Chapter 4
Optimum Design

The following six properties must be considered when selecting a wire rope:

a. Rresistance to breaking.

b. Resistance to fatigue.

c. Resistance to abrasive wear.

d. Resistance to crushing.

e. Resistance to corrosion.

f. Reserve strength.

This chapter contains information that will help the designer/specifier evaluate each property to obtain an optimum design.

4-1. Service Conditions and Failure Modes

All wire rope in permanent service will eventually fail. Its mode of failure depends on the conditions under which it operates. Gate-operating devices at Corps facilities use various combinations of different types of drums, sheaves, and guides. The gates that the devices operate are located over a wide geographical area in differing environments. Rope service conditions as determined by the design of the rope handling equipment, the frequency of use, and the environment vary greatly. This section presents general information on rope service conditions, failure modes, and additional considerations for selecting new or replacement rope.

a. Rope handling equipment.

(1) Drums. Mechanically operated gate-operating devices generally use grooved, smooth, or disk-layered cylindrical drums to transmit power to the wire rope (Figure 4-1). The grooved type drum provides the best conditions for the rope since the grooves prevent the rope from rubbing against itself. However, for good service life, the pitch and diameter of the grooves, the fleet angle, the anchoring system, and the nominal diameter of the drum must all be correct for the size and type of rope. The plain type drum requires the rope to wind tightly against the preceding wrap causing the rope to abrade against itself. The disk-layered type drum requires the rope to be wrapped over itself in multiple layers. The rope is exposed to a much higher level of crushing and abrasion. A number of older Corps facilities have devices which use flat rope which always uses disk-layered drums.

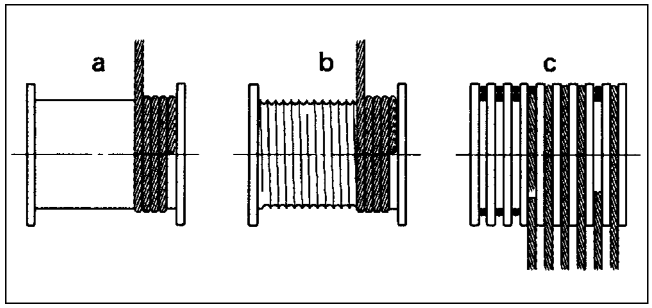

Figure 4-1. Drum types: (a) smooth, (b) grooved, and (c) disk-layered

(2) Sheaves and rollers. Some gate-operating devices use sheaves to multiply rope force or guides to change direction. Sheaves can be single or multiple on a single shaft. The layout and the type of bearings they use (plain or roller) determine the rope tension required to lift a given load (Section 4-2, “Calculating Load”). Sheave diameter, groove diameter, and condition all effect the wire rope rate of wear and fatigue. Cylindrical roller guides are also occasionally used on gate-operating devices. As with sheaves, their nominal diameter, groove diameter, and condition affect rope wear and fatigue.

b. Rope failure modes. A wire rope typically experiences any one or a combination of corrosion, fatigue, abrasive wear, and excessive stress. The following sub-paragraphs comment on each condition.

(1) Corrosion. The Corps has some facilities with gates which are not operated during normal hydrologic years, except when “exercised” for operation and maintenance (O&M) purposes. Fatigue and abrasive wear of the wire ropes is of little concern. The eventual expected failure mode at these facilities would normally be corrosion. There are also projects where corrosion, fatigue, and abrasion are all a concern. The prime failure mode depends on the

type of wire rope selected. Corrosive environments include:

(a) Submersion in fresh water, which may contain damaging substances such as chlorides, nitrates, calcium carbonates, bacteria, etc. Rope wires may be exposed to oxygen depleted areas, biological attack, and galvanic currents.

(b) Exposure to damp atmosphere either continuously or periodically, including rope in storage, with a potential for fungal induced corrosion.

