

CHAPTER 7

Rope and rope-like structures

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Abstract

A rope may be defined as a load-bearing structure that is efficient at supporting tensile loads, yet is very flexible in bending. A rope differs from other structures such as a chain, in that it is a multiple redundant structure made from a number of parallel load-bearing elements, which are usually twisted together in some way to allow the assembly to operate as a cohesive whole.

This chapter discusses some of the wide range of rope and rope-like structures found in engineering and nature. Initially the mechanics and behaviour of helical structures are discussed before moving on to examine the similarities in the design and manufacture of man-made ropes and nature's rope-like structures. Examples taken from nature include: polysaccharides (cellulose and plant cell walls) and polypeptides (collagen, tendon, arterial walls and spiders silk), which we discuss at molecular, cellular and organic levels.

Although it would be difficult to prove any direct 'inspiration from nature' on the part of rope and cable designers, a comparison of the technology of rope and similar structures such as hoses and umbilical cables reveals striking parallels with the rope-like structures in nature.

1 The mechanics of the helical structure

Some of the key mechanical features of groups of helical fibres are discussed in the following sections (for a more detailed discussion see Evans [1]).

1.1 Geometrical nature

A helix can be defined by two parameters: its radius, R , and lay (helix) angle α (α and R are defined in Figure 1). The important geometrical properties are the curvature κ and 'torsion' τ (the geometrical twist in the helix – not to be confused with mechanical torsion). In the case of



a circular helix, κ and τ are constant and non-zero throughout the structure. They can be expressed by the following simple expressions:

$$\kappa = \frac{\sin^2 \alpha}{R} \quad \text{and} \quad \tau = -\frac{\cos \alpha \sin \alpha}{R}. \quad (1)$$

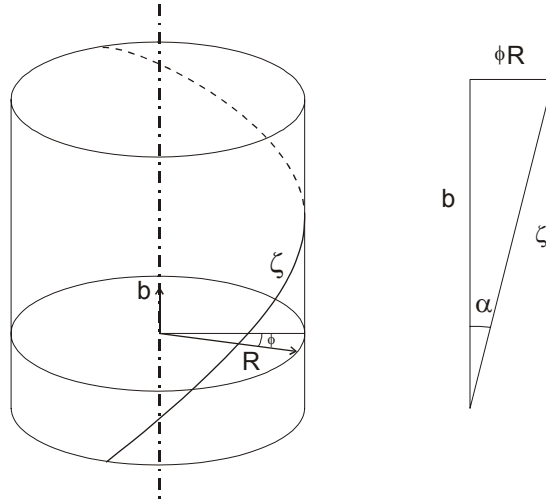


Figure 1: The geometry of a right-hand helix (defined in the same manner as a right-hand screw thread), where b is the helix length and ζ the helix space curve length.

1.2 Flexibility

One highly desirable feature of a structure consisting of helical fibres is that it can have a high axial strength and a low bending stiffness. The bending properties of any component are dependent on the distribution of cross-sectional area resisting the bending with the highest stresses furthest from the neutral plane of bending. The bending resistance of a cross-sectional shape is given by the second moment of area, which for a solid circular cross section with radius r about its centre line is:

$$I_c = \frac{\pi \cdot r^4}{4}. \quad (2)$$

If a solid circular fibre is subjected to bending about an axis that is offset from its own centre line by a distance d_i then its second moment of area about that axis, I_i , is:

$$I_i = I_c + A d_i^2. \quad (3)$$

A bundle of fibres that are held together in such a way that the fibres cannot move relative to one another will have a second moment of area the sum of the individual values of the fibres

about the centre line of the bundle. If calculated in this manner, the second moment of area for a circular bundle of fibres, will be roughly that of a circular bar of the same overall radius.

If, however, the fibres can slide freely past each other such as if they are wound in a helical fashion then the Ad^2 term in the above equation disappears, resulting in a huge reduction in the second moment of area. This is because the change in length in a helical fibre when the bundle is bent is zero, hence the only remaining contribution to the overall bending stiffness is the bending stiffness of the fibre about its own centre line, I_c .

The above theory assumes that there is no friction between fibres within the helix. However, in practice there will be friction between wires, which will make the structure stiffer than the above theory implies. The frictional effect will become more significant with each increasing helical layer and one mechanism for introducing more inter-fibre slip is through helical hierarchies as discussed in the next section.

1.3 Structural hierarchy

If it is assumed that the value of the coefficient of friction between fibres does not change depending on the layer within a helical bundle (i.e. the same amount of friction per unit length of fibre), there will be a greater force resisting slipping at greater radii as the fibre length for one turn increases. Consequently the first layer in a spiral strand will be the closest to the full-slip approximation, and the assumption will get progressively worse until at some layer the wires will have so much frictional force restricting it that it will virtually behave like a solid tube. The solution to this is to build up helical units within units. This can be done a number of times creating a repeating helical hierarchy. The advantage is that slippage is introduced at a number of levels and so a much greater flexibility can be achieved.

1.4 Crack propagation

In a parallel fibre structure, the nature of the structure itself offers an extremely useful mechanism for preventing crack propagation [2]. In a solid structure, a single crack may propagate and cause the failure of the entire structure. For a fibrous system to fail, a crack must move from within a fibre, across an interface and then into the next fibre, and so on if it is to propagate. If the interface between fibres is sufficiently weak, the highly concentrated region of tensile stress that exists just ahead of the crack tip will cause a separation of the fibre interface and blunting of the crack (effectively arresting the crack). In the case of most ropes, there is no substrate and the mechanism of load transfer between neighbouring fibres is essentially through frictional forces caused by the contact load between them. This frictional adhesion is only effective in shear across the interface. Hence the tensile stress region ahead of an advancing crack will cause a separation of the wires, and the crack will be arrested and will not continue into the neighbouring wire.

The frictional forces between the fibres, has another structural advantage. A broken fibre within the structure carries no load at the actual location of the break. However, moving away from the break, the fibre gradually takes up the load until at some distance from the break it regains its full share again. The axial length over which this occurs is known as the 'effective length'. Even a structure made of continuous long elements, such as a wire rope, may have every individual wire broken and still be able to operate. This does of course require that the wire breaks are sufficiently distributed along the rope (i.e., separated by more than twice the 'effective length'). Man-made fibre structures such as cotton rely on this effect to spin short fibres into much longer yarns or ropes.



1.5 Energy absorption

The inter-fibre shear mechanism in a parallel element type structure can be designed with significant levels of hysteresis within a load cycle, and – which may be time dependant – visco-elastic behaviour (in the case of a viscous fluid interface) or time-independent Coulomb type damping (for a frictional interface). This property can prove useful for shock absorption or for damping oscillating loads.

1.6 Tensile efficiency

The helical structure of the fibres or wires in a rope means that the structure is very flexible in bending, increasingly so at higher lay angles α . However, the higher the lay angle, the less efficient the component is at transmitting tensile load. Thus the nature of a rope will be a compromise between its ability to perform its primary function of bearing tensile load and the level of flexibility required.

An example of a rope that does not need to bend in service is the stay cable on a bridge. In this application the rope used may be of the spiral-strand construction (see Figure 6a). Spiral strand ropes are very stiff in bending and, more importantly from the bridge designer's point of view, very stiff under axial loading. The stiffness in bending is due to the fact that the wires are spun in (usually many) concentric layers at a very low helix angle. The helix angle is designed to be sufficient to hold the rope together so it may operate as a whole (it must be remembered that there will be some bending in the strand's life – especially for transportation where the strand must be spooled). The efficiency of this single helix type of rope, η , will be given by:

$$\eta = \sum_{i=1 \text{ to } n} \cos \alpha_{i \text{ wire}} \quad (4)$$

where n is the number of layers in the spiral strand. As α tends to zero the efficiency tends to 100%.

In a much more flexible stranded rope (for example, Figure 8) with a wire lay angle within the strand of α_{wire} and strand lay angle within the rope of α_{strand} , the efficiency will be lower and will be given by

$$\eta = \sum_{i=1 \text{ to } n} \cos \alpha_{i \text{ wire}} \cdot \cos \alpha_{i \text{ strand}} \quad (5)$$

1.7 Torsional behaviour of axially loaded helical structures

Another consequence of spinning fibres (or wires) in a helical arrangement is that when under tension, as well as the axial force in the rope, there will be an additional radial force. This effect has been noted and analysed for wire ropes (see for example [3–6]), a summary of which is given here.

