CHAPTER 8

OPERATIONAL CHARACTERISTICS OF ROPES AND CABLES

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1.0 INTRODUCTION

This chapter of the handbook describes the basic operational characteristics of ropes and cables. The emphasis is on “working” ropes and cables used under dynamic conditions and requiring high strength and the ability to survive cyclic tension loading and cyclic bending. Examples include ropes and cables used to suspend, tether, or tow various payloads from floating or submerged platforms. Ropes and cables used in more passive applications (such as for guy lines or bottom-laid power or sensor cables) are not addressed directly, although many of the following chapter sections can be applied to these applications, as well.

1.1 Nonmenclature

The term “rope” applies to a flexible tension member used to transmit a tensile load to a remote location and which has sufficient flexibility to accommodate repeated bending over sheaves and drums. Included in this category are wire ropes and also nonmetallic ropes made of high-modulus fibers (for example Kevlar fiber from du Pont or Spectra fiber from Allied Chemical). Ropes made of low-modulus fibers (for example polyester, nylon, or polypropylene) are not discussed.

The term “cable” applies to a flexible tension member which, in addition to a strength member, includes power and/or signal conductors within its structure. As in the case of ropes, cables are used to transmit tensile loads to remote locations, and they typically have sufficient flexibility to accommodate repeated bending over sheaves and drums. Again, the strength member may be either metal wires or non-metallic fibers.

1.2 Chapter Organization

The intent of this chapter is to provide information about various types of working ropes and cables having both metallic and non-metallic strength members. Since cables are more complex in both design and materials selection than are ropes, a majority of the following discussion is directed at cables. Additional information specific to ropes is presented separately.

The chapter begins with descriptions of typical cable configurations. Cable reaction to tensile loading is then explored with discussions of constructional and elastic stretch, the significant internal loads and stresses, tension-induced torque and rotation, the potential for hockling and kinking, and cable reaction to rotation.

Next, cable reaction to bending is described, including the associated stresses and motions experienced by the cable components, the effects of bending on breaking strength, and the influence of sheave wrap angles and cable cycling stroke amplitudes on fatigue performance.

Also included are discussions about motion compensation systems, sheave design, cable reeving configurations, winding on drums, and terminations. Finally, cable failure mechanisms and retirement criteria are discussed.

The focus of the chapter then turns to ropes with emphasis on those aspects of rope behavior which differ from the behavior of cables. Simple equations are presented for estimating the torque characteristics of common 6-strand wire ropes. Also included are the results of extensive laboratory tests to evaluate the cyclic bend-over-sheave fatigue life of several selected wire ropes.

The chapter is concluded with a brief discussion of recent developments in the area of mathematical modeling of ropes and cables.

2.0 TYPICAL CABLE CONFIGURATIONS

Cables typically fall into one of three basic design categories. The most common configuration is one in which the power and/or signal conductors are contained within the center of the cable and are surrounded by the strength member and, perhaps, an overall jacket. Another configuration has a center strength member that is surrounded by the power and/or signal conductors and, perhaps, an overall jacket. Finally, in rare cases, a cable may have a strength member which lies along side of and is attached to a separate assembly of power and/or signal conductor elements. A large number of design and material choices exist within these categories.

Operational systems which subject cables to high tension loads combined with bending over sheaves and drums typically use cables which have an external strength member and, perhaps, an overall jacket. This configuration provides the best protection and service life for the core conductors, it is easily handled using conventional winch systems, and it can be designed to provide high strength, good torque balance, and good cyclic tension and cycle bending fatigue performance. Because of its widespread use, this cable configuration will be the main subject of the following discussion. However, many of the concepts presented may also be applied to other cable configurations.

Typical configurations of cables having external strength members of steel wire are shown in Figure 8-1. Cables with two layers of armor wires are most common. However, more than two layers of armor wires can be used if increased cable strength or weight is required.

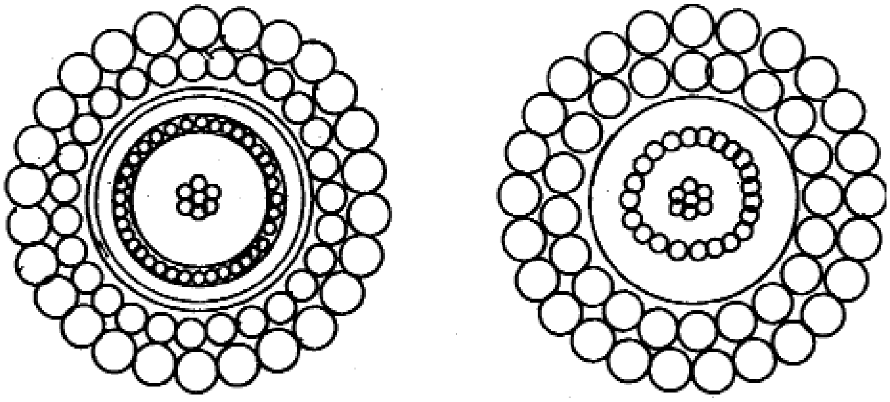
If a cable has a large core assembly with many conductors, then a full double armor design may provide excessive cable weight and more strength than required. The alternative is a spaced armor design where the armor wires within each layer are widely spaced and are held in position by an integral extruded jacket.

Cables which use non-metallic fibers rather than steel wires as the strength member elements typically have the fiber applied either as a braid or in several contrahelically served layers. Higher strength, lower stretch, and better flexure performance can typically be achieved with a multiple layer, contrahelically served strength member with the fiber layers separated by some type of low-friction isolation tape. In either case, the cable typically includes an overall extruded or braided jacket.

With few exceptions, all elements of an operating cable (power conductors, signal conductors, and strength members) are assembled with helical paths within the cable structure to accommodate bending of the cable. While the discussion which follows is directed primarily at cable strength members, it applies to all helically wrapped elements within the cable structure.

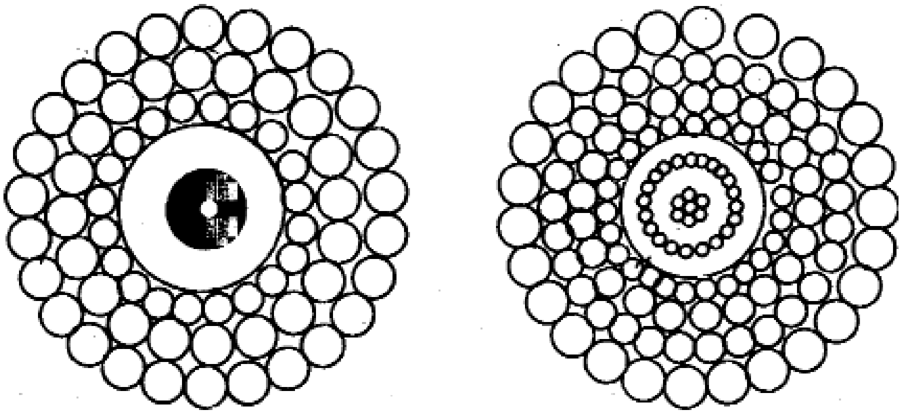
3.0 CABLE REACTION TO TENSILE LOADING

This section of the chapter discusses the reaction of a cable to straight tensile loading. A later section explores the effects of combined tension and bending.



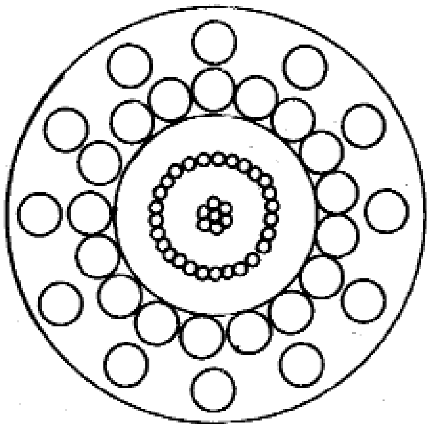
EQUAL WIRE NUMBERS IN TWO LAYERS

EQUAL WIRE SIZES IN TWO LAYERS



THREE-LAYER ARMOR

FOUR-LAYER ARMOR



SPACED ARMOR

TYPICAL CABLE CONFIGURATIONS

FIGURE 8-1

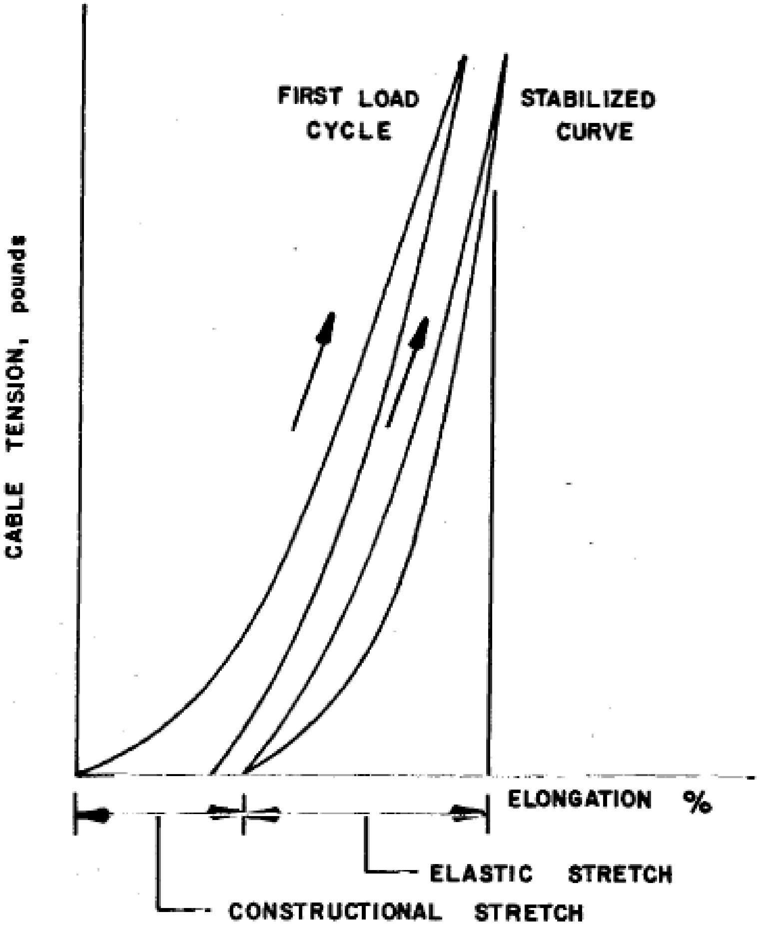
3.1 Constructional and Elastic Stretch

The tension-induced elongation of a new cable consists of two components, the constructional stretch and the elastic stretch, as shown in Figure 8-2. The magnitude of either of these components is likely to be both time and strain rate dependent.

Constructional stretch is most evident in cables having external strength members. As tension is applied to such cables, the strength members exert a radial pressure on the core. This pressure produces deformations of the core elements and filler materials due to both material compressibility and the elimination of voids within the core structure. In addition, for the case of steel wire strength members, the inner wire layer presses against the core jacket and causes the jacket material to move into the interstitial cusp-shaped voids between adjacent wires. There may also be slight contact deformations at the interface between the strength member layers. For the case of non-metallic fiber strength members, no cusp filling occurs, but the individual fiber layers experience some degree of compaction. All of these factors contribute to a reduction in cable diameter and a corresponding increase in cable length.