(c) Exposure to airborne salt. Galvanized carbon steel, stainless steel, and Kevlar ropes have been used for their resistance to corrosion. Lubrication can have either positive or negative effects (Section 2-5, "Wire Materials" and Section 7-3, "Lubrication").

(2) Fatigue. Fatigue usually results from contact with sheaves and drums. Rope moving over drums, sheaves, and rollers is subjected to cyclic bending stresses. Stress magnitude depends on the ratio of the tread diameters of the drums and sheaves to the diameter of the rope. Fatigue is also affected by lubrication and the condition of the surface over which the rope is bending. In order to bend around a sheave, the strands and wires of a rope must move relative to one another. This movement compensates for the difference in diameter between the underside and top side of the rope. Lack of rope lubrication or excessive pressure caused by too small of groove diameter limits wire slip. This increases bending and fatigue. Some devices require rope to change bending direction from drum to sheave, or from one sheave to another. Reverse bending further accelerates wire fatigue. Wire rope featuring lang lay construction and small wires tends to be effective in reducing fatigue (Sections 2-1, "Classification," 4-6, "Service Life," 4-8, "Bending Radii," and 7-3, "Lubrication").

(3) Abrasive wear. Wear from abrasion, like fatigue, normally results from contact with sheaves and drums. Wire rope, when loaded, stretches much like a coil spring. When bent over a sheave, its load-induced stretch causes it to rub against the groove. As a result, both the rope and groove are subject to abrasion. Within the rope, wires and strands move relative to each other, and additional abrasion occurs. Excessive abrasion can be caused by the sheave or drum being of too soft of a material, or having too small of a tread diameter. Other factors include too much rope pressure, an improper groove diameter, or an improper fleet angle. Movement of rope against roller guides can cause excessive abrasion. Improper tensioning can allow rope to rub against metal or concrete structures. Wire rope featuring lang lay construction and large wires tends to be effective in reducing abrasive wear (Sections 2-1, "Classification," 4-6, "Service Life," 4-8, "Bending Radii," and 7-3, "Lubrication").

(4) Excessive stress. Excessive stress in Corps applications has generally resulted from attempted operation when a gate is inoperable because of ice and debris or gate misalignment. To some extent, safety devices to limit rope tension can reduce the probability of a failure (Section 7-4, "Ice and Debris Removal"). Excessive stress can result from improper tensioning in a device using multiple ropes (Section 6-3, "Installation").

a. Additional considerations. The wire rope at existing Corps installations will eventually need to be replaced. The retired rope and fittings should be inspected and analyzed to determine the prime distress mode (fatigue, abrasive wear, corrosion, or excessive stress). U.S. Army Construction Engineering Research Laboratories (CERL) can provide assistance in this determination. This should be considered in the selection of the replacement rope and fittings to provide the most cost effective service life. Existing equipment modifications or replacement should be considered in the initial screening of options when considering wire rope replacement. The existing design or the condition of the existing equipment may not allow the service life desired from any replacement rope. For example:

(1) The existing drums and sheaves may be so worn that new rope is quickly abraded.

(2) Sheave or drum diameters may be too small for the rope required for the load, resulting in a quick fatigue failure of the rope.

(3) There can be a significant decrease in rope tension if sheaves with plain bearings are replaced

with roller bearings. This modification could allow the replacement of an improved plow steel rope with a lower strength stainless steel rope, yet the factor of safety could be satisfactory and the rope would have much better corrosion characteristics.

Finally, replacing equipment using wire rope with equipment using chains, gears, or other machinery may be the best option.

4-2. Calculating Rope Load

The following sections include information on sheaves and loads due to bending which must be considered in calculation of rope load for a gate-operating device. A sample problem is included in Appendix J which includes a number of other factors which must also be considered.

