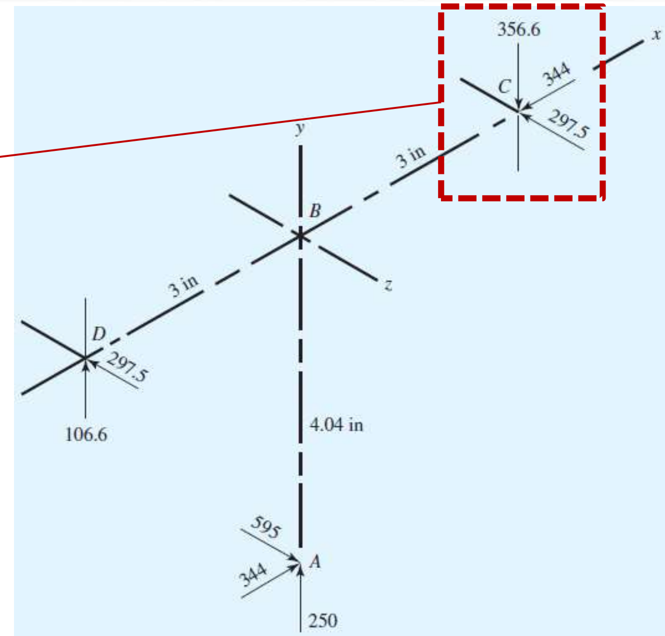
max(e) < 0.44; therefore,
This is most likely > e (Table 11-2, P.572)

Proceed assuming Fa/(VFr) > e.

Table 11-2 (P.572)

F_a/C_0	e	$F_a/(VF_r) \le e$ X_1	Y_1	$F_a/(VF_r) > e$ X_2	Y_2
0.014*	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0		
0.042	0.24	1.00	0		
0.056	0.26	1.00	0		
0.070	0.27	1.00	0		
0.084	0.28	1.00	0		
0.110	0.30	1.00	0		
0.17	0.34	1.00	0		
0.28	0.38	1.00	0		
0.42	0.42	1.00	0		
0.56	0.44	1.00	0		

*Use 0.014 if $F_a/C_0 < 0.014$.



Iteration 1: Estimate X2 and Y2 $\quad X2 := 0.56 \quad Y2 := 1.63$

Equivalent Bearing Load $\quad F_e := X2 \cdot V \cdot F_r + Y2 \cdot F_a = 820.821\ lbf$

Catalogue Rating Load $\quad C_{10} := a_f \cdot F_e \cdot \left(\dfrac{x_D}{x_0 + \theta_1 \cdot (1 - R_D)^{\frac{1}{b}}} \right)^{\frac{1}{a}} = 11936.81\ lbf$

$$C_{10} = 53.1\ kN$$

Use Table 11.2 (P.573) to pick a Angular Contact Ball Bearing

60	110	22	1.5	70	99	47.5	28.0	55.9	35.5

Pick 02-60 mm bearing

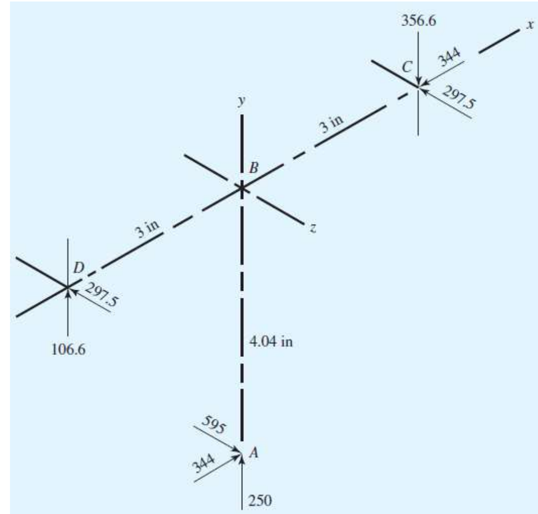
Bearing Load Rating from Catalogue $\quad C_{10} := 55.9 \cdot kN \quad C_0 := 35.5 \cdot kN$