When tension is removed from a cable, there is some recovery of diameter and a corresponding reduction in cable length (in addition to the length reduction caused by the elasticity of the load bearing elements). However, a portion of the core compression and cusp filling or fiber compaction may be relatively permanent. The result is a residual cable elongation referred to as constructional stretch. Since some cable materials may exhibit time dependent elastic properties, a portion of the constructional stretch may dissipate as the cable remains a low tension for a period of time. However, the lost portion will be regained when tension is again applied to the cable.

In some cases, this constructional stretch may actually be larger than the additional elastic stretch at normal Operating tensions. This quasi-permanent change in cable length must not be overlooked as a potential contributor to the premature failure of certain cable components. For example, the total strain experienced by the core elements will be a function of both the constructional and elastic elongation. A large constructional stretch may produce excessive strain on optical fibers and, in the long term, may contribute to fiber failures at moderate cable tensions or even during storage of the cable at low tension between missions.



TYPICAL CABLE ELONGATION CHARACTERISTIC

FIGURE 8-2

3.2 Stress and Torque Balance

As discussed later, it is usually desirable for a cable to have good torque balance so that it produces little torque when loaded with both ends constrained and little rotation when loaded with one end free to rotate. Certain outdated approaches to cable design (specifically the use of simplified, linear analyses such as the “torque ratio” equation) may produce cable configurations which, at first, appear to offer good torque balance. However, these cables may actually have very large torque and rotation imbalances. The cause of this imbalance is often related to the tension-induced or pressure-induced diameter reductions experienced by the cable component layers.

The change in diameter of a cable having an external strength member (with the exception of a braided strength member) can alter the load sharing among the strength member layers. As the load sharing (stress balance) changes, so does the torque contribution of the various layers.

For example, if a double-armored cable should have the same or a higher helix angle for the inner armor wires as compared to the outer, then the effect of tension-induced cable diameter reduction will be to cause the outer armor layer to carry most of the applied tension. Conversely, if the helix angle of the outer armor layer is significantly larger than that of the inner, the applied tension will be carried primarily by the inner layer. In either case, the cable elongation, breaking strength, and torque and rotation balance are adversely affected.

Cables with non-metallic fiber strength members pose the additional complication that the fiber layers may experience compaction (the elimination of void area) as a consequence of cable tension or external hydrostatic pressure. The compaction of a given fiber layer can affect not only the tension and torque contributions of that layer, but also the contributions of any layers wrapped around it. Whenever one fiber layer experiences compaction and becomes thinner, the overwrapped layers are allowed to seek a reduced pitch diameter. When this happens, the outer layers shed some or all of their tensile bad. The result is a potential reduction in cable strength and elastic modulus and an upset of the cable torque balance.

There is, however, an optimum combination of helix angles for the various strength member layers which will allow the strength member to maintain good stress and torque balance regardless of the magnitude of the tension-induced diameter changes. Cable design and analysis software (such as CABLE SOLVER developed by Tension Member Technology) can be used to establish this optimum strength member geometry.

It is important to note that the cable strength member is not the only potential source of cable torque imbalance. The cable core may carry a significant portion of the applied cable tension and may produce a large torque. The tension and torque contributions of the core can be quite high in cables which have large power conductors or other core elements with a significant cross-sectional area of material with a high elastic modulus.

The analysis of the core contribution to overall cable behavior is complicated by the fact that most core materials have nonlinear stress versus strain characteristics. For example, the copper wire used in most power and signal conductors has such a low elastic limit that it often experiences strains well above its yield point. As a consequence, the tension and torque contributions of the conductors may be nonlinear and may change with repeated load cycling or bending of the cable. Here, again, modern nonlinear cable design and analysis software is required to gain an understanding of the core contribution to cable behavior.

A cable characteristic which is distinct from the torque versus tension behavior is the torsional stiffness. Torsional stiffness is a measure of the ease with which a cable will rotate in response to internally generated or externally applied torque. In general, small diameter cables are torsionally soft, and they will exhibit large amounts of rotation in response to relatively small amounts of torque imbalance. Also, cables with non-metallic fiber strength members are generally much more torsionally soft than are similar cables with metallic strength members.

The torsional stiffness of a cable may be highly directional, especially for cables with two or three layers of armor wires. Cables of these designs will typically rotate much more easily in the direction to loosen the outer layer of wires. In this case, to produce a cable with a minimum amount of rotation, it is desirable for any amount of torque imbalance to be in the direction which causes a tightening of the outer layer of wires. Cables with four layers of armor wires tend to have high torsional stiffness in either direction of rotation.

4.0 CABLE HOCKLING AND KINKING

It is usually desirable for a cable to have good torque and rotation balance to minimize the possibility of cable hockling and kinking in service. A hockle is a loop which forms in a cable and then becomes twisted so that the portions of the cable on either side of the loop become helically wrapped around each other. The hockle, itself, may not seriously damage the cable, but it renders the cable useless where a tension load must be transmitted to a payload. Any application of tension to a hockled cable may cause the hockle to tighten, thereby producing permanent cable deformation and kinking. In a steel wire armored cable, the outer armor wires may become badly displaced or bird caged as a result of this hockling and kinking.

The generation of a hockle in a cable requires only that a slack loop of sufficient size be allowed to form in a cable which contains a sufficient amount of stored torsional energy. If a cable contains no torsional energy, then the formation of a slack loop is not likely to produce a hockle. Similarly, if even a small amount of tension is maintained on the cable so that a slack loop cannot form, then no hockling will occur even if the cable contains a rather large amount of torsional energy.

There are a number of ways in which a cable can inadvertently form a slack loop. For example, when a payload is lowered to the sea floor, it may be difficult to determine exactly when the payload touches bottom, especially in deep water. If excess cable length is deployed after bottom contact, then a slack loop will form at the lower end of the cable. In other situations, it is possible to form a slack loop near the upper end of a tow or tether cable due to motions of the support platform. For certain combinations of payload weight, cable deployed length and elasticity, and platform motions, a resonant condition may produce snap loading of the cable. During snap loading, the cable may repeatedly experience slack loop formation.

There are several sources for the torsional energy required to potentially force a cable slack loop to become a hockle. Obviously, a cable which is not a torque-balanced design will produce torque in response to applied tensile loading. it is usually assumed that when the tension is reduced to zero, the torque will become zero, also. However, this assumption is true only if the tension is zero over the entire cable length.

Consider, for example, a long, heavy, nontorque-balanced cable used to lower or tow a payload which is not allowed to rotate. Because of cable weight and/or hydrodynamic drag, the tension at the surface will be higher than the tension at the payload. The cable torque versus tension behavior as determined in the laboratory may indicate that the cable torque will be highest where the tension is highest. However, in the absence of externally applied twisting moments along the cable, the cable will not support a torque gradient over its length.

To seek uniform torque in the presence of a tension gradient, the cable will experience mid-span rotation (even though no rotation occurs at the cable ends). The rotation near the surface will be in the direction to reduce the tension-induced torque, and the rotation near the payload will be in the opposite direction to produce the opposite effect. The magnitude of the rotation will depend on the cable length, tension gradient, torque imbalance, and torsional stiffness.

This rotation will tend to make the torque uniform throughout the cable length. Thus, if the cable tension should go to zero so as to form a slack loop at any location, then there will be a potential for hockling to occur. In other words, if a nontorque-balanced cable has significant tension anywhere along its length, then hockling is possible even at remote locations if slack should occur.

The use of a swivel will not eliminate the possibility of hockling of a nontorque-balanced cable. The swivel may allow the cable to rotate at the payload so as to maintain zero torque, and depending on the cable length and torque imbalance, the swivel may experience a large number of turns. However, if the cable tension should suddenly drop to zero, the cable rotational inertia and hydrodynamic drag and the swivel friction may prevent the swivel from spinning back fast enough to maintain zero cable torque. The result may be a hockle if a slack loop should form. In addition, any cable rotation allowed by a swivel can be harmful to the cable as discussed below.

Even if a cable has been designed to have good torque balance, it may still develop some torsional energy if it has experienced any twisting. Induced twist can occur during the lowering or raising of a nonsymmetrical payload, by maneuvering of a tethered vehicle so as to accumulate turns in the cable, or by the cable handling techniques. For example, if a cable is deployed manually and is allowed to pull out of a coil which is lying on the deck, it will develop one turn of twist for each wrap in the coil. Similarly, a cable handling system which does not incorporate a drum, but which allows the cable to lie in a cage or basket, will produce one complete twist of the cable for each loop of cable in the basket. Depending on the diameter of the cable and on its inherent torsional stiffness, this twisting may be sufficient to produce a hockle if a slack loop should be allowed to form.

Whether a cable actually forms a hockle depends on the magnitude of the torque imbalance, the size of the slack loop, and the bending and torsional stiffness of the cable. For example, a cable with a high bending stiffness will require a huge slack loop and a high residual torque before the loop will close to form a hockle. Conversely, a very flexible cable may develop a hockle with a relatively small slack loop.

5.0 CABLE ROTATION

Cable rotation (twisting) has a number of adverse effects other than the potential formation of hockles. One of the major consequences of rotation is a reduction in cable breaking strength. This effect is most significant in cables having external contrahelical strength members arranged in either a braid or multiple layers. When a cable is rotated, the strength members which are wrapped in one helical direction are tightened, while those which are wrapped in the opposite helical direction are loosened. The resulting stress imbalance not only reduces the cable breaking strength, but also reduces the cable fatigue performance.

Cables which have high-modulus fiber strength members (such as KEVLAR) may exhibit a dramatic reduction in breaking strength as a result of small amounts of induced rotation. On the other hand, steel armored cables may be able to better accommodate small amounts of rotation because the ductility of the steel allows the wires in both helical directions to reach their yield point prior to rope failure in tension.

Another potential consequence of cable rotation is the rapid failure of conductors within the core. Most cables having a complex core design incorporate several layers of conductors which are typically assembled with alternately right-lay and left-lay helical directions. With this type of core design, no matter which way the cable rotates, some of the conductors will tend to tighten while the others tend to loosen.

Since cables having external strength members tend to become shorter no matter in which direction they are rotated, the conductors which tend to tighten will experience some strain relief due to shortening of the cable. However, those conductors which tend to loosen and develop excess length as a result of cable rotation will experience even more loosening due to shortening of the cable. In the extreme, the conductors may develop z-kinks which can rapidly lead to conductor or insulation failures.

If it is known that a cable will experience induced rotation in service, it is possible to design the cable to be twist tolerant. All conductor layers must have the same helical direction so that they will tighten and loosen together in response to cable rotation. Furthermore, if the direction of the cable rotation is known (such as the rotation induced by a cable handling system), the helical direction of the conductors must be in the direction that causes the conductors to be tightened as the cable rotates. Finally, the lay angle of each conductor layer must be carefully chosen to minimize the additional conductor strain induced by the cable rotation.

Extensive cable rotation tests have revealed that properly designed cables can survive many thousands of cycles of severe twisting without electrical or mechanical failure. Conversely, cables which have not been designed for twist tolerance may survive only a few cycles of moderate twisting. Cable design software (such as CABLE SOLVER developed by Tension Member Technology) can be used to establish the optimum helix angles for the conductor layers.

Of course, whenever possible, cable rotation should be avoided so as to achieve maximum cable breaking strength and fatigue performance. In some systems, it may be necessary to employ a swivel to decouple a torque-balanced cable from a turning payload. Conversely, it may be equally important to eliminate a swivel in a system which uses a nontorque-balanced cable with a stable and nonrotating payload. Regardless of the details of the service conditions for a specific cable, it is usually quite helpful for the cable to be manufactured with an obvious and permanent stripe positioned longitudinally along the cable jacket. This stripe will allow any cable rotation to be identified and quantified so that measures can be taken to minimize the number of accumulated turns.