We consider the simple case of six fibres about a central core. On loading (Figure 2a), because of the angle that the strands make with the axis of the rope, the fibre load (R_f) will be composed of a vertical (R_ℓ) and horizontal component ($R_f \sin \alpha$) – Figure 2b. The magnitude of the forces R_f and $R_f \sin \alpha$ will depend upon the applied load R_ℓ and the lay angle α , that is the



angle the fibres make with the centreline of the rope. If we assume that each of the fibres is similarly loaded (at any one layer or level – in this example there is only one layer), then the moment M will be a function of the rope load and lay angle, the number of strands N_{fibres} and the radius R at which the force $R_f \sin \alpha$ acts (Figure 2c). Thus:

$$M_{total} = \sum N_{fibres} \cdot R_f \sin \alpha \cdot R. \quad (6)$$

The rotational characteristic of helical structures can cause considerable problems in rope applications, especially those where the end is not fixed, which will result in rotation of the rope under load. Consequently, rotation-resistant ropes have been designed to avoid these problems. The rotation resistant rope is a multi-layer rope with one or more layers spun in the opposite direction. Thus the sum M_{total} in eqn. (6) can be designed to be zero or as near zero as possible.

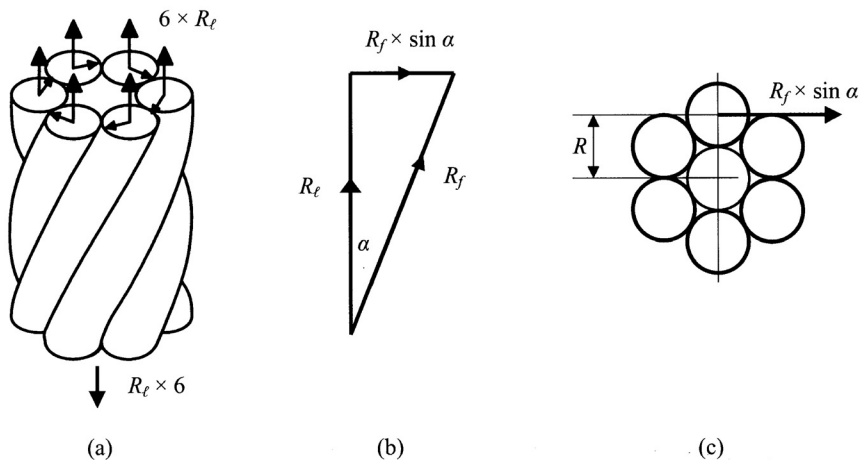


Figure 2: Forces in a helical structure [6].

Another problem related to the effect of the resultant twist in a rope structure is the effect of imposed twist; that is, twist forced into a rope by an external source. This can cause considerable damage to both non-rotation resistant (six strand, etc.) and especially rotation resistant (spiral, multi-strand) types of construction. Twist may be forced into the structure by connection to a component that is either in a twisted state or is of a different torsional stiffness [7], or, may be caused by interaction with the system in which the rope operates [8].

1.8 The effect of helical lay angle on pressure containment

A rope-like structure that has similarities with rope, but differs in its primary function, is a reinforced hose. In this structure, the requirement is not the transmission of tensile load, but control and containment of a pressurised fluid. In order to contain the pressure, yet maintain a flexible structure, a helical armouring of one or more layers of high tensile wire is used. As the armoured hose may well have fixed ends, it is important to maintain a dimensionally stable structure.

Consider a helical hose reinforcement wire wound at a lay angle, α , which is purely in tension, the axial and circumferential forces, F_a and F_c , respectively, must be related to the lay angle by the following relationship:

$$\tan \alpha = \frac{F_c}{F_a}, \quad (7)$$

where the axial force, F_a , can be calculated from the pressure, P , and the cross-sectional area of the end of the hose as follows:

$$F_a = P\pi R^2; F_c = PRS, \quad (8)$$

where the pitch, S , can be calculated from the reinforcement geometry in terms of the winding radius and lay angle. Combining these equations and solving for the lay angle, α , gives the 'neutral angle' as:

$$\alpha = 54.74^\circ. \quad (9)$$

If fibres are wound at this angle, then the wires will be completely in tension and a single-layer design will be optimised. At any other angle, when the hose is pressurised it will tend to get either longer and thinner or shorter and fatter as the wires move toward the neutral angle.

2 Engineered rope-like structures – ropes and hoses

2.1 Brief historical introduction

2.1.1 Ropes

Ropes have been in use to transmit or support loads for as long as man has used tools. The first 'ropes' were vines that might have been used to help climb trees or rock faces to collect, for example, fruits or honey. Later, strips of animal hide were cut and plaited to produce stronger ropes. By the time of the Egyptians, ropes of hemp or manila fibres were spun to combine and lengthen fibres to produce ropes that were capable of transmitting significant loads [9]. Figure 3 found in the tomb of Tehuti-Hetep, which dates from 2000–1800 BC shows the production of continuous fibre through the various stages of manufacture [10]. Figure 4 from the same tomb gives some idea of not only the lengths of rope that the Egyptians were capable of producing, but of the breaking loads obtainable. Ridge [11] estimates the tractive force required to move the colossus at 12.5 tonnes, implying a breaking strength of each rope to be about 3 tonnes.

By using such materials and manufacturing techniques, stronger ropes could be made by simply spinning more fibres together and increasing the load-bearing area. One of the largest recorded natural-fibre ropes was a four-strand core fibre rope 15 inches in diameter, which according to Hipkins [12] was used in the launch of Brunel's *Great Eastern* in 1858. This great size of rope would obviously have been difficult to handle, yet there was a growing demand for ropes capable of transmitting larger and larger loads. This requirement led to development of the wire rope: in 1834 Wilhelm Albert made the first experiments using wire ropes in the 'Caroline' pit at Clausthal in the Harz mountains, Germany.



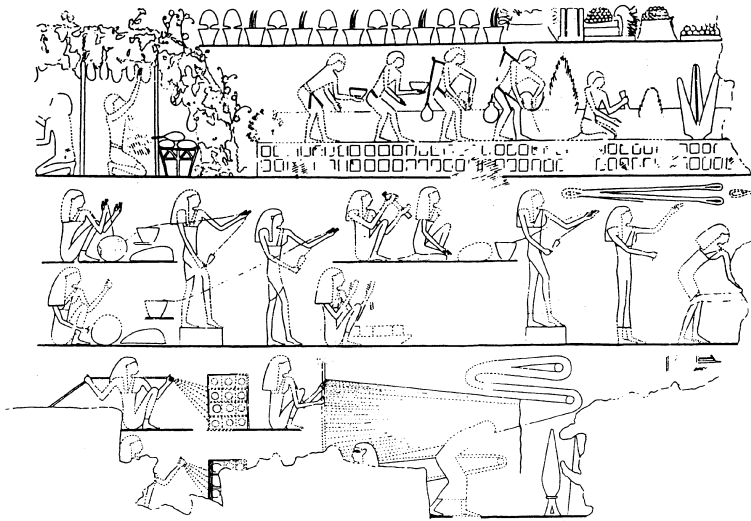


Figure 3: Manufacture of palm fibre rope, 2000–1800 BC [10].

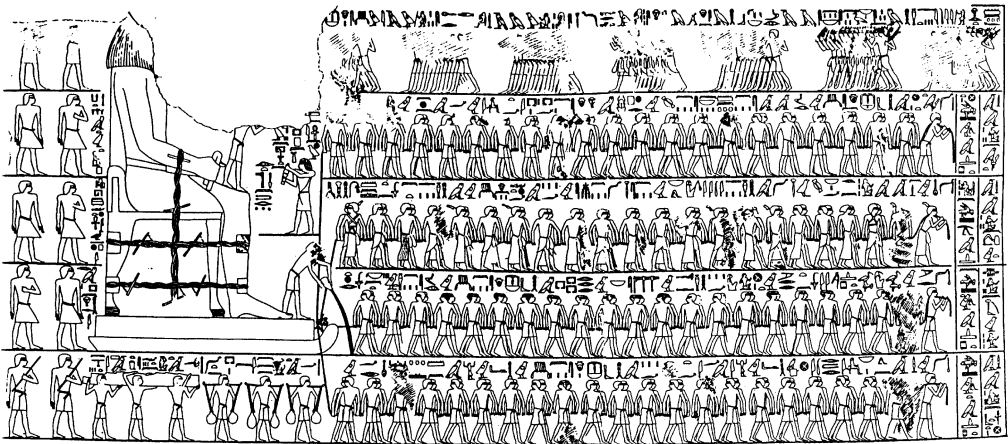


Figure 4: Transport of a colossus using fibre ropes, 2000–1800 BC [10].

The wire rope was rapidly adopted, and manufacturers were quick to experiment with different constructions. Figure 5 shows some of the types of wire rope offered by the English manufacturer Andrew Smith [13].