4-3. Sheaves

a. Static load. The static load (no movement conditions) for various single- and multiple-sheave block tackles is calculated by dividing the total load by the part-number (number of supporting ropes) of the sheave (Figure 4-2). However, note that rope selection is not based on static load.

b. Dynamic load. The dynamic load (movement conditions lifting) can be significantly greater than static load. Rope selection is based on dynamic load. A portion of a rope's tension is lost as it flexes over sheaves and overcomes the friction in the sheave bearings. The dynamic load factors for various single- and multiple-sheave block tackles are given in Figure 4-3. Compare the static versus dynamic rope tension for a sheave with ten supporting ropes and plain bearings. The static tension is 0.100 of the load. The dynamic tension is 0.156 of the load. In this case, the dynamic rope tension is over 50 percent greater than the static rope tension.

c. Plain versus roller bearings. Dynamic loads for sheaves with roller bearings can be significantly less than for sheaves with plain bearings. For example; compare a 10-part sheave with plain bearings to a 10-part sheave with roller bearings. Their respective rope tensions are 0.156 and 0.123 of the load. The plain bearing sheave system requires its rope to be subjected to 27 percent greater tension. The large difference between plain and roller bearings should be noted. If the plain bearing sheaves for this example were replaced with roller bearing sheaves, a stainless steel rope (with a 10 percent lower strength) could be substituted and have a higher factor of safety than the original rope (Appendix J).

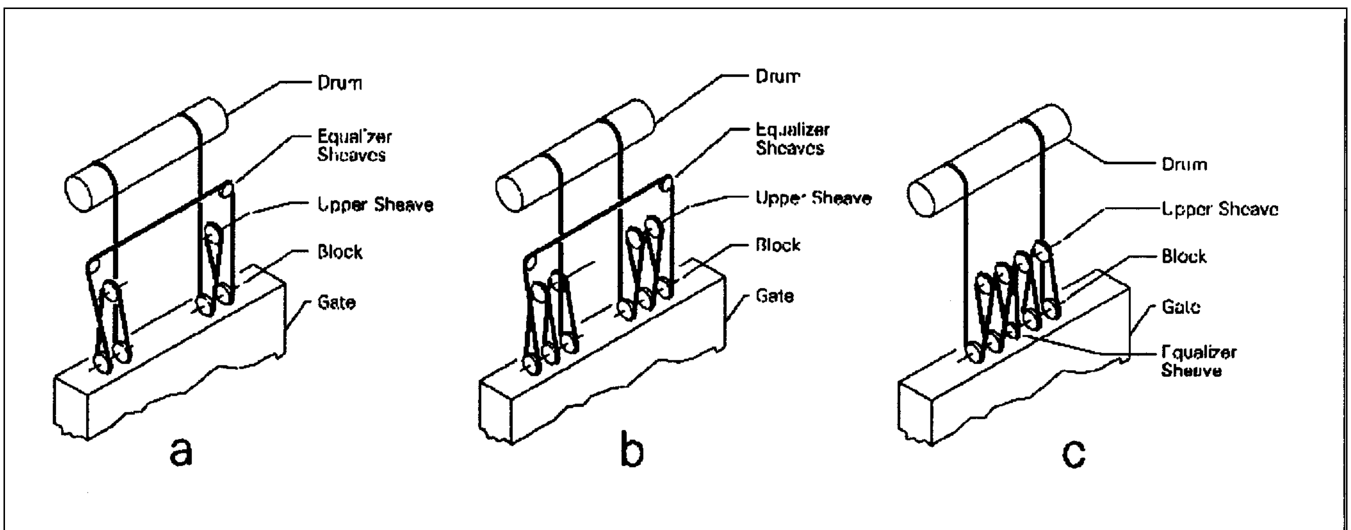

Figure 4-2. Various drum and sheave arrangements: (a) An 8-part sheave, (b) A 12-part sheave, and (c) A 10-part sheave. The part-number is determined by counting the number of supporting ropes