6.0 CABLE BEHAVIOR IN BENDING

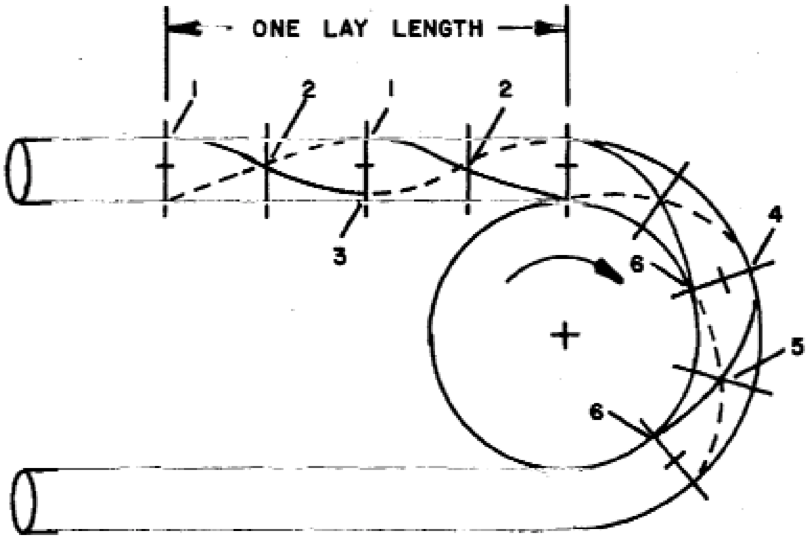
When a cable is subjected to combined tension and bending, the forces and motions imposed upon the individual elements are responsible for the deterioration and final retirement of the cable. It is useful to understand the factors which affect the magnitudes of these forces and motions so that cables may be designed and used property, thereby avoiding premature failure.

6.1 Element Motions During Cable Bending

Consider a cable which is passing over a sheave as shown schematically in Figure 8-3. In the straight portion of the cable, all elements within a given layer (for example, all outer armor wires) have precisely the same length within a given length of cable. Furthermore, if the straight portion of cable is divided into sections of equal length (for example, one-fourth lay length increments as shown in Figure 8-3), then the elements in one cable section have the same length as elements in another cable section. In other words, the length of an element between Positions 1 and 2 is the same as the length of that same element between Positions 2 and 3.

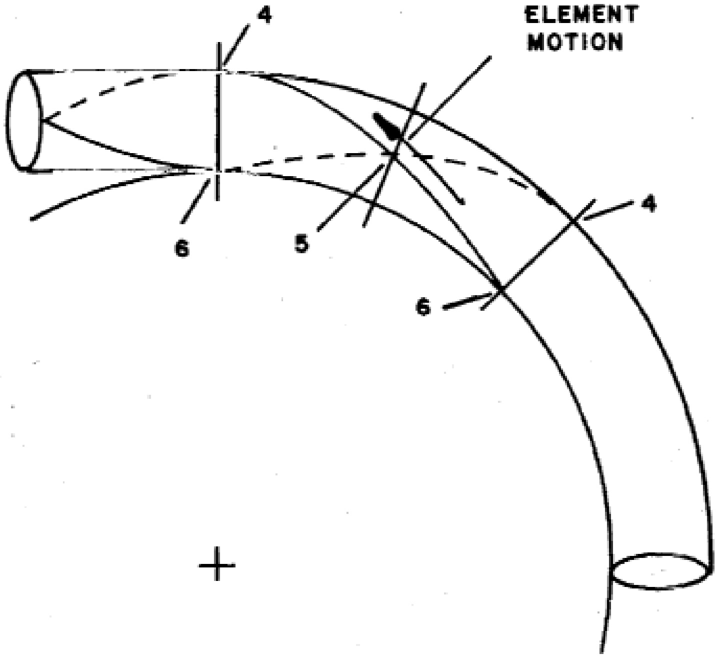
However, after the cable has been bent into a sheave, the length of an element from Position 4 to Position 5 is greater than the length of the same element from Position 5 to Position 6. Thus, in the process of being bent onto the sheave, the cable experiences relative motions among its individual elements to accommodate the distortion of the helical geometry. As the cable passes onto the sheave, the high contact forces at the sheave-to-cable interface prevent element motions in this region (Position 6). To accommodate the length differences described above, each cable element experiences a small amount of motion relative to adjacent layers in the vicinity of Position 5 as shown in Figure 8-4. Little or no motion actually occurs among elements located at Position 4.

To determine the magnitude of these element motions, a mathematical model was developed by Tension Member Technology. This model allows the analysis of any helical structure which is deformed to any desired bending diameter. The details of this analysis are beyond the scope of this chapter, but the results are summarized in Figure 8-5.



ELEMENT GEOMETRY IN A BENT CABLE

FIGURE 8-3

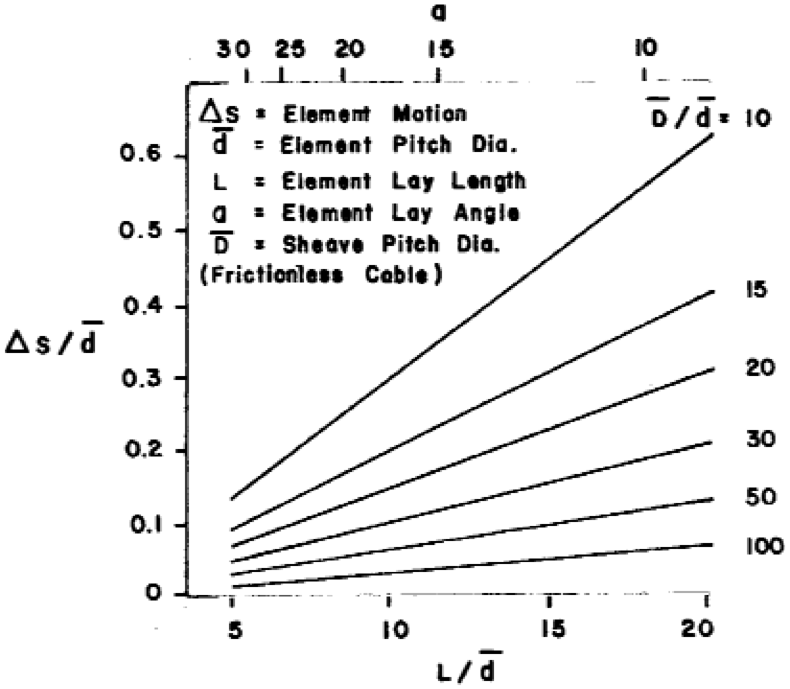


ELEMENT MOTION BY CABLE BENDING

FIGURE 8-4

Consider, for example, a cable having two layers of steel armor wires and an outside diameter of one inch. Assume that the diameter of each outer armor wire is 0.080 inch and, therefore, the pitch diameter of this layer of wires is 0.920 inch. Also assume that the lay length of the outer armor wires is 9.2 inches or 10 times the pitch diameter.

If this cable is bent over a sheave which provides a 27.6-inch bending pitch diameter for the cable (30 times the pitch diameter of the outer armor wires), then, as shown in Figure 8-5, the motion of each outer armor wire relative to the cable axis is approximately 0.10 times the pitch diameter of the outer wires or approximately 0.009 inch. Physical measurements of cable specimens during bending at zero tension (a condition which approaches the frictionless-cable model of the theoretical analysis) have confirmed that the actual element displacements are approximately the same as those predicted in Figure 8-5.



CABLE ELEMENT MOTIONS DUE TO
CABLE BENDING OVER A SHEAVE

FIGURE 8-5

Within a given layer, the relative motion between any two adjacent elements becomes smaller with increasing numbers of smaller diameter elements in that layer. However, the motion of an element in one layer relative to an adjacent contrahelically wrapped layer is affected only to a small degree by the number of elements and the element diameters in each layer. All relative motions (both interlayer and intralayer) become smaller with increasing element helix angles.

Similar motions are exhibited to a greater or lesser degree by all helically wrapped elements within a cable, not just the strength members. It is this relative motion within and between element layers which provides a cable with its flexibility. However, these motions also give rise to the shearing forces and abrasive deterioration which leads to cable failure.

If all of the elements were locked together so that no relative motion could occur, then a cable would have a very high bending stiffness, and the elements would experience high tensile strains on the side of the cable away from the sheave throat and compressive strains on the side of the cable adjacent to the sheave throat. However, the mobility of the elements within the cable structure allows the excess element length on the side of the cable toward the sheave throat to make up for the deficiency in length on the side of the cable away from the sheave throat. As a result, the tensile stress remains much more uniform along the length of each element than would be the case if all elements were locked up so that no relative motions could occur.

6.2 Effects of Element Motions on Cable Strength Members

The consequences of element motions near Position 5 in Figure 8-4 can be observed in the laboratory during cyclic-bend-over-sheave fatigue tests of cables having braided Kevlar fiber strength members. During repeated bending over sheaves with normal operating tensions, such cables eventually fail mechanically due to fiber abrasion in the vicinity of Position 5, with little abrasion being apparent in the vicinities of Position 4 and 6.

Improved performance is obtained if a fiber strength member is applied in contrahelically served layers separated by low-friction isolation tapes (such as Mylar). The isolation tapes all but eliminate the layer-to-layer abrasion. Furthermore, since the individual fibers are so tiny and the number of fibers in each layer is enormous, the relative motion and, thus, the abrasive wear between adjacent fibers within a given layer is negligible.

In the absence of significant fiber wear within and between layers, outstanding cable flexure performance may be achieved.

In the case of cables with steel wire strength members, the relative motions within and between the armor layers contribute to some degree of wear which may remove the protective zinc coating on galvanized wires and, thus, promote the corrosive deterioration of the armor. However, wire armored cables usually do not exhibit a significant strength loss due to internal wear. Rather, they develop fatigue failures of individual wires due to variations in the tension, bending, torsion, and localized compressive contact stresses produced by cable tension, bending, and twisting.

Any reduction of element motions typically improves cable bending fatigue performance. An examination of Figure 8-5 reveals that the element motions can be reduced either by increasing the bending diameter of the cable or by decreasing the element lay lengths (increasing the element helix angles). An increase in helix angles is usually accompanied by a slight increase in cable diameter and a slight reduction in cable elastic modulus and achievable breaking strength for a given quantity of load bearing wire or fiber. The reduction in breaking strength is usually of no consequence, since the usable service life of a cable is determined by the residual breaking strength after some period of flexure cycling and not by the original breaking strength. Thus, the use of higher helix angles to improve fatigue performance is usually advantageous if the corresponding slight increase in cable diameter and elasticity can be tolerated.

The tension applied to a cable causes the helically wrapped elements to exert a radial force on the portion of the cable around which they are wrapped. This radial force acts in conjunction with the internal cable friction to retard the element motions described above. As a consequence of the friction forces within a cable, each element experiences a variation in tension along its length as the cable is bent. For example, referring to Figure 8-4, the portion of an element between Positions 4 and 5 experiences an increase in tensile loading as internal friction forces retard the motion of that element. Only in ideal frictionless cable would the tensile loading remain uniform along the length of a given element. Thus, a factor which contributes to cable deterioration during bending, in addition to element wear, is a variation in the effective tensile load experienced by each element. The resulting variation in tensile stress acts to accelerate fatigue crack initiation and propagation in metallic components. Of course, good cable lubrication to reduce these friction effects will improve cable bending performance.