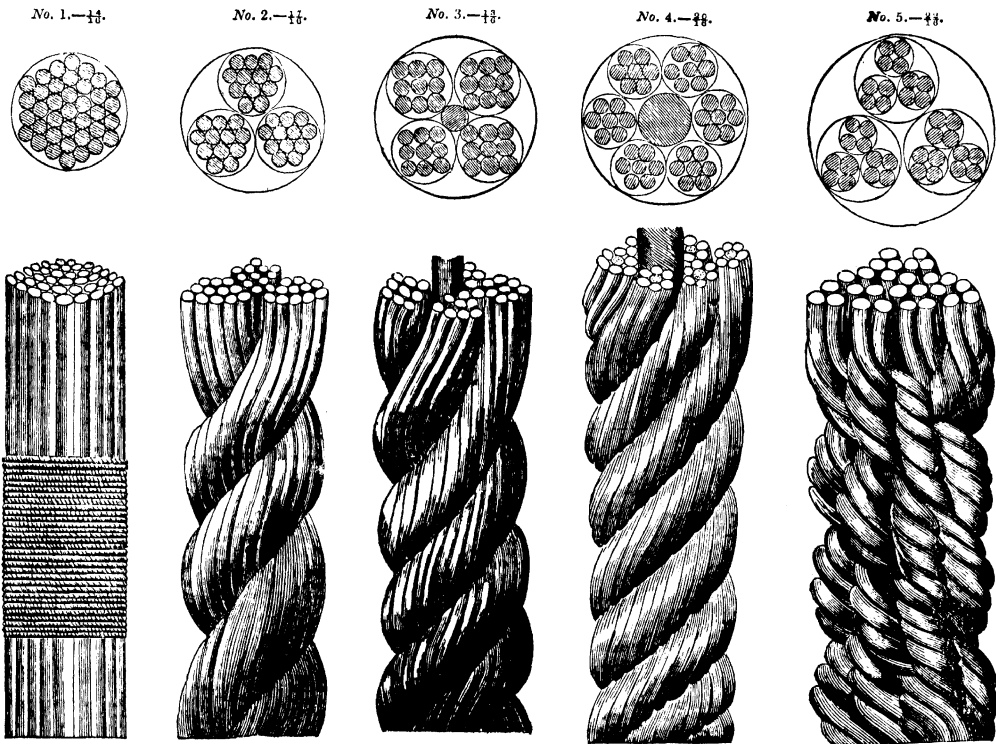


Figure 5: Examples of early wire rope designs from Smith [13].

2.1.2 Hoses

In parallel to these developments, as early as 400 BC hose was being used to transport water for fire fighting [14]. In this era, the hose was made out of ox gut. Firemen filled bags with water and then forced them into the ox gut by either sitting or stomping on the bag.

In 1673, two Dutchmen, Van der Heiden and his son, developed fire “hoase”. These 50-foot lengths of leather tubes were sewn together in a similar fashion to the way shoemakers made boots. In 1807, two members of the Philadelphia Hose Company, James Sellers and Abraham Pennock revolutionised fire hose when they developed a way to rivet leather strips together. The hoses were made of the thickest and best rear-quarter cowhides. In Boston, in 1825, the Mayor reported 100 feet of hose doing the work that formerly required 60 men hauling buckets.

The next improvement came in 1821, when James Boyd received a patent for rubber-lined, cotton-webbed fire hose. Another major advancement came when Charles Goodyear discovered the vulcanisation process for rubber in 1839; the technique effectively cross-links rubber and gives a much more robust material. By this time a number of manufacturers existed and the number of hose designs began to proliferate significantly.

A growth in the number and quality of available materials (such as wire drawing, production of synthetic polymer fibres), coupled with a constantly evolving and increasing number of applications needing specific solutions, has led to a wide range of constructions of ropes, hoses and related structures available in the modern world. A description of some of the common constructions are detailed in the following sections.

2.2 Wire ropes

The building block of the wire rope is the wire, several of which are spun together into the basic unit, termed a strand. At its simplest, a strand is a group of wires spun together, usually a helical layer of wires over a straight central core (or 'King' wire).

As discussed earlier in Section 1, if increased strength is required, maintenance of flexibility can be accomplished by adding more helical layers rather than simply using larger wires, although in all practical rope design the final choice will be a compromise between the two factors. Additionally, depending upon the mechanical properties required in service from the rope, different types of wires and strands will be combined in different ways.

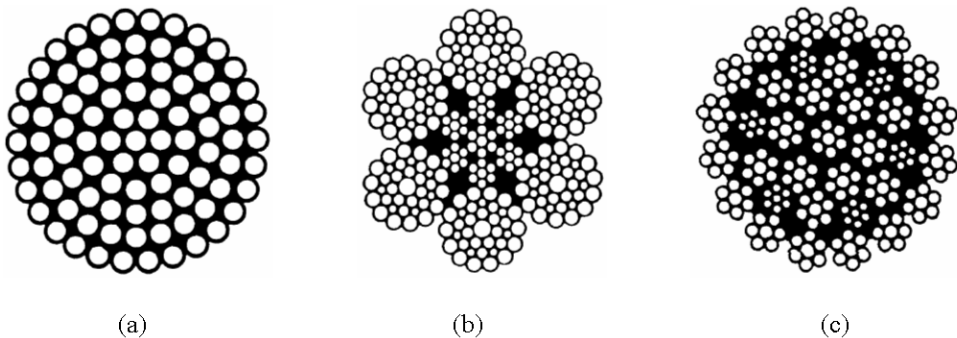


Figure 6: Examples of the three main groups of wire rope construction: (a) spiral strand [15], (b) six strand with IWRC [16]; and, (c) rotation-resistant [16].

We can define three main classes of rope that are discussed in more detail:

1. spiral strand (Figure 6a);
2. six (or eight) strand with independent core (Figure 6b); and,
3. multi-strand (also termed semi-rotation resistant or rotation-resistant) (Figure 6c).

2.2.1 Spiral strands

The spiral strand is the simplest form of rope, consisting of concentric layers of helically spun wires (Figure 6a). The wires tend to be spun at a low lay angle in order to achieve greatest efficiency (see Section 1.6), but still retain some form of cohesive structure. Owing to the dense packing of the wires that may be achieved in a spiral strands, and the low lay angle, the spiral strand is a very stiff rope type, both in bending and axially. These properties make the construction ideal for applications such as bridge stays, which will not operate over pulleys and require high axial stiffness.

An additional feature of the spiral strand is, that by careful design, it can be manufactured so that when subject to an axial load, the resultant moment of the layers is zero (Section 1.7). In order to achieve this balance, it is necessary to spin some layers in the opposite direction (hand) to others. Since the outer layers of wires will dominate the reaction of the rope, owing to the fact that not only are the wires further away from the King wire but there will also be more of them per layer (assuming the wires have the same or similar diameter), there will not be the same number of layers of each hand. Furthermore, the layers of wires are not spun alternately left hand (LH) and right hand (RH), but tend to be grouped, for example starting

from the core: LH, LH, LH, RH, RH. This grouping of the hand of the layers of wires has the additional advantage of reducing the number of cross or ‘trellis’ contacts that will occur through the strand (Figure 7a).

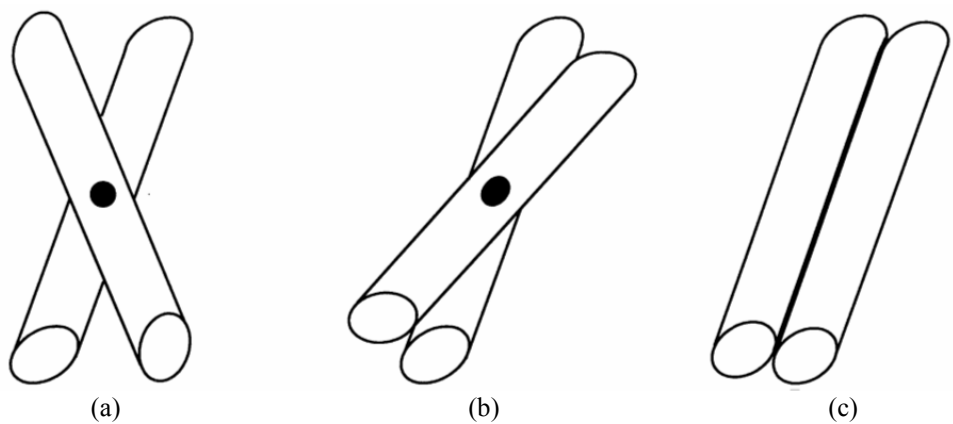


Figure 7: Types of contacts between wires: (a) trellis; (b) cross lay; and, (c) equal lay.