Parts of Line	With Plain Bearing Sleeves	With Roller Bearing Sleeves
1	1.09	1.04
2	.568	.530
3	.395	.360
4	.309	.275
5	.257	.225
6	.223	.191
7	.199	.167
8	.181	.148
9	.167	.135
10	.156	.123
11	.147	.114
12	.140	.106
13	.133	.100
14	.128	.095
15	.124	.090

Figure 4-3. The table presents dynamic rope tension as a portion of load for sheaves with various numbers of supporting ropes. Note that parts-of-line, part-number, and the number of supporting ropes are the same

4-4. Nominal Strength

Nominal strength is the industry accepted breaking strength for a wire rope. Nominal strengths for various wire ropes are given in Appendix C. They should be used when making design calculations. A minimum acceptance strength 2-1/2 percent lower than the published nominal strength has been established as the industry tolerance for testing purposes. This tolerance serves to offset variables that occur during sample preparation and the actual physical test of the wire rope.

4-5. Factor of Safety

a. Dynamic loaded ropes. The factor of safety (FOS) for a dynamic loaded rope on a new Corps gate-operating device should be at least 5, based on nominal strength, the part-number, and the dynamic load. A higher FOS may be justified for an installation where many loading cycles are anticipated and fatigue is a concern. Service life will be longer for a rope with a higher FOS (Figure 4-4). For rope replacement, the same FOS guidelines are recommended. However, the FOS may not be the most important criteria for selection of replacement rope. Current criteria calls for motor stall torque on Corps gate-operating devices to be 0.700 of the nominal strength of the wire rope. However, it may not always be possible to select replacement wire rope which meets the existing criteria. For those devices a strain gauge "trip-out" could be installed to shut down the motor in case of an overload for protection of the rope.

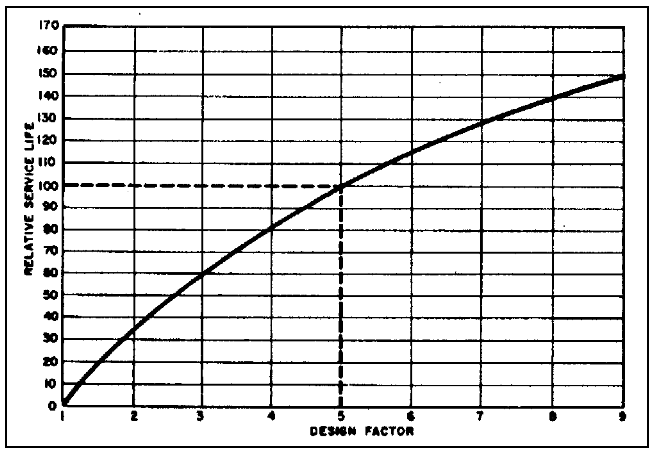

Figure 4-4. Relative service life versus factor of safety

b. Static loads. Some ropes are used for locating or stationing parts of the devices. These ropes should have a FOS of at least 3.0. The FOS in this case would be based on static load and nominal rope strength.

c. Efficiency reductions for sheaves and pins. A rope passing over a curved surface, such as a sheave or a pin, is reduced in strength (or efficiency). The reduction depends on the severity of the bend. Figure 4-5 indicates the efficiency losses for rope bending over sheaves or pins. Efficiency reductions

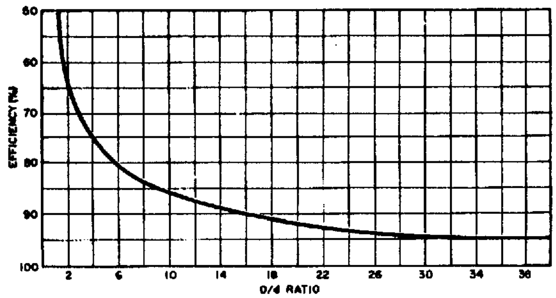

Figure 4-5. The reduction in efficiency of a wire rope bent over a pin or sheave varies with the ratio of the rope diameter (d) compared to the sheave or pin diameter (D)

for sheaves and pins must be considered in determining its FOS.