Another consequence of the element motions and friction forces within a cable is a distortion of the geometry of that portion of cable immediately adjacent to a sheave tangent point. Because of the non-uniform tensile load distribution in the strength members around the cable circumference (higher element tensions away from the sheave, and lower element tensions toward the sheave), the cable does not remain a smooth circular cylinder, but develops a helical distortion or corkscrew over a short section of its length near the sheave. Close observation of a cable which is passing over a sheave will reveal a small standing wave at each sheave tangent point as a consequence of this helical deformation.

Cables elements with small helix angles experience greater motions and larger tension variations than do elements with larger helix angles. Therefore, cables containing elements with small helix angles often exhibit more obvious helical deformations during bending. In extreme cases, this helical deformation can lead to the circumferential migration and bunching of the strength members on one side of the cable. When this occurs, the inner layers of cable elements may protrude through the outer layers, and gross deformation of the cable structure may be the result.

The element displacement and friction forces described above also give rise to cable heating during flexure over sheaves. Such heating is of little consequence during normal deployment and retrieval operations where the cable may experience bending over several sheaves, but only infrequently. On the other hand, if a cable is subjected to repeated bending over the sheaves of a motion compensation system while at a high tension load, then the friction-induced temperature build up can be quite significant and, when added to any electrical resistive heating, can lead to accelerated failure of certain insulation materials. Cable heating can be reduced by the application of a lubricant to a cable to reduce the internal friction and to improve the heat transfer away from the cable.

6.3 Effects of Element Motions on Cable Core Components

The electrical conductors or optical fibers within the core of a cable also experience similar element motions and friction forces. However, in this case, the elements may have insufficient tensile strength to accommodate the induced element motions in the presence of high internal cable friction.

As a consequence, conductors may experience strains far in excess of their yield point between Positions 4 and 5 in Figure 8-4, while the same conductors may experience longitudinally compressive loads and z-kinking between Positions 5 and 6. Then, if the same section of cable should pass over another sheave so as to be bent in the opposite direction (a reverse bend), then that portion of the conductor which was previously strained beyond its yield point will be forced into longitudinal compression, while the adjacent section which was previously compressed will be strained beyond its yield point. The consequence will be rapid failure of the conductor and insulating materials. This type of deterioration is frequently observed in cables which incorporate small interstitial conductors at locations well away from the cable centerline.

On the other hand, larger power conductors which have ample tensile strength may be able to accommodate the, induced motions without rapid failure. However, even these conductors may eventually exhibit cup and cone tensile failures (rather than classical fatigue failures) as a result of the large strains induced in the conductors during cable bending.

There are several steps that can be taken to avoid premature failure of conductors which must be located at a significant distance from the cable centerline. One approach is to combine several small conductors together into a twisted pair, triad, or quad so that the assembly has ample extensibility to accommodate the length changes imposed by cable bending without exceeding the yield point of the conductor material. If it is not possible to combine small conductors into complexes, then it may be necessary to use a high conductor helix angle so as to minimize the motions within the cable structure or to fabricate an elastic conductor by wrapping one or more layers of copper filaments around a small diameter nylon rod.

In any case, careful attention must be paid to the design of a cable core so that all elements have sufficient strength, elasticity, and helix angle to accommodate the deformations which occur as the result of cable bending. Also, all core materials should be selected with due consideration given to their friction characteristics, since low element-to-element friction will enhance the bending performance. In this regard, the cable void-filling material should not “glue” the core elements together so as to retard element motions.

6.4 Cable Strength Reduction Due to Bending

Cable breaking strength is an important parameter of most cable design specifications, and the strength is usually determined by a tensile test of a straight cable specimen. For many cable applications, this approach is adequate. However, in some cases, it may be important to know the cable strength under conditions of bending over the sheaves and/or drum of the cable handling system, since the maximum cable tension usually occurs at this location.

Laboratory experiments have shown that if a cable is wrapped around a sheave with both ends attached to a loading plate and is then pulled to failure (without sheave rotation), the cable will break at one of the sheave tangent points (at a point where the cable becomes bent onto the sheave) and with some reduction in breaking strength. This reduction may be significant if the sheave is small. If the same type of cable is pulled to failure while it is moving over the same sheave (such as during retrieval of a payload), the reduction in breaking strength will be even greater.

In the static case, the cable is bent over the sheave at essentially zero tension prior to being pulled to failure. As the cable is initially bent, all internal elements are able to move as necessary to accommodate the bend without their motions being retarded by high internal cable friction. Then, during the break test, the load sharing among all elements is fairly uniform, and the cable breaking strength approaches that of a straight cable (unless the sheave is quite small).

In the dynamic case, the cable experiences continuous bending as the sheave rotates. As the tension increases, so does the internal cable friction which retards the element motions induced by the bending. The result is a non-uniform tension distribution among the cable elements and a reduction in the achievable cable breaking strength. During laboratory experiments, this strength reduction has been as great as 30 percent for some cables. Usually, cables with small helix angles for the strength members exhibit the largest strength reduction during bending. Again, smaller sheaves produce more strength loss.

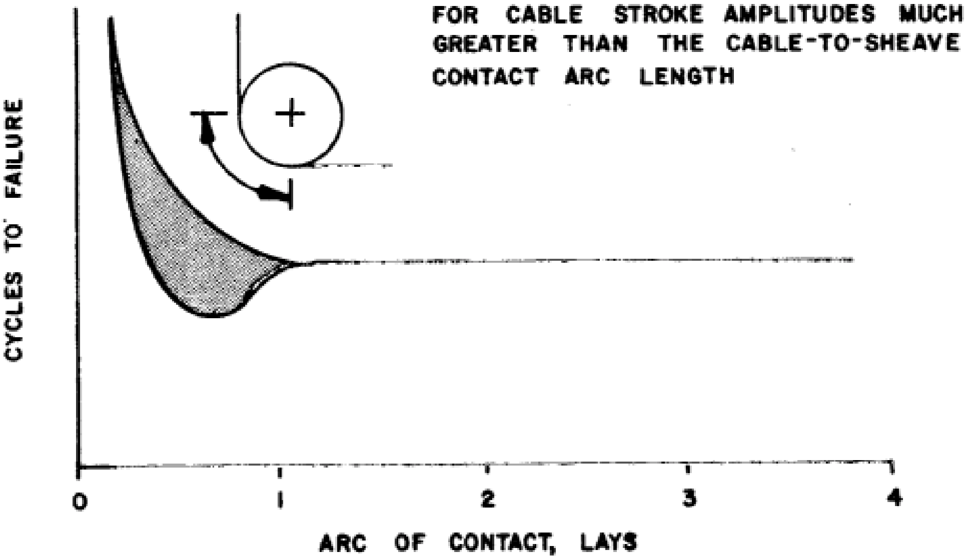
6.5 Effects of Cable Wrap Angles on Sheaves

All of the bending-induced changes in stresses and relative motions among the cable components as described above take place in the immediate vicinity of the cable-to-sheave tangent point. Because of the internal friction within the cable structure, the affected portion of the cable is relatively short. In other words, portions of the cable which are a short distance away from the sheave, or portions of a cable which are on the sheave a short distance away from a sheave tangent point, experience no changes in internal stresses or motions and are not influenced by the bending of other portions of the cable.

If the arc of contact between the cable and sheave exceeds approximately one lay length, then there will be a certain portion of cable in contact with the sheave which, having undergone stress changes in the vicinity of one tangent point, will experience no further changes in its state of stress until it approaches the second tangent point. Thus, for typical deployment and retrieval operations, the bending fatigue life of a cable is not influenced by the wrap angle on a sheave as long as at least one lay length of the cable is in contact with the sheave. (See the following Section 7.0 for special considerations regarding cable wrap angles on sheaves.)

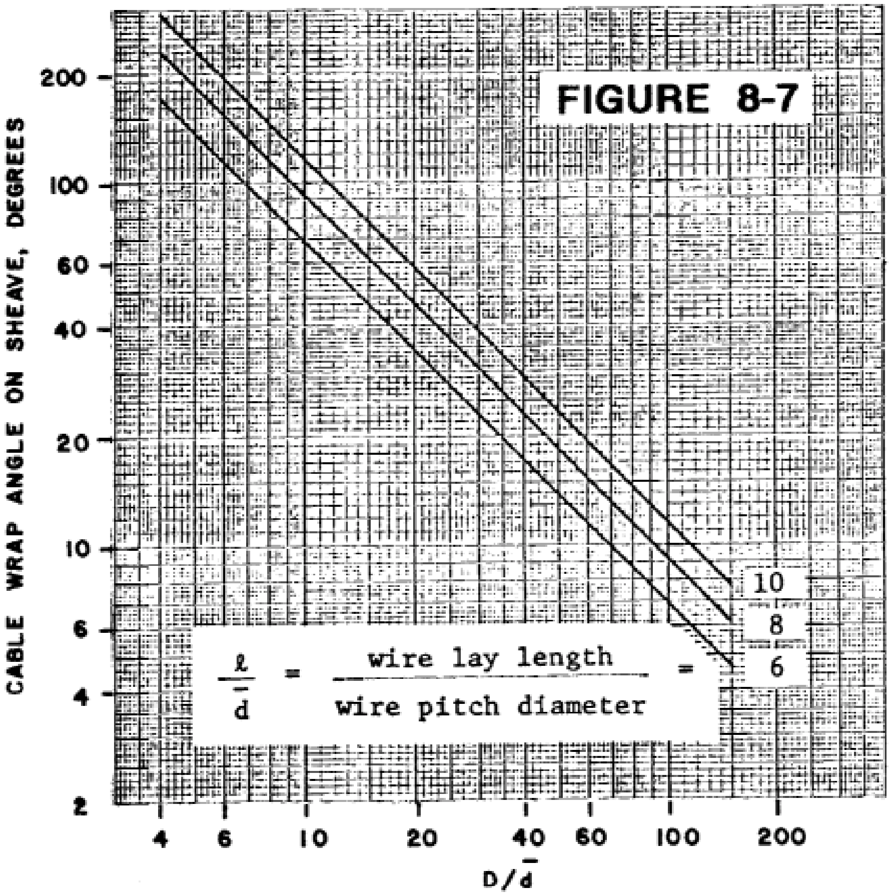
Cables which are deployed and retrieved through a series of fairlead sheaves will have a bending fatigue life which will be the same regardless of the cable wrap angles on the sheaves, at least for contact arcs equal to one or more lay lengths of the strength members. For a contact arc of less than one lay length, the bending fatigue damage produced by a sheave is typically less, but there are notable exceptions to this rule. Depending on the specific cable design, the sheave-to-cable diameter ratio, and the operating tension, a cable contact arc of one-half lay may be more damaging than a longer contact arc. This behavior is shown graphically in Figure 8-6.