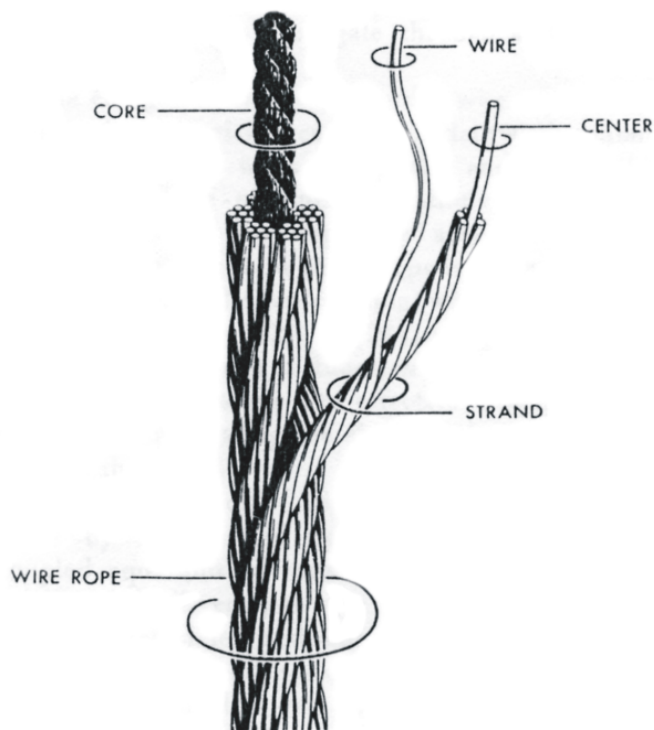


Figure 8: A stranded wire rope from Costello [17].

2.2.2 Stranded wire rope

The stranded wire rope is made up of typically six or eight strands spun helically about a central core (Figure 8 and 9). The three strand rope is an exception to this rule, being formed without a core (Figure 9a). Ropes with four or five outer strands are not generally used as they do not give a very circular cross section. Unlike the spiral strand discussed in the previous section, the fundamental property of the stranded rope is flexibility, and the ability to operate over a pulley (also termed sheave). Thus, the layers of wires in the strands are all spun in the same direction in order to avoid the damaging cross contact between wires.

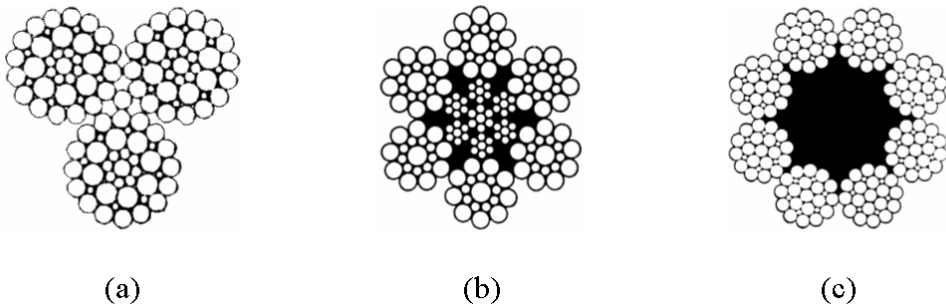


Figure 9: Different classes of stranded wire rope: (a) three strand [18]; (b) six strand with IWRC [16]; and, (c) eight strand with fibre core [19].

2.2.2.1 Strand constructions In order to provide a uniform load sharing between the layers, the concentric layers of wires in the strand must have the same lay angle. However, owing to the difference in radius between concentric layers, this will mean that different layers will have different lay lengths. The constant-lay-angle strand was the basis of the first strands used in stranded rope, the most common type being the 12/6/1, built up of wires of the same diameter as shown in Figure 10a. A strand built up of layers with a constant lay angle would have been easier to manufacture as there would be no need to change the gearing of the stranding machine for each layer. As a result of the different lay lengths, even though the layers are spun in the same direction there will be discrete cross-contact points, as shown in Figure 7b. This type of construction is therefore known as ‘cross-lay’. Any advantages that the cross-lay construction accrues from equal load sharing between its layers are outweighed by the disadvantage of the stress concentrations caused at the inter-layer point contacts.

It should be noted that this argument also applies to the spiral strand discussed above; however, since the lay angle of the layers is lower than that of a stranded rope, the load sharing between layers is already better. A different lay angle may be used in a layer or layers of wires to aid in the torque balance of the whole structure.

By accepting that for stranded ropes it is more important for the wires in different layers to lie parallel to each other so that they have equal lay lengths rather than equal lay angle a much better contact condition is obtained. The wires in and between the layers now have a line rather than cross contact (see Figure 7). This type of construction is termed equal-lay, and is now by far the most commonly used.

In addition to the contact benefits described above, if wires in one layer can be arranged to sit in the groove wires of the adjacent layer, the packing efficiency will be further improved.

This idea is the basis for constructing strands with different wire diameters. There are three common constructions of two layer equal-lay strands: Seale, Warrington and Filler.

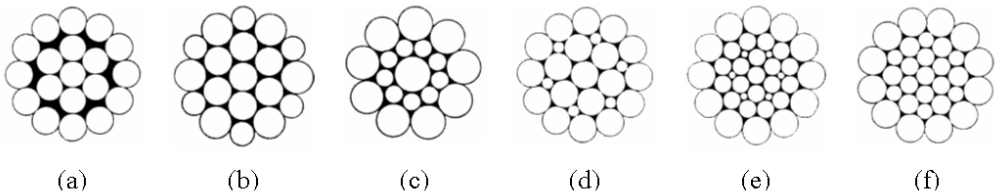


Figure 10: Common strand constructions used in stranded rope applications: (a) simple strand (12/6/1) cross-lay, note the common wire size; (b) Warrington (6+6/6/1) equal-lay; (c) Seale (9/9/1) equal-lay; (d) Filler wire (12/6+6F/1) equal-lay; (e) Filler-Seale (12/12/6+6F/6/1) equal-lay; and, (f) Warrington-Seale (12/6+6/6/1) equal-lay [20].

The Seale construction (patented in 1885 by Thomas Seale [21]) consists of a number of large wires laid around an equal number of smaller wires, in such a way that each outer wire lies in the valley of the two underlying wires, as shown in Figure 10c. This has a very good packing density and, because of the large diameter of the outer wires, excellent wear properties, although with a reduction in rope flexibility. Where flexibility is not a major consideration, this is considered the best equal lay construction [22]. The Filler wire construction (patented in 1894 by W. B. Brown [23]) consists of an even number of wires laid around an inner layer of half that number, where each valley is filled with a small wire (Figure 10d). The number of valleys is thereby doubled so in the next layer, each outer wire beds in the valley formed by one main wire and one of the filler wires. This construction is more flexible than the Seale, but has a poorer packing density. The Warrington construction (patented by Dixon in 1888 [23]) has an outer layer of wires with twice as many as the inner layer. The outer layer of wires consists of alternate wires of two diameters (see Figure 10b). This construction has very good flexibility, but a poorer wear resistance than the Seale [11]. For equal lay-strand construction with three or more layers, generally some combination of Warrington, Seale or Filler wire is used (e.g., the Warrington–Seale and Filler–Seale as shown in Figure 10e and f).

2.2.2.2 Types of strand lay Strands can either be wound in a left-hand or right-hand helix within the rope, the only difference between these being the direction of the resultant torque that will be produced upon loading. In addition to the strand lay, there are two possibilities of wire lay direction within the strand: ordinary lay and Lang's lay. In ordinary lay, the strands are laid in the opposite direction to the wires within the strand (Figure 11a and b). In Lang's lay (patented by John Lang in 1879 [24]), wires are spun in the same sense as the strands (Figure 11c and d). Under tensile loading, both ordinary and Lang's lay ropes will rotate. Lang's lay rope is especially prone to this, and will untwist indefinitely if the ends are allowed to rotate. For this reason, stranded ropes must only be used where the ends are restrained from rotating. The main advantage of Lang's lay rope is its increased resistance to wear owing to the fact that a longer length of individual wire is exposed on the surface of the rope – this is especially useful in running-rope applications.

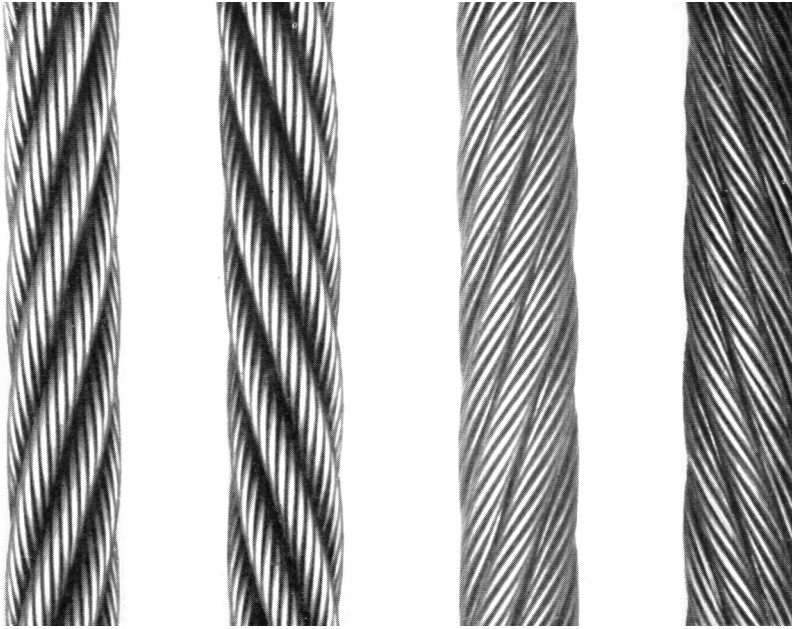


Figure 11: Types of rope lays: (a) right-hand ordinary lay (RHO); (b) left-hand ordinary (LHO); (c) right-hand Lang's lay (RHL); and, (d) left-hand Lang's lay (LHL) [20].