d. Terminal efficiencies. End terminations must develop the full strength of the rope. Also see Sections 3-1, "Sockets" and 3-3, "Drum and Miscellaneous Terminations" and Appendix D.

e. Reserve strength. The calculated FOS of a new wire rope may be fairly accurate compared to its actual FOS. However, as the rope is used abrasion and fatigue, particularly at the ropes outer wires, reduce its strength. The term reserve strength defines the combined strength of only a wire rope's inner wires that tend to be less affected by abrasion and fatigue (Figure 4-6). Consider a 6x31 classification rope which has 12 outside wires. The inner wires only have a reserve strength of 43 percent. Such a rope with an original FOS of 5 in a severely worn condition would have a much lower FOS since the outer wires have 57 percent of the rope's strength.

4-6. Service Life

As stated earlier, wire rope used in Corps gate-operating devices experiences corrosion, fatigue, and/or abrasion. Excessive stress should not occur. Corrosion, fatigue, and abrasion are distress modes that progress with time and/or use. At an existing installation it may be possible to predict service life for a replacement rope with some accuracy if the service life of an old rope in the same application is known. For a new installation, service can be

Number of Outside Wires	Percent of Reserve Strength
3	0
4	5
5	3
6	8
7	22
8	27
9	32
10	36
12	43
14	49
16	54
18	58

Figure 4-6. Number of outside wires versus reserve strength for 6-, 7-, and 8-strand wire rope

predicted from experience gained on similar existing installations (Section 7-2, "Retirement").

4-7. Rope Length/Stretch

a. General. This section discusses two types of rope elongation, constructional stretch, which occur during the early life of the rope, and elastic stretch which is dependent on the rope's loading. Both are pertinent to determining the length of the rope.

b. Constructional stretch. When a load is applied to a new wire rope, the rope's diameter decreases and its length increases. The amount of this stretch is influenced by a rope's construction and material. FC ropes stretch more than IWRC ropes because a fiber core compresses more than a steel core. (Figure 4-7). Constructional stretch generally ceases at an early stage in the life of a rope. The constructional stretch of individual ropes in multi-rope drums vary. This

Rope Construction	Approximate Stretch*
6 strand FC	.5% to .75%
6 strand IWRC	.25% to .5%
8 strand FC	.75% to 1%

* Varies with the magnitude of the loading

Figure 4-7. Constructional stretch for various rope constructions

may require much tensioning effort to equalize the load. Pre-stretching is a practical and inexpensive way to reduce constructional stretch (Section 2-8, "Manufacturing"). Constructional stretch must be considered when specifying rope length and for design of adjustment mechanisms on operating devices.

c. Elastic stretch. It is necessary to know the elastic stretch of a wire rope to specify its length. Elastic stretch is the recoverable deformation of the metal itself. It is dependent on the rope's metal area and the modulus of elasticity of the metal. A reasonable approximation can be made using the equation and information in Figures 4-8 through 4-10. Rather than calculating elastic stretch, wire rope can be measured under tension at the manufacturing facility and socketed for a more accurate length.

$$\Delta L = \frac{\Delta F \times L}{A \times M}$$

Where

ΔL = Change in Length (ft)

L = Length (ft)

ΔF = Change in Load (lbs)

M = Modulus of Elasticity (psi)

or

$$\Delta L = \frac{G \times \Delta F \times L}{A \times M}$$

Where

ΔL = Change in Length (m)

L = Length (m)

ΔF = Change in Load (kg)

M = Modulus of Elasticity (MPa)

Figure 4-8. Elastic stretch equation

d. Adjustable fittings. Adjustable fittings such as turnbuckles should be considered if tensioning is required. It is important to allow sufficient adjustment length to tighten the rope (as opposed to loosening).