Figure 8-7 shows the cable wrap angles on a sheave required to produce an arc of contact equal to one lay length for various sheave diameters. This graph assumes that the cable has a external strength member and that the outer layer has a lay length equal to six, eight, or ten times its pitch diameter (a helix angle of 27.64, 21.44, or 17.44 degrees, respectively):



EFFECT OF SHEAVE CONTACT ARC ON CABLE BENDING FATIGUE LIFE

FIGURE 8-6



WRAP ANGLE OF A CABLE ON A SHEAVE CORRESPONDING TO A CONTACT ARC OF ONE LAY LENGTH OF THE OUTER LAYER STRENGTH MEMBERS

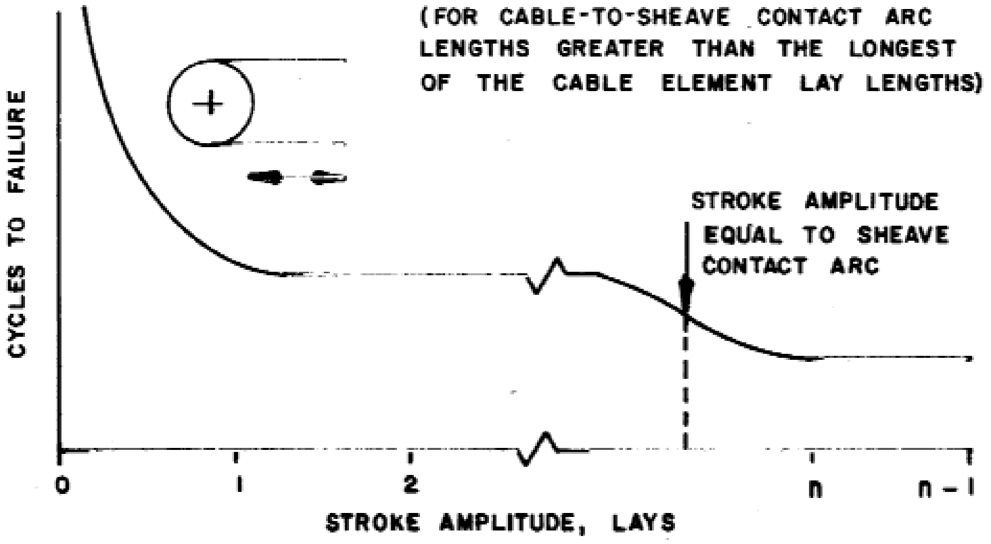
One of the important conclusions which can be drawn from these considerations is that a sheave diameter should not be arbitrarily reduced just because a cable happens to have a relatively small wrap angle on that sheave. A single, small deflection sheave or roller can produce more cable damage than all of the other sheaves in the fairlead system. Even worse is the replacement of a sheave with a series of small rollers in the interest of saving space. This procedure can quickly destroy a cable which supports any significant tensile load.

6.6 Effects of Cable Stroke Amplitude Fatigue Life

The above discussions assume that the cable is being deployed and retrieved with a stroke amplitude that is quite large. In this case, the cable experiences two straight-bent-straight bending cycles at each sheave, one during deployment and another during retrieval.

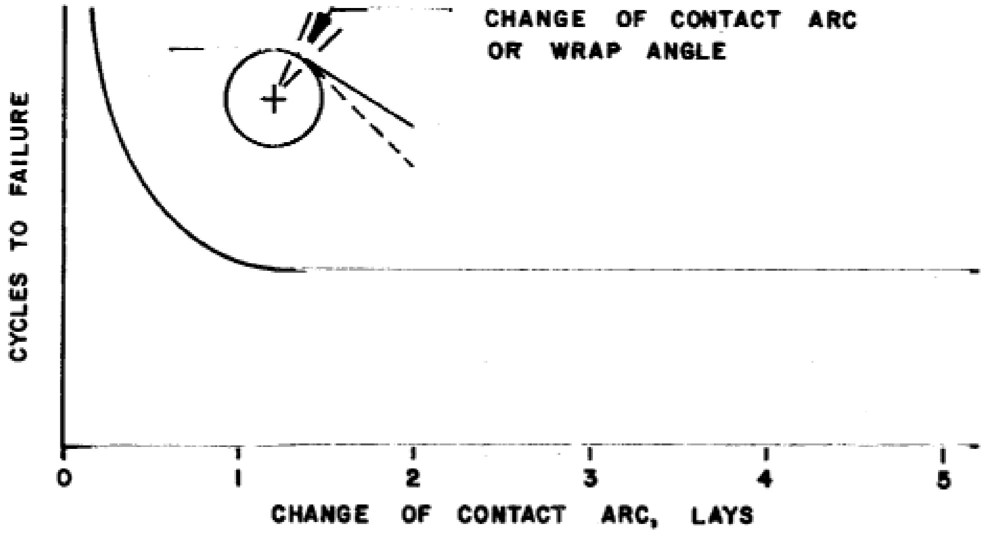
If the cable stroke amplitude is diminished to less than the cable-to-sheave contact length, then the cable will experience only one straight-bent-straight bending cycle during a complete deployment and retrieval sequence, and the cable life in the system will be essentially doubled. This behavior is shown in Figure 8-8. For the case of a large cable-to-sheave wrap angle, the cable fatigue life will remain the same with decreasing stroke amplitude until the stroke amplitude equals approximately one lay length of the outer strength members. For even shorter stroke amplitudes, the cable fatigue life will increase further.

Consider the case of a tow cable which makes contact with an overboarding sheave as shown in Figure 8-9. Ship motions will cause the cable to experience continuous flexing at the sheave. For relatively calm conditions, the length of cable involved in the flexing may be less than one lay length of the outer strength members, and the cable fatigue life may be quite good. However, if the bending zone of the cable approaches one lay length, then a condition of full bending will be experienced, and the cable may rapidly accumulate fatigue damage. Figure 8-7 may be used to determine the change of cable wrap angle corresponding to a bending zone of one lay length of the outer strength member.



EFFECT OF CYCLING STROKE AMPLITUDE ON CABLE BENDING FATIGUE LIFE

FIGURE 8-8



EFFECT OF BENDING AMPLITUDE AT OUTBOARD SHEAVE ON CABLE BENDING FATIGUE LIFE

FIGURE 8-9

7.0 MOTION COMPENSATION SYSTEMS

If a cable is to be used under severe dynamic conditions, some type of motion compensation system may be required to decouple the motions of the host vessel from those of the payload. Two common types of systems are the bobbing boom and the ram tensioner.

7.1 Bobbing Boom Systems

In the bobbing boom system, the cable passes over a sheave that is located at the end of an articulated boom. The position of the boom is controlled by a hydraulic ram and pressurized accumulator system, and the boom bobs up and down in response to vessel motions so as to maintain a more or less constant cable tension. This type of system is least damaging to the cable since only a short cable section experiences repeated bending of the type shown in Figure 8-9. By periodically changing the position of the cable by only a few feet, it is possible to distribute the cable wear so as to prolong cable life.

7.2 Ram Tensioner Systems

In a ram tensioner, the cable passes over one or more sheaves that are connected to a hydraulic ram and pressurized accumulator system. The ram provides a pneumatic spring which acts to maintain the cable tension at a more or less constant value as the cable strokes in and out in response to vessel motions. In this type of system, special consideration must be given to cable wrap angles and sheave spacing.

Obviously, the system should employ as small a number of sheaves as possible to minimize the bending fatigue damage to the cable. Furthermore, these sheaves should be spaced as far apart as necessary to assure that no single section of the cable comes into contact with more than one sheave during each heave cycle. Should a section of cable pass over two sheaves with each heave cycle, the total bending fatigue life of the cable will obviously be one-half of that which could be achieved if the sheaves were further apart.

Another important factor which influences the total achievable cable fatigue life is the arc of contact between the cable and each sheave in the fairlead system. (It should be noted that the previous discussion of cable contact arc effects applied to typical deployment and retrieval operations and not to motion compensation.) During active motion compensation, if the cable stroke amplitude is less than the cable arc of contact with a sheave, then each heave cycle will produce one straight-bent-straight cable bending cycle.

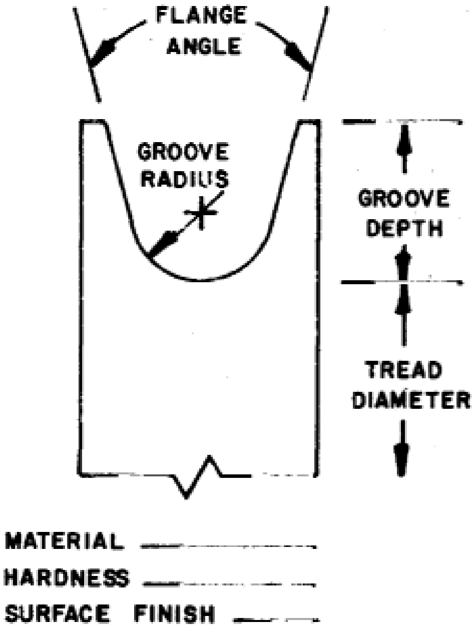
If, on the other hand, the amplitude of cable motion should exceed the length of the cable arc of contact on the sheave, then a section of the cable will pass onto, completely around, and off of the sheave as the cable strokes in one direction, and it will return to its original position as the vessel completes one heave cycle. In this case, a section of the cable will receive two straight-bent-straight bending cycles during each heave cycle.

Thus, a cable wrap angle of 180 degrees will allow cable motions (heave amplitudes) twice as large as could be accommodated with a wrap angle of 90 degrees before each heave cycle produces two cable bending cycles. In the long term, a motion compensation system which employs larger cable wrap angles will accumulate fewer cable bending cycles and will enjoy a longer cable service life.

8.0 SHEAVES FOR CABLES

The sheaves in the cable handling system should be as large in diameter as practical to maximize cable service life. In addition, the sheave grooves must be smooth, and the groove diameter should be the same as the cable diameter when measured at zero tension. A sheave groove which pinches the cable or which fails to support the cable properly will diminish the cable bending life. A cable should never be used on a sheave grooved for a cable of larger diameter. It is also important that all sheaves are properly aligned so that the cable experiences little or no fleet angle. Any sheave misalignment will cause cable wear due to rubbing on the sheave flanges. Figure 8-10 shows the various factors to be considered during sheave design.

Sheave flanges for many applications typically have an included angle of approximately 30 degrees. This configuration provides adequate cable support and will accommodate small cable fleet angles without causing unusual cable wear. (The fleet angle is the departure angle between cable and the plane of the sheave.) In some situations, however, it may not be possible to avoid a large fleet angle. For example, a vehicle tether cable may experience large out-of-plane motions at an overboarding sheave due to changes in the relative positions of the vehicle and the support vessel. In this situation, a large flange angle may be required to prevent the cable from coming into contact with a potentially sharp edge at the top of the sheave flange.



SHEAVE DESIGN PARAMETERS

FIGURE 8-10

A sheave groove depth of one cable diameter is usually satisfactory for many applications. However, deeper grooves may be needed to assist in reeving a cable through a handling system or to assure that the cable does not come out of the grooves during extreme operating conditions. If a cable has even a small fleet angle at a sheave, special attention must be paid to both the groove depth and the flange angle. Otherwise, the cable may come into contact with the top edge of the flange. For example, a sheave flange half angle of 15 degrees does not imply that a fleet angle of 15 degrees can be accommodated. The actual maximum fleet angle will be a function of both the sheave-to-cable diameter ratio (Did) and the groove depth. The larger the Did ratio, the greater the required groove depth to avoid cable contact with the top edge of the flange.

The sheave diameter which is appropriate for a given system depends on the details of the cable design, the severity of the operating tensions, the desired cable service life, and the consequences of a cable failure. Some cable designs and operational requirements demand large sheaves, while others allow smaller sheaves to be used. In selecting sheave sizes it should be remembered that small, increases in sheave diameter can produce dramatic increases in cable life.

Plastic lined or nylon sheaves may offer some advantage for steel wire armored electromechanical cables in terms of cable wear and wire-to-sheave contact stress. However, in situations where a highly loaded cable repeatedly passes back-and-forth over a sheave in a motion compensation system, especially when transmitting large amounts of electrical power, it may be advantageous to avoid the use of nonmetallic sheaves or sheave liners because of cable heating considerations. A metal sheave can act as a heat sink to reduce cable heating under these conditions.