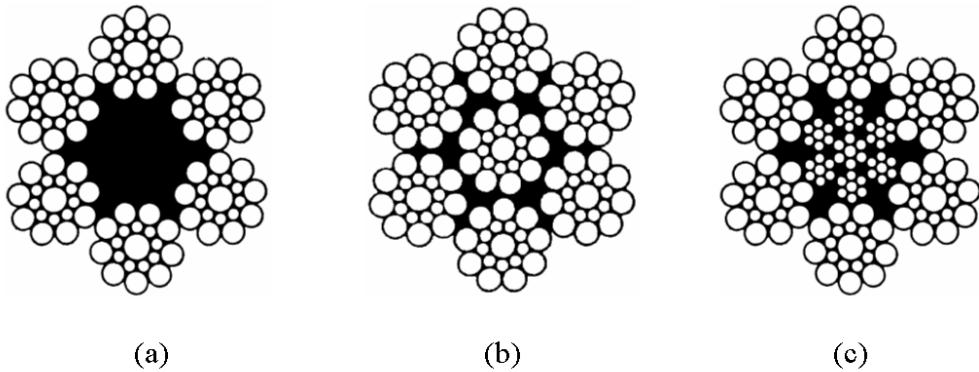


Figure 12: Three different kinds of cores used in stranded rope as follows: (a) Fibre core (FC) so the rope is $6 \times 19(9/9/1) + FC$ [16]; (b) Wire strand core (WSC) the rope is $6 \times 19(9/9/1) + WSC$ [15]; and, (c) Independent wire rope core (IWRC), the rope is $6 \times 19(9/9/1) + IWRC$ [16].

2.2.2.3 Types of core The main function of the core within a stranded rope is to provide support for the outer strands. The three types of core are shown in Figure 12 and are as follows:

- The fibre core (FC), which consists of a bundle of thermoplastic fibres. This construction has good flexibility and the core may be heavily lubricated to give good lubrication during service. However, this type of core may not be sufficiently rigid to prevent cross-sectional distortions where there is significant lateral loading in service (Figure 12a).
- The wire strand core (WSC) is a simple solution to the problem of lateral loading. The core is another strand similar to the outer strands. This does, however, give an inherently stiffer rope (Figure 12b).
- The use of an independent wire rope core (IWRC) - a core that is a rope in its own right, gives a rope good flexibility while providing a good support for the outer strands against lateral forces. The IWRC also gives a much better contact with the outer strands because of its circular profile (Figure 12c).

2.2.3 Multi-strand ropes

A more complex variation of the stranded rope, which combines the flexibility of a stranded rope with the possibility to resist rotation under load characteristic of the spiral strand, is the multi-strand or rotation resistant rope (Figure 13). One of the simplest classes of rotation-resistant rope is the 17×7 (seventeen strands of seven wires each), as seen in Figure 13a. However, with only two layers of strands, it is not possible to create properly balanced construction, and this type of rope is termed semi-rotation resistant.

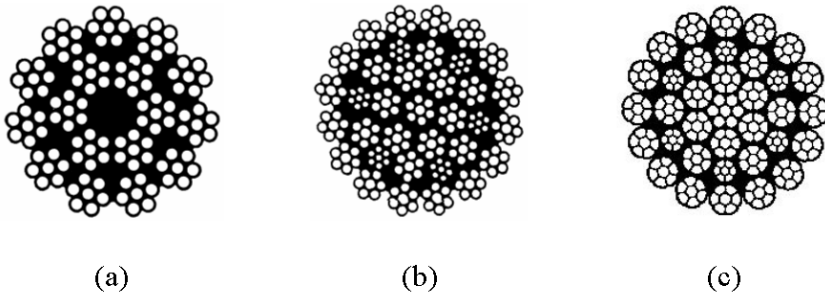


Figure 13: Semi-rotation-resistant and rotation-resistant rope constructions (a) 17×7 ; (b) 35LS; and, (c) 34LR die-form[®] [16].

Multi-strand ropes with three or more layers of strands can be designed to give rotation resistance. Figure 13b shows a 35-strand rope where the outer strands are spun about the rope axis in the opposite direction to the inner strands. This type of rope is ideal for use on cranes.

A major drawback of the rotation-resistant classes of rope is that in service they tend to fail from the inside owing to the cross contacts between the first and second layers: very few if any wire failures will be visible on the outer strands, whilst the core may have hundreds of breaks! This makes accurate inspection very difficult, and effectively prohibits the use of this type of rope in some safety-critical applications [25].

One variant that improves the contact conditions of the wires in the rope and of the rope as it operates over pulleys is the die-form construction (Figure 13c). The die-form type of rope is so called because each of the strands are put through a die or alternatively rolled, to compact the strands and create a more circular section.

2.2.4 Rope constructions with shaped wires or strands

A further development in strand construction is to use shaped wires. The most common reason for using shaped wires is to give the outside of a spiral strand a more circular cross section and better wear properties. Two examples of this are the half-lock and full-lock spiral strands as shown in Figure 14a, b. These two constructions are very stiff, but have excellent wear properties. A locked-coil rope would typically be used as a track rope for an aerial cable way, whilst the half-lock might be used as the guide rope for a car in a mine hoist system.

Where flexibility is still required, stranded ropes with a more circular cross section can also have similar advantages to those described above. This is achieved by the use of shaped strands. The strands are usually either oval or triangular shaped (Figure 14c, d). For example, triangular strands consist of a triangular-shaped king wire that is then spun in the usual manner with standard circular wires (usually with a Seale construction).

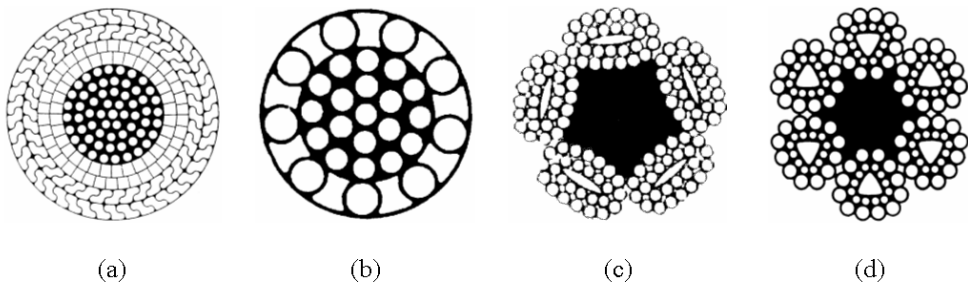


Figure 14: Examples of constructions with shaped (non-round) wires or strands: (a) full-lock coil structural strand (44Z/38S/38T/32T/24/18/12/6/1) [26]; (b) a half-lock strand (9+9H/12/6/1) [16]; (c) flattened-strand $5 \times 28(16/11/1) + \text{FC}$ [18]; and, (d) triangular six strand $6 \times 25(12/12/\Delta) + \text{FC}$ [27].

2.2.5 Production of wire rope

Figure 15 provides a simplified over-view of the stages involved in the production of a wire rope. Starting from the steel billet the rod is first produced, then subject to heat treatment. The heat-treatment process known as “patenting” is a crucial part of the manufacture of medium- and high-carbon steel wires, giving them sufficient ductility to be drawn, while retaining the high strength advantages.

The patenting process involves an austenization of the wire at high temperature followed by an extremely rapid cooling to temperature below the transformation temperature of 723°C . This results in an almost isothermal transformation of the austenite structure into a pearlite structure with a very fine laminate structure (an order of magnitude finer than the coarse pearlite structure found in plain carbon eutectoid steel). The undrawn patented wire has a tensile strength of between 800 and 1300 N/mm^2 depending on the inter-laminal spacing of the pearlite [28] (a finer spacing giving a higher strength). The drawing process is capable of more than doubling this strength caused by work hardening and increased alignment of the grain structure along the wire axis. Typical wire grades in wire ropes are 1770 , 1960 and 2160 N/mm^2 . Following heat treatment, the wires must be cleaned and fluxed to prepare for the initial wire drawing.