Rope Classification	Area	
	SQ. IN.	SQ. MM
6 x 7 FC	.384	258
6 X 37 FC	.410	276
6 X 19 FC	.427	289
8 X 19 FC	.360	243
6 X 19 IWRC	.475	321
6 X 37 IWRC	.493	333

Figure 4-9. Approximate metal areas of 26 mm (1-in.) wire rope of various constructions

Rope Classification	0% to 20% Loading		21% to 65% Loading	
	PSI	MPa	PSI	MPa
6 x 7 FC	11,700,000	80,670	13,000,000	89,670
6 x 19 FC	10,800,000	74,470	12,000,000	82,740
6 x 37 FC	9,900,000	68,260	11,000,000	75,850
8 x 19 FC	8,100,000	55,850	9,000,000	62,060
6 x 19 IWRC	13,500,000	93,080	15,000,000	103,430
6 x 37 IWRC	12,600,000	86,880	14,000,000	96,530

Figure 4-10. Approximate modulus of elasticity for various wire rope classifications

4-8. Bending Radii

Wire rope operating over sheaves and drums is subjected to cyclic bending stresses. The magnitude of bending stresses are dependent on the ratio of the diameter of the sheave or drum to the diameter of the rope. It is difficult to identify the sheave or drum size most economical for a particular installation. However, it is generally best to not use drums or sheaves smaller than recommended by the manufacturer or smaller than given in Figure 4-11. Figure 4-12 indicates how service life is affected by the bending a rope is subjected to.

4-9. Bearing Pressure

Excessive wear is most often caused by a combination of rope load which is too high, a drum material which is too soft, or drum and sheave tread diameters which

Construction	Suggested Minimum D /d Ratio
6 x 7	42
19 x 7 or 18 x 7 Rotation Resistant 6 x 19 S	34
6 x 25 B Flattened Strand 6 x 27 H Flattened Strand 6 x 30 G Flattened Strand 6 x 31 V Flattened Strand 6 x 21 FW 6 x 26 WS	30
8 x 19 S 7 x 21 FW 6 x 25 FW 6 x 31 WS 6 x 37 FWS	26
7 x 25 FW 6 x 36 WS 6 x 43 FWS 7 x 31 WS	23
6 x 41 WS 6 x 41 SFW 6 x 49 SWS 7 x 36 WS 8 x 25 FW 19 x 19 Rotation Resistant 35 x 7 Rotation Resistant	20
6 x 46 SFW 6 x 46 WS 8 x 36 WS	18

Figure 4-11. Acceptable values for the D/d ratio (where D = sheave or drum diameter and d = rope diameter)

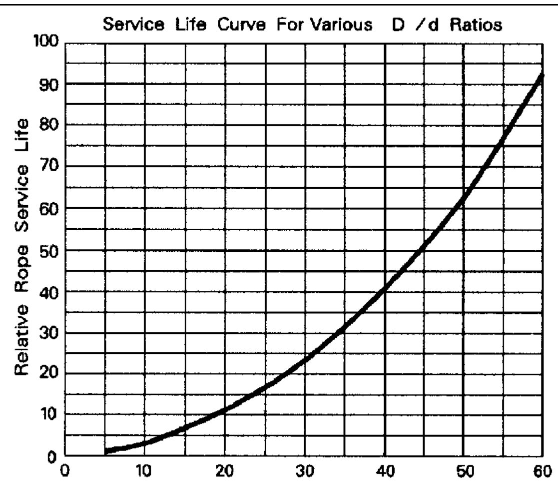

Figure 4-12. Service life of wire rope will vary with bending radii

are too small. Unit radial pressure between the rope and grooves (as calculated in Figure 4-13) represent the first and last factors. Allowable unit radial pressure for drums and sheaves varies with material (Figure 4-14). Note that the materials listed in the table are available in a wide range of hardness, so the pressure values will vary. Note also, that if the allowable radial pressure is exceeded, the drum or sheave's grooves will wear rapidly, eventually causing accelerated wear of the rope.