$$fc0 := \frac{F_a}{C_0} = 0.043$$

F_a/C_0	e	$F_a/(VF_r) \le e$ X_1	Y_1	$F_a/(VF_r) > e$ X_2	Y_2
0.014*	0.19	1.00	0	0.56	2.30
0.021	0.21	1.00	0	0.56	2.15
0.028	0.22	1.00	0	0.56	1.99
0.042	0.24	1.00	0	0.56	1.85
0.056	0.26	1.00	0	0.56	1.71
0.070	0.27	1.00	0	0.56	1.63
0.084	0.28	1.00	0	0.56	1.55
0.110	0.30	1.00	0	0.56	1.45
0.17	0.34	1.00	0	0.56	1.31
0.28	0.38	1.00	0	0.56	1.15
0.42	0.42	1.00	0	0.56	1.04
0.56	0.44	1.00	0	0.56	1.00

*Use 0.014 if $F_a/C_0 < 0.014$.

EXAMPLE 11–7



Iteration 2: Revise e

Find neiboring constants from Table 11-1 (P.572)

$fc1 := 0.042$ $e1 := 0.24$ $fc2 := 0.056$ $e2 := 0.26$

$$e := \frac{(fc0 - fc1)}{fc2 - fc1}(e2 - e1) + e1 = 0.242$$

Confirmed Fa/(VFr) > e. Use e to interpolate constants X2, and Y2

Iteration 2: Revise X2 and Y2

$X2 := 0.56$ $Y21 := 1.85$ $Y22 := 1.71$

$$Y2 := \frac{(fc0 - fc1)}{fc2 - fc1}(Y22 - Y21) + Y21 = 1.839$$

Equivalent Bearing Load $F_e := X2 \cdot V \cdot F_r + Y2 \cdot F_a = 892.7\ lbf$

$F_e = 3970.95\ N$

Catalogue Rating Load $C_{10} := a_f \cdot F_e \cdot \left(\frac{x_D}{x_0 + \theta_1 \cdot (1 - R_D)^{\frac{1}{b}}} \right)^{\frac{1}{a}} = 12982.16\ lbf$

$C_{10} = 57.75\ kN$

Use Table 11.2 (P.573) to pick a Angular Contact Ball Bearing

65	120	23	1.5	74	109	55.9	34.0	63.7

Pick 02-65 mm bearing

Bearing Load Rating from Catalogue $C_{10} := 63.7 \cdot kN$ $C_0 := 41.5 \cdot kN$

$$fc0 := \frac{F_a}{C_0} = 0.037$$

Iteration 3: Revise e

Find neiboring constants from Table 11-1 (P.572)

$fc1 := 0.028$ $e1 := 0.22$ $fc2 := 0.042$ $e2 := 0.24$

$$e := \frac{(fc0 - fc1)}{fc2 - fc1}(e2 - e1) + e1 = 0.233$$

Confirmed Fa/(VFr) > e. Use e to interpolate constants X2, and Y2

Iteration 3: Revise X2 and Y2

$X2 := 0.56$ $Y21 := 1.99$ $Y22 := 1.85$

$$Y2 := \frac{(fc0 - fc1)}{fc2 - fc1}(Y22 - Y21) + Y21 = 1.901$$

Equivalent Bearing Load $F_e := X2 \cdot V \cdot F_r + Y2 \cdot F_a = 914.14\ lbf$

$F_e = 4066.3\ N$

Catalogue Rating Load $C_{10} := a_f \cdot F_e \cdot \left(\frac{x_D}{x_0 + \theta_1 \cdot (1 - R_D)^{\frac{1}{b}}} \right)^{\frac{1}{a}} = 13293.92\ lbf$

$C_{10} = 59.13\ kN$

Use Table 11.2 (P.573) to pick a Angular Contact Ball Bearing

65	120	23	1.5	74	109	55.9	34.0	63.7	41.5

Pick 02-65 mm bearing (Design remains the same as previous iteration)