9.0 CABLE REEVING CONFIGURATIONS

In the simplest system, the cable is deployed directly from its storage drum without passing over any sheaves or through any guide rollers. Other systems require relatively complex reeving configurations where the cable must pass over a number of sheaves. Regardless of the simplicity or complexity of the system, safety considerations should not be neglected. Whenever possible, personnel walkways should be designated away from the cable system to avoid having the cable pass near or through a commonly used walkway. An equally important consideration is the recoil path the cable will have in the event of a catastrophic failure. Cable recoil can inflict serious damage and injury at locations well away from the normal route of the cable. Where necessary, barricades should be erected to absorb the energy of a recoiling cable.

Cable systems vary not only in their complexity, but also in their frequency of use. Some systems require a cable to be deployed and retrieved relatively infrequently, while other systems may subject the cable to nearly continuous load and flexure cycling. In any case, there are a number of system design guidelines which will improve cable service life.

Of course, the number of sheaves in the system should be kept to a minimum whenever cable flexure life is a concern. Also, the greater the number of desired cable flexure cycles, the greater will be the required sheave diameters and operating safety factors.

All components of a cable handling systems should be arranged so as to minimize the cable fleet angles at the drum and sheaves. A large fleet angle can lead to cable mis-spooling on the drum or cable wear due to rubbing against adjacent wraps on a drum or against sheave flanges. A large fleet angle is also detrimental because it can produce a small-radius cable bend at a sheave flange in a plane perpendicular to the plane of the sheave. These small-radius bends are potentially as damaging to the cable as small sheaves.

Whenever possible, the cable routing from the drum and through the various sheaves should be chosen so as to eliminate reverse bending of the cable. A cable which is bent in the same direction over two sheaves will have considerably better service life than if it is subjected to a reverse bend over the same two sheaves. While it is sometimes impossible to avoid reverse bending of a cable, the consequences of this reeving configuration must be recognized.

It is a common misconception that a cable can be routed in a large-radius arc over a series of small-diameter rollers without affecting the performance which would otherwise be obtained by use of a single sheave of the same radius. While this arrangement may be acceptable for cable tensions near zero, the small rollers may severely damage the cable at normal operating tensions. Each roller wilt subject the cable to a severe bending condition even though the cable wrap angle at each roller may be very small. Thus, it is always advantageous to eliminate guide rollers whenever possible in favor of sheaves having the proper geometry.

Finally, it is important that a moving cable not come into contact with any stationary structure. In addition to possible abrasive damage to the jacket or strength member, steel armor wires may experience sufficient frictional heating to form a very thin layer of untempered martensite on the outer surface at the contact location. Martensite is very hard and brittle, and it will develop small cracks as soon as the cable is subjected to any significant tension or bending. These cracks will then propagate rapidly through the remainder of the wire cross section to produce premature wire failures.

10.0 CABLE WINDING ON DRUMS

For those systems in which the cable tension is always quite low at the drum (systems employing some type of traction winch), the cable life will probably not be influenced to a great extent by the details of the drum design. However, for those systems which require the cable to be wrapped on the drum under high tensions, the drum can be a major source of cable damage.

The factors which affect cable life are the drum diameter, the number of cable layers, the type of grooving, and the uniformity of winding. The influence of these factors can vary from one installation to another. However, the cable will usually benefit from a large drum diameter, proper grooving, and the use of a level-wind system to achieve smooth winding.

If a cable must be wound on a drum in multiple layers and must also sustain a significant tension load, cable damage may occur due to crushing of the bottom layers on the drum, localized pinching and bending due to uneven winding at the drum flanges, or “cutting in” where the outer wrap of cable becomes buried within the inner wraps in response to a high tension load. The potential for crushing of the inner cable layers can be minimized by using a large diameter drum which reduces both the radial force developed by the cable and the required number of cable layers. The drum should also be properly grooved. The use of riser and filler strips at the drum flanges will reduce the potential for localized cable damage at the flanges where the cable rises from one layer to the next. Also, the potential for cutting in of a cable can be reduced if the cable is wound on the drum so that the inner layers have a high tension.

Proper winding of a cable will usually require some type of level-wind system to guide the cable onto the drum. Synchronization of the level-wind mechanism with the cable lead on the drum is critical to avoid mis-spooling. Also, care must be taken in the design of the level-wind sheaves or rollers to assure that they are not a source of premature cable damage.

If no level-wind system is used, the first fixed-position sheave must be positioned far enough away from the drum to limit the cable fleet angles (usually to less than 1-1/2 degrees). Excessive fleet angles can produce mis-spooling on the drum and also cable wear due to rubbing on sheave flanges or against adjacent cable wraps on the drum.

To allow the cable tension to be maintained at a low value on the drum, some type of traction winch can be used. A common system uses a double-drum capstan as discussed elsewhere in this handbook. In this system, the cable passes over a pair of grooved drums in a series of half wraps. One or both of the drums is driven electrically or hydraulically, and the friction between the cable and the drum grooves allows a significant tension gradient to be developed, thereby allowing the cable to be wound on the storage drum at a low tension. (An electromechanical or fiber optic cable should not be used on a single, flat-faced type of capstan such as is often used for mooring ropes.)

11.0 CABLE VOID FILLERS

It is important for any electromechanical cable to be properly void filled to minimize the change in diameter during tensile loading and the associated constructional elongation. However, for any cable which is to be operated over sheaves, the void fillers used within the core must not be of the type which remain liquid, no matter how high the viscosity may appear to be. Repeated cycling of the cable over a sheave will cause such void fillers to be milked away from the sheave contact zone due to the increased pressures produced by cable contact with the sheave. The void filling material will then accumulate just beyond the sheave contact zone and will produce bulging of the cable or even total rupture of the core jacket. Elastomeric void fillers, such as DPR, are much preferred.

Also, as discussed earlier, the cable void-filling material should not “glue” the core elements together so as to restrain element motions during cable bending. The consequence will be an amplification of the strain experienced by each core element and premature failure of core conductors or optical fibers.

12.0 CABLE TERMINATIONS

The ideal cable termination restrains the cable core and external strength members in such a manner as to duplicate the stress distribution in the cable elements which would be present in an undisturbed continuation of the original cable. Compression of the cable core by the strength members when the cable is under tension prevents the core tram slipping longitudinally inside the cable and allows the core to extend through the strength member termination without affecting the stress distribution in the strength members.

Four basic types of cable terminations are in common use. The drum-grip termination is simplest in concept. It consists of a wide sheave having either a flat face or a helical, conformal groove upon which are wrapped several turns of cable. The friction between the cable strength member and the drum face provides a means for transferring the stress in the cable to the grip. A portion of the cable tension is transferred to the drum for each wrap of cable, and the low-tension end of the cable is anchored with a suitable secondary termination which can accommodate the lower tension level. The drum grip is particularly effective for steel-wire armored cables, and it may be used to provide a means of easily reterminating a cable in the field.

To achieve a high termination strength efficiency using a drum grip, the same drum geometry requirements as mentioned for sheaves must be met; i.e. a large drum-to-cable diameter ratio, a groove diameter equal to the cable diameter at zero tension, and a small fleet angle. (Termination efficiency is defined as the ratio of the terminated cable breaking strength to the mid-span breaking strength achievable with ideal terminations, expressed as a percent.) Drum-grip terminations with high strength efficiency are usually large in diameter and are relatively heavy.

Termination efficiencies of near 100 percent are achievable with drum grips for steel wire armored cables without external jackets. However, jacketed cables can encounter problems when terminated with drum grips. If the coefficient of friction between the cable strength member and the jacket is less than the coefficient of friction between the jacket and the face of the drum grip, the strength members may slip inside the jacket. Then, upon repeated load cycling, the entire load will eventually appear at the secondary termination resulting in cable failure at that location. (If the secondary termination is capable of handling the entire load, then the drum grip is superfluous.) This same jacket slippage problem can occur in systems utilizing traction sheaves, and total jacket delamination may be the final result.

The resin-filled .socket termination is a proven technology used successfully with steel wire armored cables, and termination strength efficiencies of 100 percent are commonly achieved. However, for the case of cables having non-metallic fiber strength members, high strength efficiency can be routinely achieved only with very small cables with breaking strengths of a few thousand pounds. For larger cables, strength efficiencies of as little as 60 percent are often encountered.

A factor contributing to the low strength efficiency of resin terminations when used on Kevlar fiber strength members is the fact that, unlike steel wires which can yield under tension and allow all wires to share the load, Kevlar fibers fail without yielding. Thus, careful preparation of the Kevlar before pouring the resin in the socket is essential for good fiber load sharing.

External compression-type terminations apply radial compression over some length of the cable and transfer the stress in the cable tension elements to some type of external termination. Woven wire mesh grips (“Chinese finger” grips), single-layer and double-layer helical wire grips, and split-pipe grips fall into this termination category: They are quite effective on steel strength member cables and may work well on externally jacketed cables if the coefficient of friction between the jacket and the strength members is high enough. If this is not the case, the termination and a section of the jacket may pull off of the cable at a rather low tension.

In general, external, compression-type terminations are not suitable for cables with multiple layers of non-metallic fiber strength members, especially cables designed with low internal friction to provide good bending fatigue life. In this case, the friction between layers may not be sufficient to allow load transfer to take place from layer to layer so as to provide uniform loading of all fibers.

Cables with non-metallic fiber strength members may be successfully terminated with special splicing techniques. The TMT Braid-Splice Termination uses a separate fiber eye assembly which is spliced into the end of the cable, and it can be used even with cables fabricated with low-friction fiber finishes. This splice requires some rearrangement of the geometry of the strength member fibers at the end of the cable to form a special braided geometry. Although time consuming to install, this termination is light in weight and typically provides a strength efficiency of 100 percent (tensile test specimens break mid span). The splice geometry must be carefully engineered for each specific cable to provide uniform core compression over the length of the splice to avoid damage to the cable core.

13.0 CABLE FAILURE MECHANISMS AND RETIREMENT CRITERIA

Cables used in the ocean have several modes of failure which may occur if the cable does not first encounter accidental damage such as entanglement with propellers or slipping off of the sheaves of the handling system. One common mode of failure is tensile overload due to snap loading induced by the dynamics of ship motions, such as during deployment or retrieval of a payload. Snap loading can induce cable tensions many times greater than the nominal operating tension, and it can produce slack loops and the potential for hockling and kinking.

Internal cable failure mechanisms include:

(1) Abrasive wear of strength member components

(2) Fatigue failure of metallic strength members

(3) Circumferential migration of non-metallic strength members causing cable cork screwing

(4) Breakage or shorting of electrical conductors

(5) Breakage of optical fibers

(6) Thermal damage of the cable due to resistive heating and/or heating due to continual cycling over sheaves within motion compensation equipment

The potential for cable failure due to resistive heating must not be underestimated. The conflicting requirements of neutral buoyancy, small diameter, high strength, and high power capability often result in cables which operate at elevated temperatures. Usually, once the cable is underwater, the heat dissipation into the water is sufficient to keep the internal temperatures within acceptable limits. When the cable is in air or is wound on a drum, severe heating problems often occur.

Cables with non-metallic fiber strength members are particularly susceptible to thermal damage because of the low thermal conductivity of the strength member and the cable jacket. One means of partially relieving this problem is to impregnate the fiber with a grease or other thermally conductive material. However, the lubrication effect of the grease can increase the probability of fiber migration and corkscrewing of contrahelically served strength members.