$$p = 2T / Dd$$

Where

d = Nominal diameter of rope (in)

D = Tread dia. of sheaves /drums (in)

p = Unit radial pressure (psi)

T = Load on rope (lbs)

or

$$p = 200T \, (G) / Dd$$

Where

d = Nominal diameter of rope (mm)

D = Tread dia. of sheaves /drums (cm)

p = Unit radial pressure (kPa)

T = Load on rope (kPa)

G = Acceleration of gravity 9.807 ($m/sec.^2$)

Figure 4-13. Rope Bearing Pressure

4-10. Fleet Angle

Fleet angle (Figure 4-15) must be within certain limits for smooth winding on drums and to prevent wire rope from crushing and abrading, either on itself or against drum grooves. The limits are 1/2 degree minimum to 1-1/2 degrees maximum for smooth drums and 1/2 degree minimum to 2 degrees maximum for grooved drums.

		Regular Lay Rope			Lang Lay Rope		Flattened Strand Lang Lay
		6 x 19	6 x 37	8 x 19	6 x 19	6 x 37	
Cast Iron 125 Brinell	psi	480	585	680	550	660	800
	kPa	2280	4030	4690	3790	4550	5520
Carbon Steel Casting 160 Brinell	psi	900	1075	1260	1000	1180	1450
	kPa	620	7410	8690	6900	8140	10,000
Manganese Steel, Induction Hardened or Flame Hardened Ground Grooves	psi	2400	3000	3500	2750	3300	4000
	kPa	16,550	20,690	24,130	18,960	22,750	27,580

Figure 4-14. Allowable rope bearing pressure for various sheave/drum materials

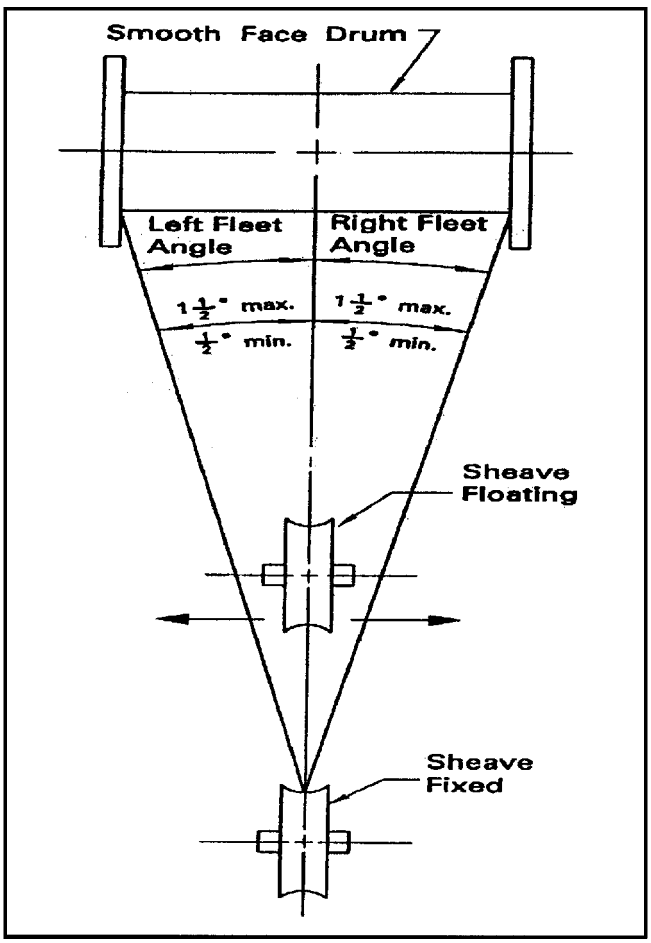

Figure 4-15. This figure illustrates the definition of fleet angle