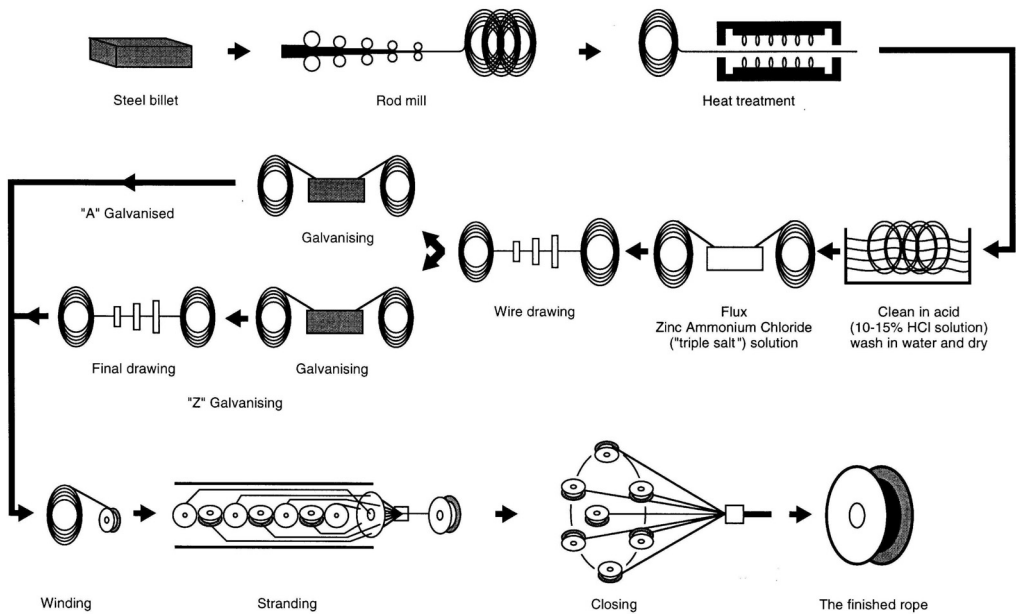


Figure 15: Stages in the production of a wire rope (after Bridon [16]).

Depending upon whether the wires in the rope are to be galvanised or bright (natural) finish, the next stage in the process is to galvanise the wires. Galvanising used to be applied using the electro-deposition technique, but this method is not used now, hot-dip galvanising being preferred. The thickness of the zinc coat applied to the wire will be a function of the speed of travel of the wire through the bath and the temperature of the bath. The elevated temperature will cause some softening of the wire, and where a higher strength is required the wire will undergo a final drawing after galvanising. Since the final drawing process will remove some of the zinc coat it is not used where the heavier 'A class' of galvanising is required. ('A class' galvanising is used typically for ropes in marine applications.)

The wires are now ready for stranding (creating the rope strands) and are spooled onto bobbins. Depending upon the capacity of the machine and the numbers of wires in the strands, the strands may be formed in one or more than one pass of the stranding machine. Following stranding, the rope strands are assembled in a closing machine to form the final rope.

One aspect of stranding and closing that deserves mention here is the removal of the twist in the wire or strand as it is being spun about the central core (which passes along the centre axis of the machine). The route to the development of helical winding was the invention of the Cordelier, by Edmund Cartwright in 1786. Although the Cordelier (Figure 16) was designed for yarns in the weaving industry, it incorporates the basic principle of epicyclic gearing to add or remove any twist in the yarns as they are spun together.

Dickinson describes the principle of the Cordelier thus: 'The spools of yarn are supported in a rotatable frame; on the axis of each spool is a toothed wheel, gearing through an idle wheel, with a corresponding toothed wheel on the axis of the frame. The toothed wheel on the spool is the same diameter as the wheel on the axis and therefore as the frame is rotated, the spool remains stationary relative to the axis. By altering the diameters of the two wheels, the

spools may be made to overtake or else lag behind the revolutions of the axis, and thus put in or leave out twist as desired; uniformity in laying is thus ensured.' [29].

An additional manufacturing process that has been found to be beneficial to the final mechanical properties of rope (and hose) is that of pre-forming of the wires and strands into a helix before they are wound into the final component. This has the result of reducing contact stresses within the component and also reduces the level to which a free end will try to unwind. Figure 17 shows a close-up of a pre-forming head such as will be used in a wire rope closing machine (Figure 18).

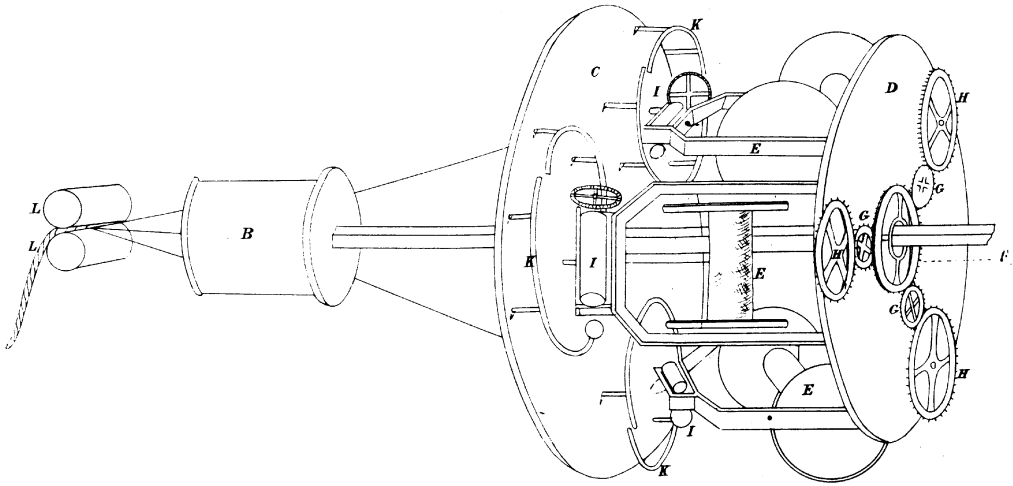


Figure 16: Cartwright's 'Cordelier' showing the principle of the gearing used to take the twist out of the fibres as the strand is spun. From Cartwright's patent [30].

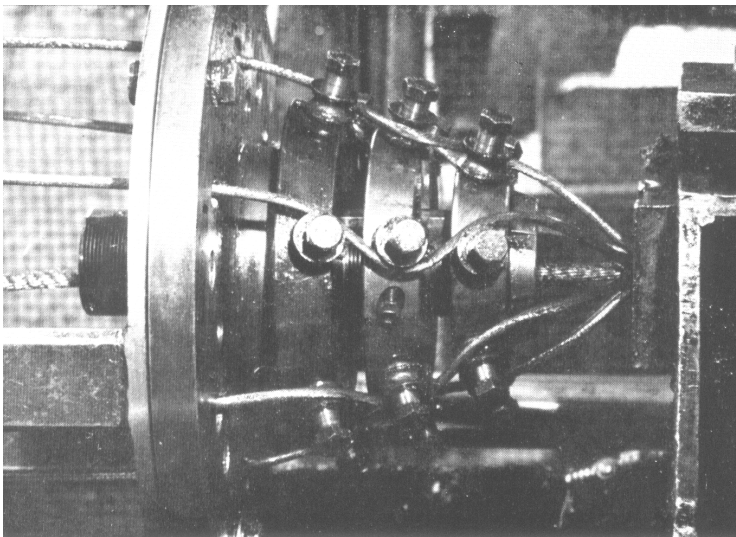


Figure 17: Pre-forming head on a rope-closing machine [20].

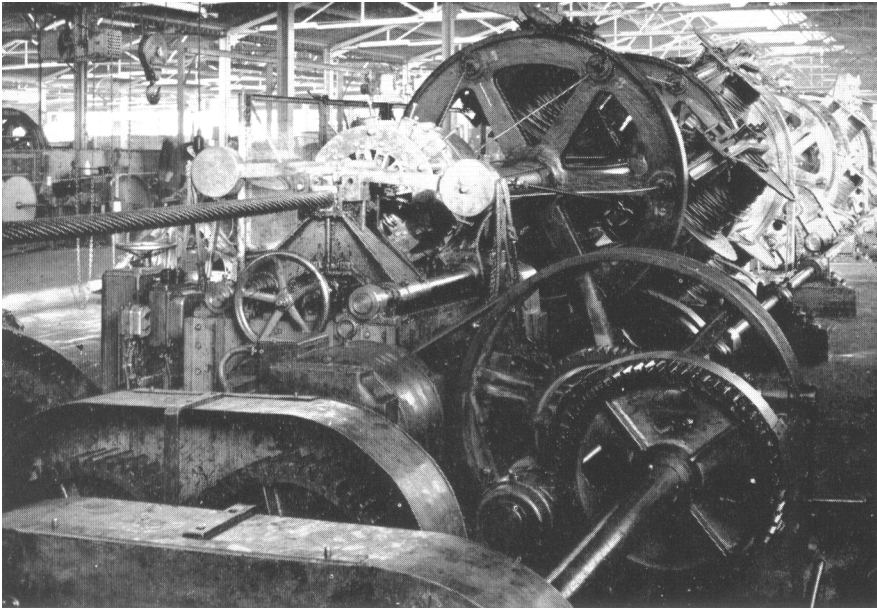


Figure 18: Rope-closing machine. Note the bobbins to the right of the picture and the closing head in the centre [20].