Since many cables are retired from service following, rather than prior to, some cable failure, it is desirable to limit the cable damage to a localized area. The failure of communication or control system elements in a cable may scrub a mission, but the payload can usually be retrieved by means of the cable strength member. If an electrical or optical failure occurs near one end of the cable, and particularly if it is due to an external cause rather than general internal wear, cutting off the damaged section and retermination of the cable is a reasonable approach. This technique also applies when opens in the power conductors cause loss of power to the vehicle.

A serious type of cable failure is shorting of the power conductors when the system does not have adequate safeguards to prevent additional cable damage. Cables particularly susceptible to thermal heating damage during short circuits are those which use several power conductors in parallel to achieve the required conductor cross-sectional area for one phase of a circuit. For example, if three power conductors are used in parallel to carry 15 amperes and are protected by a single 15 ampere circuit breaker, shorting of one of the three conductors to a return conductor at a damage site can cause that conductor to carry most of the current with little current being tarried by the two remaining power conductors. This type of fault may not trip the circuit breakers and may allow the insulation on one conductor to be thermally damaged along the entire length of the cable between the power source and the short circuit. This damage is likely to force early retirement of the cable.

Power systems should be designed to accommodate shorts and opens in power conductors without causing any additional local damage such as arcing at the location of the cable short circuit. This approach can prevent additional damage and will allow a failure analysis to be performed on the damaged section. The addition of conductive blocking compounds and drain wires to the cable core allows the use of ground-fault detector circuits at the power source. These circuits disconnect the power to the cable upon detection of electrical leakage above a predetermined level to either sea water or the cable drain wires. This system prevents power surges from passing through a shorted section of cable and heating the entire length of the power conductors sufficiently to thermally damage the conductor insulation.

The importance of cable failure analysis cannot be over emphasized. After any failure, a section of cable including the failure location should be saved for analysis. The end toward the payload should be marked, and a cable map prepared showing the location of the failed section in relationship to the handling system sheaves. The cause of failure, if known, the sea state, and other operating conditions should be recorded.

It is important to determine whether a failure is due to externally or internally induced cable damage. If externally induced, then an examination of the operational procedures is in order. If internally induced, the cable may be worn out or have design deficiencies which make it unsuitable for use under existing conditions. A change in operational procedure may reduce the cable stresses to a level which will allow the cable to perform satisfactorily.

14.0 SPECIAL CONSIDERATIONS FOR WIRE AND NON-METALLIC ROPES

The preceding portions of this chapter are directed at various types of cables which combine power and/or data transmission elements with flexible metallic or non-metallic strength members. Much of this information can be applied to metallic and nonmetallic ropes, as well. However, there are a number of special considerations for ropes which deserve additional discussion. The remainder of this chapter is directed at ropes used in the ocean environment.

15.0 TYP1CAL ROPE CONFIGURATIONS

Wire ropes typically have one or more layers of helically wrapped strands, each of which is made up of one or more layers of helically wrapped wires. The core of the wire rope, if any, may be a natural or synthetic fiber rope, a strand similar to one of the main rope strands, or an independent wire rope core (IWRC).

Many wire rope materials and designs are available with a variety of physical characteristics in terms of strength, flexibility, torque and rotation balance, abrasion resistance, and corrosion resistance. Examples of common wire rope configurations appear in Figure 8-11.

It is recognized that the term “wire” is often used in the field to identify a wire rope. However, for the purpose of this chapter, the term “wire” will apply to an individual metal wire that is used as a component of a more complex rope structure.

Ropes made of high-modulus, non-metallic fibers are a fairly recent development, arid their designs continue to be refined as test and field performance data are accumulated. Many of these ropes are similar in geometry to wire ropes, while others incorporate special design features to enhance their strength and bending-fatigue performance.

16.0 ROPE TORQUE

With the exception of 3-strand torque balanced ropes and certain ropes with multiple layers of strands, most metallic and non-metallic ropes develop a significant torque when loaded in tension.

The torque produced by a rope is due to both the helix of the main strands and the helix of the individual strength members (wires or non-metallic fiber bundles) within the strands. In a regular lay construction (which has opposite helix directions for these rope components), the net rope torque is lower than for a Lang lay construction (which has the same helical direction for all components).

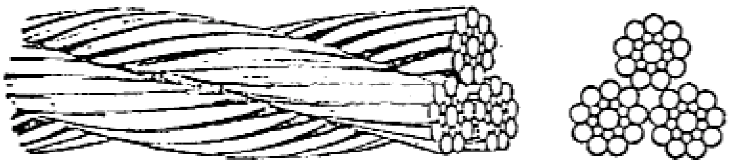
The torque produced by 6-strand, fiber-core wire ropes can be approximated by:

$$\text{Regular Lay Rope Torque} = 0.55\frac{d}{L/d}T \quad \text{(inch - pounds)}$$

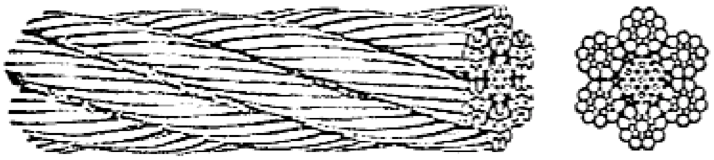
$$\text{Lang Lay Rope Torque} = 0.91\frac{d}{L/d}T \quad \text{(inch - pounds}$$

where:

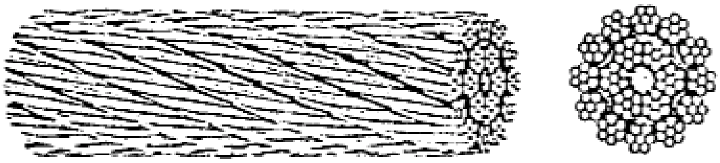
d = nominal rope diameter, inches
L = rope lay length, inches
T = rope tension, pounds.



3 x 19 Searl Right Regular Lay



6 x 19 Searl Right Regular Lay, IWRC



18 x 7 Non Rotating, Fiber Core

TYPICAL WIRE ROPE CONSTRUCTIONS

FIGURE 8-11

For many working wire ropes, the ratio L/d is in the range of 6.25 to 6.5.

Whenever two ropes are connected together, they should be of similar diameter and construction, and if not, they should have similar torque versus tension characteristics. Otherwise, the connection will rotate as the two ropes seek the same torque value. This rotation will adversely affect the strength and fatigue properties of both ropes, especially ropes constructed from high modulus, non-metallic fibers.

17.0 ROPE HOCKLING AND KINKING

The discussion early in this chapter about hockling and kinking of cables is applicable to ropes, as well. However, since most ropes develop considerably more torque than do most cables, the potential for rope hockling and kinking is much greater. The reader is encouraged to review the earlier discussion of this subject.

18.0 ROPE ROTATION

Many ropes exhibit huge amounts of rotation if one end is allowed to turn. Generally, the rotation is in the direction to loosen the outer layer of strands and increase the lay length of this strand layer.

If a rope has more than one layer of strands, any rotation will typically have a major effect on the load distribution among the strand layers. For example, if a specimen of 19x7 spin resistant wire rope is allowed to rotate freely as it is pulled to failure, the breaking load will be approximately 30 percent lower than that of a specimen pulled to failure with the ends restrained to prevent rotation.

Rotation of a regular lay wire rope tends to tighten the outer wires of each strand, while rotation of a Lang lay rope tends to loosen the outer wires. This stress redistribution within each strand can adversely affect the rope breaking strength and fatigue performance. Furthermore, the wire looseness in a Lang lay rope can lead to “secondary bending” of the outer wires as the rope passes over a sheave. This secondary bending can lead to premature wire fatigue failures.

The use of a swivel with a rope is sometimes required to decouple the rope from a spinning load. However, all ropes provide the best performance if used with the ends restrained from rotation.

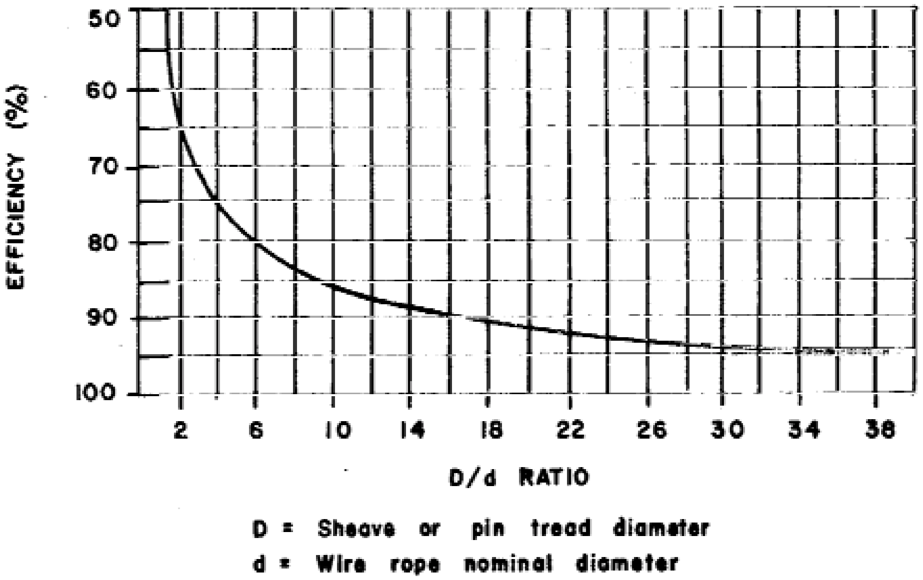
19.0 ROPE BEHAVIOR IN BENDING

The discussions presented earlier in this chapter about the behavior of cables in bending also apply generally to ropes. The reader is encouraged to review this information to develop a basic understanding of rope behavior. The following comments amplify this information as it applies specifically to ropes.

20.0 ROPE STRENGTH REDUCTION DUE TO BENDING

As in the case of cables of all types, ropes also exhibit a reduction in breaking strength when pulled to failure while wrapped around a sheave or pin. The strength reduction is greater with smaller bending diameters. It is also greater if the rope is moving over a rotating sheave than if it is stationary over a non-rotating sheave.

Approximate strength efficiencies achievable with 6x19 and 6x37 Class ropes appear in Figure 8-12. In this case, the rope is assumed to be loaded symmetrically around the sheave or pin, with no rope motion relative to the sheave or pin.



APPROXIMATE STRENGTH EFFICIENCE OF WIRE ROPE WHEN BENT OVER SHEAVES OR PINS OF VARIOUS SIZES

FIGURE 8-12

21.0 SHEAVES FOR ROPES

An earlier section of this chapter discussed the design of sheaves for use with various types of cables. This same information also applies to sheaves used with wire and non-metallic ropes. However, there are a few additional considerations which apply specifically to ropes.

Since the diameter tolerance for a new wire rope can be as great as five percent over the nominal rope diameter, sheaves for wire ropes are generally designed to have a groove diameter approximately five percent larger than the nominal rope diameter to avoid pinching the rope.

To achieve the longest possible operating life for both wire ropes and sheaves, steel sheaves should be hardened to avoid wear and changes of groove shape. Unhardened sheaves can become “corrugated” so as to develop a wear pattern which can accelerate the wear of the rope.

Non-metallic sheaves (for example, nylon sheaves) and sheaves with plastic lined grooves can provide increased rope life in some cases. However, as discussed below, the corresponding change in wire rope failure modes may necessitate a modification of the rope retirement criteria. Also, non-metallic or plastic lined sheaves may be disadvantageous for installations where either a wire rope or a non-metallic rope is used with a ram-tensioner motion compensation system. The repeated bending of the rope over the sheaves can lead to excessive rope temperatures, since non-metallic sheaves are unable to function as a heat sink. In this case, metallic sheaves may be required to minimize temperature build up in the rope.