An essential element to the wire rope construction that has not been discussed until now is the lubricant. Lubricant has two purposes: firstly, and primarily, it is to reduce the friction between contacting wires, allowing them to slide freely and reducing the effects of fretting fatigue during use. Secondly, the lubricant has the added benefit of acting as coating to help prevent corrosion. Lubricant is heated to the melting point to allow easy application at the closing head during all stages of making a strand. The lubricant is applied to the wires just before they enter the guide (or 'nips'), and again to the strand as it emerges from the nips. More lubricant is applied in the closing stage of the rope manufacture. Once a rope has been assembled it is extremely difficult to lubricate the interior, particularly in the case of the spiral and multi-strand type constructions, consequently the rope must be thoroughly lubricated at all stages of manufacture. Different grades of lubricant are used depending upon the service of the rope, for example a light lubricant for a lift rope, whilst for ropes offshore, a heavy bituminous marine lubricant would be used.

2.3 Hose

Hoses typically consist of a number of fundamental components [31]: the inner core; reinforcement; and, an outer cover (see Figure 19).

2.3.1 Inner core

The inner core is a tube the main function of which is to contain the hydraulic or pneumatic medium, it is usually made of either polymer or elastomer. The inner core prevents leakage of the fluid and it is loaded in almost hydrostatic conditions

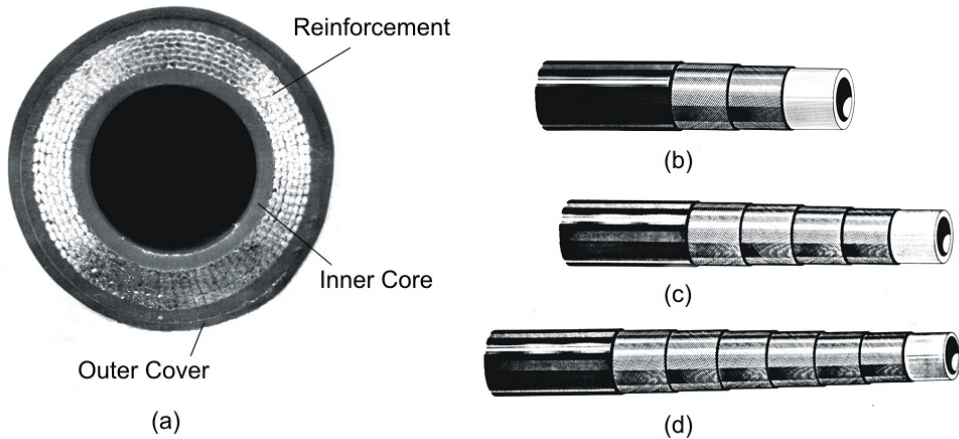


Figure 19: (a) The cross section of a six-layer Polyflex hose, indicating the basic components of the hose. (b) two-layer spiral hose, (c) four-layer spiral hose, (d) six-layer spiral hose (from Polyflex [32]).

2.3.2 Reinforcement

The reinforcement is the main load-bearing component and consists of layers of fibres or wires wound around the inner core. The reinforcement will be either braided or spiral wound.

Braiding involves weaving both left- and right-hand helical fibres on the same layer to produce a jacket or sheath such as shown in Figure 24a. In order to braid the wires effectively they must be thin enough to bend into place. The braiding has the advantage that upon loading or pressurisation, the hose will not twist. However, the strength of the braiding may not be sufficient for all applications.

Where greater strength is required, spiral armouring is used. This created a structure that is similar to the spiral strand rope described in Section 2.2.1, with the core wires replaced by the tube. Depending upon the strength required, the armouring will be built up in layers. As with the spiral strand, some level of torsional stability may be achieved if more than one layer of armouring is used. It must also be remembered that the armouring may be required to maintain axial-dimensional stability as described in Section 1.8.

2.3.3 Outer cover

The outer cover is concerned mainly with protecting the reinforcement from wear and corrosive attack. It contributes little to the strength or stiffness of the hose structure.

2.3.4 Related structures – flexible risers and umbilical cables

When oil is transported from the sea bed to a floating platform it is done by means of a flexible riser, the most common type of which is known as a non-bonded flexible pipe (for example, see Figure 20).

These are a much larger diameter than hoses and an important consideration is to prevent collapse from the external seawater pressure while retaining flexibility. Consequently such structures have layers such as locked coils and corrugated carcasses to prevent internal collapse, as well as wire layers for hoop and longitudinal strength.

Another requirement of floating platforms is to control the well head remotely from the platform. This is enabled by umbilicals (Figure 20) which are a number of hoses and electrical cables, wound together inside a large hose-like structure. The large external hose protects the hydraulic and electrical flexible sub-units from external pressures while maintaining adequate flexibility to allow for platform movements.

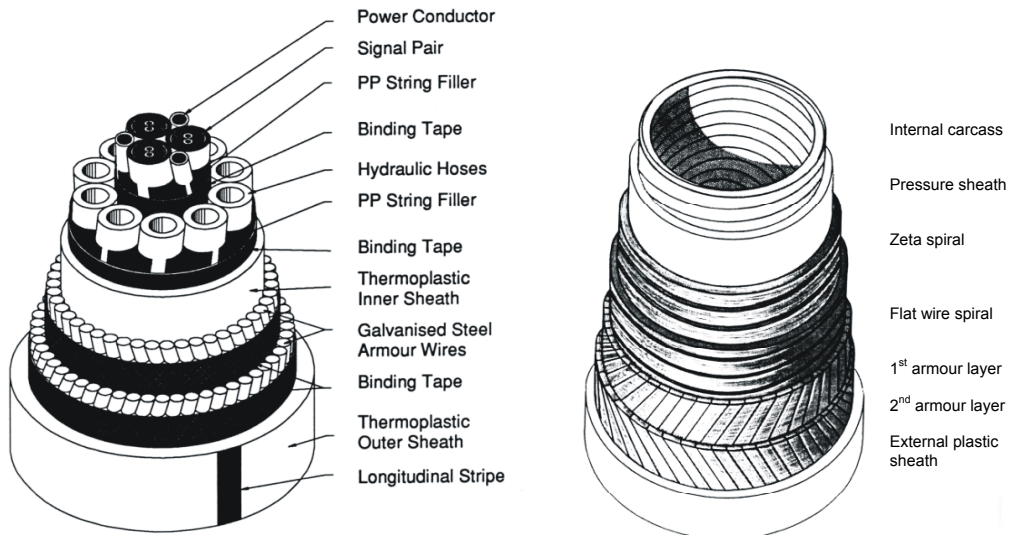


Figure 20: An example of an umbilical manufactured by Dunlop-Coflexip [33], and an example of a flexible pipe manufactured by Coflexip [34].

2.3.5 Production of hose spiral armouring

The application of armouring to a hose is very similar to the production of a spiral strand. In the case of hose, inner core bundle or tube is fed from a spool through the axis of the winder. The main difference in the application of the armouring will be that it is wound at a much greater lay angle, for reasons discussed in Section 1.8. The consequence of the steeper winding angle is that there will be proportionally many more wires in each layer than in the case of a rope. Hence hose spiral-winding machines have many more rotating bobbins of wires on each winding wheel, and do not incorporate epicyclic gearing to remove twist in the wire. However, the much steeper angle at which a layer of hose wire is wound means that introducing twist along the axis of the wire is not a problem.

2.4 Synthetic fibre ropes

The development of synthetic fibres as we know them today was largely due to the research effort from the early 1920's to World War II by Carothers and Staudinger. After WWII, nylon 6.6, a product of the work of Carothers at Du Pont in N. America (in the 1930's), became the first commercially available man-made fibre [35]. Polyester (poethylene terephthalate) fibres were first developed into commercial products by Winfield and Dickson in the 1940'/1950's.