22.0 ROPE FAILURE MECHANISMS AND RETIREMENT CRITERIA

The tension-induced radial forces exerted by the outer strands of a rope produce high localized contact loading between adjacent strands. In a wire rope, these contact forces produce very high contact stresses in the individual wires. The contact stresses are often responsible for the initiation and propagation of fatigue cracks and the eventual fatigue failure of the rope. This is the dominant failure mechanism for ropes subjected to cyclic-tension loading.

In the case of a wire rope with an independent wire rope core (IWRC), the internal contact stresses often cause the core to break up so that it ceases to contribute to the rope strength. Then, not only is the strength contribution of the core lost, but the IWRC continues to be a source of high contact stresses for the wires in the main strands and accelerates fatigue failure of the entire rope. For some applications, a rope with an IWRC provides poorer long term performance than a rope with a fiber core, even though the latter has a lower initial breaking strength.

When a wire rope is bent over a sheave or drum, the change in curvature produces bending stresses in the individual wires, and the relative motions among the strands produce internal wear and variations in the load distribution among the strands. (See an earlier section of this chapter for a detailed discussion of cable behavior in bending.) It is interesting to note, however, that unlike a simple beam in bending, the maximum bending stresses in a rope do not occur in the wires furthest from the center of rope curvature. Instead, they occur in the wires adjacent to the rope core. If a rope should be subjected to bending over a very small sheave at a very low tension, it will eventually fail due to the accumulation of wire breaks in the interior of the rope. The insidious nature of this fatigue damage has led to unexpected rope failures.

However, in a great majority of common wire rope applications, the location of the wire fatigue failures is on the surface of the rope where the wires contact a steel sheave or other rope wraps on a drum. These failures are often erroneously attributed to bending stresses, but they are actually the result of the high contact stresses in the wires at the surface contact locations.

If a non-metallic or plastic-lined sheave is substituted for a steel sheave, the surface contact stresses will be essentially eliminated, and the rope may enjoy an improved fatigue life. In this case, the wire failure locations may change to the strand-to-strand or strand-to-core contact sites. Although the rope life in terms of cycles to failure may be improved by the elimination of steel sheaves, the change in rope failure mode may have an important effect on the rope retirement criteria.

For example, if a rope used on steel sheaves is retired on the basis of the number of visible broken wires (for example, six broken wires per lay), this criterion may no longer be valid with non-metallic sheave grooves since the rope may fail internally, not externally. In many applications, the ability to assess the condition of a rope through broken-wire counts may be much more important than the potential rope life improvement offered by non-metallic sheaves. Serious accidents may occur unless the rope retirement criteria are carefully matched to the rope failure mechanisms for any particular application.

23.0 WIRE ROPE FATIGUE DATA

The usable life of a wire rope in a particular application may be limited by one or more of the following factors:

1. Metal Fatigue
2. Internal or External Abrasion
3. Internal or External Corrosion
4. Damage due to cutting, kinking, crushing, bird caging, or tensile overload

With respect to metal fatigue, wire rope performance depends upon the rope construction and material, the sizes of any sheaves or drums over which the rope must operate, the operating tension, and the type of lubrication applied to the rope.

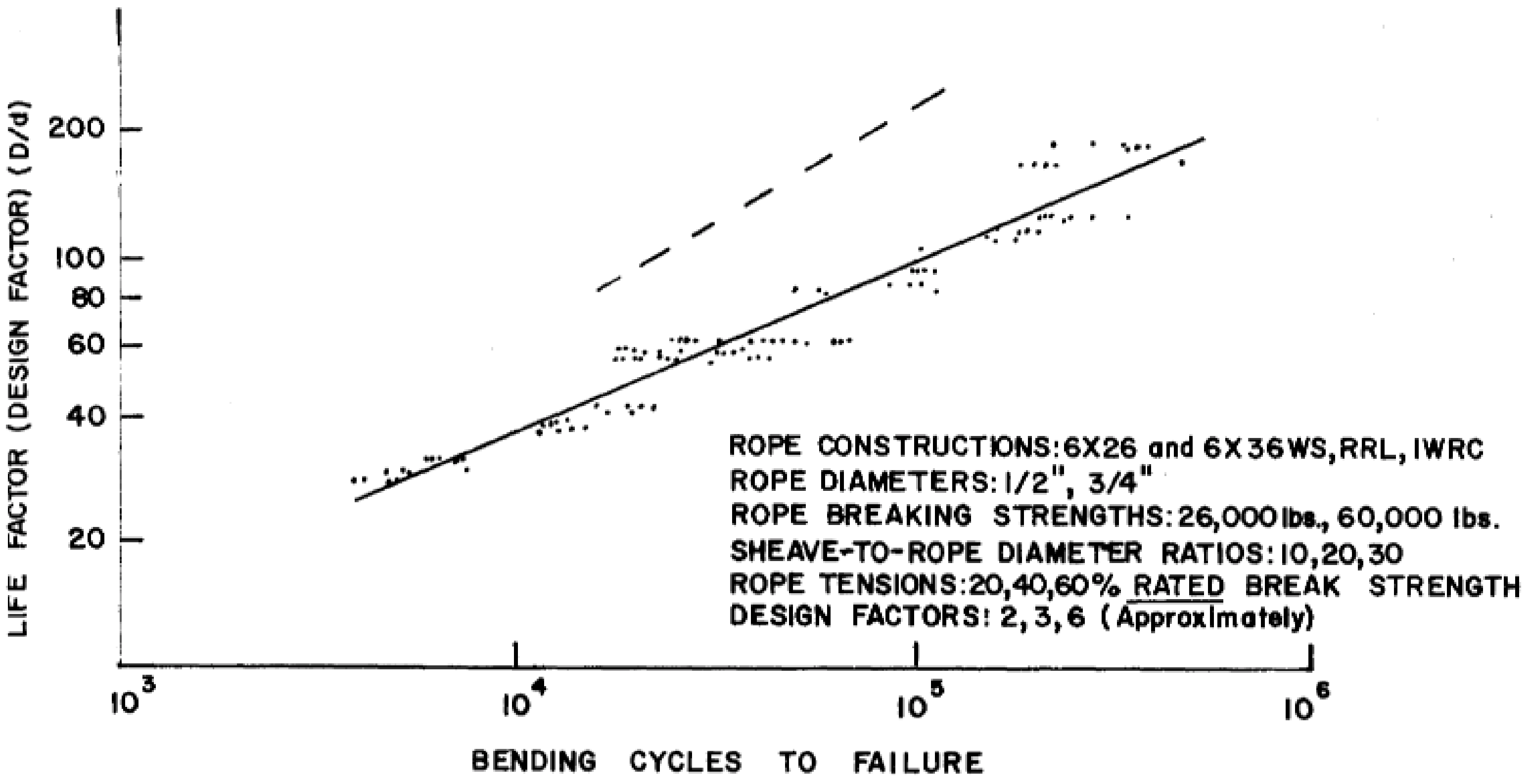
For most rope applications, there is no optimum sheave size or Design Factor. (The Design Factor is the ratio of the rope breaking strength to the operating tension and is sometimes referred to as the Safety Factor.) Unless the rope must be retired for reasons other than metal fatigue, the rope life will benefit from larger sheaves and higher Design Factors. Considerations of system size, weight, and cost will establish the practical limits for these parameters.

To evaluate rope bending fatigue performance under ideal laboratory conditions, a series of tests was undertaken with the following test parameters:

Rope Diameters - 1/2 and 3/4 inch
Rope Constructions - 6x26 and 6x36 Warrington Seale, Right Regular Lay, IWRC
Rope Material - Extra Improved Plow Steel
Sheave-to-Rope Diameter Ratios - 10, 20, and 30
Design Factors - 2, 4, and 6 (approximately)

All four ropes were manufactured from the same lot of steel by the same manufacturer, and all had the same type of lubrication. Four rope specimens were cycled to failure for each possible combination of rope diameter and construction, design factor, and sheave size. Furthermore, the specimen selection and test sequence were totally randomized to allow statistical analysis of the test results. The test results appear in Figure 8-13.

The tests were conducted with a rope cycling stroke amplitude sufficient to allow a rope section four lay lengths long to pass onto, around, and completely off of the sheave with each machine stroke. Thus, this rope section experienced two straight-bent-straight bending cycles with each complete machine cycle (two strokes). In Figure 8-13, the bending cycles to failure (complete parting of at least one complete rope strand) are plotted as a function of a dimensionless parameter defined as the Life Factor. The Life Factor is the product of the Design Factor and the Sheave-to Rope Diameter Ratio (Did). In this case, the sheave diameter, D, is the pitch diameter measured at the rope center line.



WIRE ROPE BENDING FATIGUE DATA

FIGURE 8-13

Even though the test conditions varied widely in terms of the combinations of sheave size and rope tension, all of the test results are fairly well normalized when presented in terms of the Life Factor. This approach allows estimates of rope life for other combinations of sheave size and rope tension not specifically included in the test program.

It should be noted, however, that wire ropes of other sizes, constructions, material strengths, and manufacturing lots will produce different test results. However, only a few tests are required to establish the position and slope of the Life Factor curve for any specific rope.

Experience has shown that the bending fatigue life of a wire rope diminishes with increasing rope diameter. For example, the dashed line in Figure 8-13 corresponds to the approximate fatigue life of a 3-1/2-inch diameter rope tested during another program. Other tests of 1-3/4-inch diameter ropes produced results between those of the curves presented in Figure 8-13. Because of these variations of fatigue life with rope size as well as with rope construction, care must be exercised in using the results of tests of one rope to predict the fatigue life of a different rope.

24.0 MATHEMATICAL MODELING

An important accomplishment in recent years has been the development of mathematical models for use in the design and analysis of ropes and cables. Commercially available computer programs can be used to analyze rope and cable designs prior to manufacture for the purpose of predicting performance in both tension and bending. These programs not only minimize the requirement for prototype fabrication and testing, but they also provide insight into failure mechanisms and means for improving overall rope or cable performance.

An example of such a program is CABLE SOLVER 1 developed by Tension Member Technology for the analysis of steel wire armored electromechanical and fiber optic cables. This program takes into consideration the compressibility and nonlinear stress versus strain behavior of various cable materials, and the accuracy of the mathematical model has been validated through extensive laboratory testing.

The program accepts as input:

(1) Details of the actual or assumed cable geometry

(2) Data regarding certain physical properties of the various materials in the structure

(3) A choice of analysis strategy including either applied tension or strain, end constraint (fixed end, free end, or induced rotation), cable diameter reduction methodology, core model, and external hydrostatic pressure

The program provides the following output:

(1) The initial as-manufactured or as-designed cable geometry including helix angles, lay lengths, exact coverages, radii of curvature, compactions, cusp fill, and diameters of the various element layers

(2) The deformed geometry of the loaded cable including all of the above parameters

(3) The strain, stress, and tension experienced by each layer of elements, as well as the torque contribution of each layer, and the layer weight

(4) The overall cable characteristics including strain, tension, torque, rotation, ideal breaking strength, average core pressure, and weight.

Similar programs are also available for the analysis of cables having non-metallic fiber strength members and for both metallic and non-metallic ropes. CABLE SOLVER is not the only set of computer programs commercially available as this chapter is being written, and other programs are likely to become available as the sophistication of cable design continues to advance, especially in the area of fiber optics and with the development of new cable materials.

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