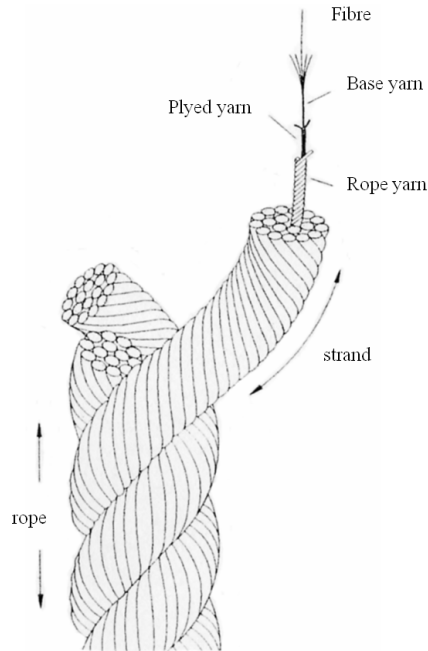


Figure 21: A three-stranded fibre rope from Leech [36], which is a five level repeating helical hierarchy.

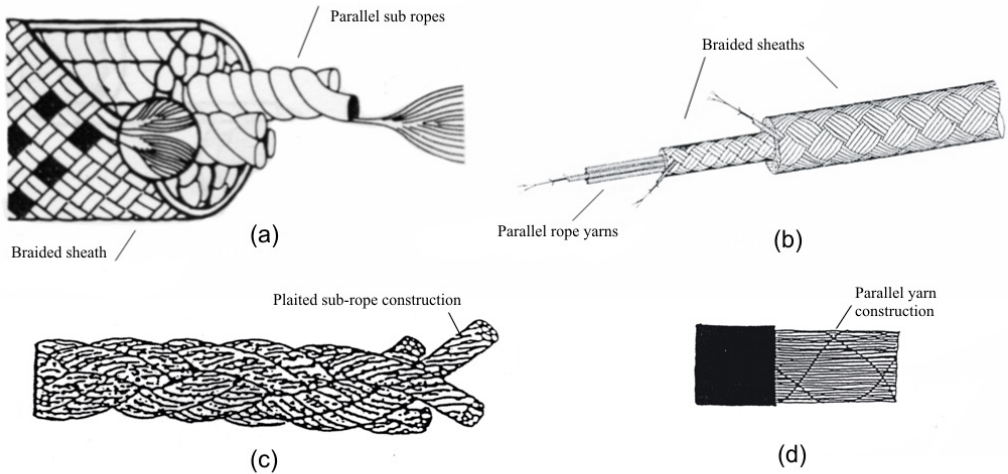


Figure 22: Four examples of rope constructions: (a) parallel sub-rope covered with a braided sheath [36]; (b) a double-braided fibre rope [36]; (c) a plaited rope [35]; and, (d) a parallel-yarn rope [35].

2.4.1 Types of fibre ropes

Polymeric filaments are either coarse mono-filament or fine multi-filament, which have diameters typically between 10 and 100 microns. (By way of reference, wire diameters are usually between 0.5 and 5 mm, some 20,000 times greater.) Yarns are formed of lightly twisted or discontinuously entangled bundles of 100 to 2000 filaments. In most rope constructions, a number of single yarns are twisted together into plied yarns, these being further combined to form rope yarns and strands. The strands are then used to produce a variety of constructions, some of them closely copying the wire rope type of constructions (e.g., compare Figure 21 with Figure 9a), or, owing to the high flexibility of the fibres, different type structures such as braided and plaited. Figure 22 shows examples of the range of fibre rope constructions in use.

2.4.2 Applications of fibre ropes

Fibre ropes have a number of properties that make them attractive alternatives to wire ropes. Currently the biggest growing application is in the use for offshore moorings. We will discuss the properties of fibre ropes with reference to the considerations for this application. Beneficial properties of polyester fibre ropes, such as are used offshore, include good strength-to-weight ratio, flexibility, ease of handling and near neutral buoyancy in seawater. Other materials such as aramid fibres, which owing to their high strength might initially seem suitable or even better as a material, would not be used for several reasons: it is too stiff, very expensive and not at all rugged. Thus it can be seen that as with wire ropes, each needs to be selected or designed with a full appreciation of the service for which the rope is required. Table 1 (which is not exhaustive) summarises some fibres and their key properties.

The near-neutral buoyancy of polyester fibre ropes in sea water is significant in that it makes possible the mooring of floating exploration and production oil platforms in the very deep waters (1000–3000 m) that are now being exploited (especially in the Gulf of Mexico and off the coast of West Africa). The benefit of the fibre rope is derived from its use in the taut moorings arrangements that are possible, such that the rope strength is used for station keeping rather than supporting the ropes self weight [35].

Fibre ropes tend not to be very resistant to crushing and abrasion, hence, where fibre ropes are used in deepwater moorings it is usual to employ a line that has a top section of chain or wire rope (usually six strand), and a bottom section to the anchor, of chain, spiral strand, or six-strand rope. The final choice of components is influenced by such factors as ease of handling, operation over a winch (top end) and abrasion / anchor embedment (at the sea bed). The use of multi-component mooring lines can lead to torsional problems as outlined in Section 1.7, but by careful design and installation these problems, for the most part, can be avoided.

Although fibre ropes are not affected by corrosion in the same way as wire ropes, they are susceptible to UV degradation. The UV degradation affects the exposed surface of the fibres, acting to reduce their strength. Hence it is more of a problem in some types of construction, such as plaited (Fig. 16c), and with smaller ropes compared with larger (where the exposed rope surface area is a greater proportion of the whole rope). Other design considerations in the selection of a fibre for an application are those of creep and elongation. Fibres such as polyamide (nylon) and polyester suffer from creep, and nylon displays considerable elongation under load. Aramid and LCP fibres on the other hand, are much stiffer and display negligible creep.

Thus it may be seen that the range and properties of the fibres used in synthetic fibre ropes varies considerably, and for any application there will a compromise between the properties and differing service requirements.



Table 1: Properties of fibre rope materials (compiled from [37]).

Fibre	Properties
Aramid (Kevlar [®] , Twaron [®]): A manufactured high-modulus fibre in which the fibre-forming substance is a long-chain synthetic aromatic polyamide of which at least 5% of the amide linkages are attached directly to aromatic rings	<ul style="list-style-type: none"> • Excellent strength-to-weight ratio • High resistance to heat (chars at 800°F) • Negligible creep • Poor abrasion resistance • Susceptible to axial-compression fatigue
Copolymer (Olyfin, polyester): The molecular combination of polypropylene/polyethylene fibres together with other fibres such as polyester	<ul style="list-style-type: none"> • Moderate strength/elongation • Low weight (floats) • Good UV resistance • Good abrasion resistance
HMPE (Plasma [®] , Spectra [®] , Dyneema [®]): High-modulus polyethylene fibres produced by gel-spinning ultra-high molecular weight polyethylene (UHMWPE)	<ul style="list-style-type: none"> • High strength-to-weight ratio • Very good abrasion resistance • Excellent dynamic toughness • Very low elongation (3–5%) • Good bend fatigue performance • Low resistance to heat • Susceptible to creep
LCP (Vectran [®]): High-modulus fibre produced by melt spinning from thermotropic liquid crystalline aromatic polyester	<ul style="list-style-type: none"> • Excellent strength-to-weight ratio • Zero creep • Excellent dynamic toughness • Excellent bend fatigue performance • Good abrasion resistance • High heat resistance (melts at 625°F)
Polyamide (Nylon): A manufactured fibre composed of linear macromolecules having in the chain recurring amide linkages, at least 85% of which are joined to aliphatic or cycloaliphatic units	<ul style="list-style-type: none"> • Good strength-to-weight ratio • Good shock-absorbing characteristics • High elongation (30–40%) • Good UV resistance
Polyester (Pet, Pen): Includes polymers composed of linear macromolecules having a chain at least 85% by mass of an ester of a diol and terephthalic acid	<ul style="list-style-type: none"> • Highest UV resistance of any fibre • Good abrasion resistance • Good strength-to-weight ratio • Moderate elongation (15–20%)
Polyolefin (PE, PP): A class of polymers in which the fibre-forming substance is any long-chain synthetic polymer composed of at least 85% by weight of ethene (ethylene), propane (propylene), or other olefin units	<ul style="list-style-type: none"> • Low weight • Low cost • Good general-purpose fibre

2.4.3 Production of man-made fibres

Traditional ropes are made from natural polymers such as hemp. Polymeric fibres used in rope making are mostly made from petrochemical feed stock. Table 1 gives more information on the composition of various commonly used fibres. In general, however, the process for producing polymers in the form of fibres is known as spinning and, although there are a number of different types of spinning, there are three generic processes:

- (a) Preparation of a viscous dope;
- (b) Extruding the dope through a spinneret to form a fibre; and,
- (c) Solidifying the fibre by coagulation, evaporation or cooling.

Some spinning techniques involve the polymer being dissolved in chemicals (wet and dry spinning), but the preferred method of spinning (for example nylon and polyester) is melt spinning; this involves the use of molten polymer that is solidified after the spinning by cooling (Fig. 23).

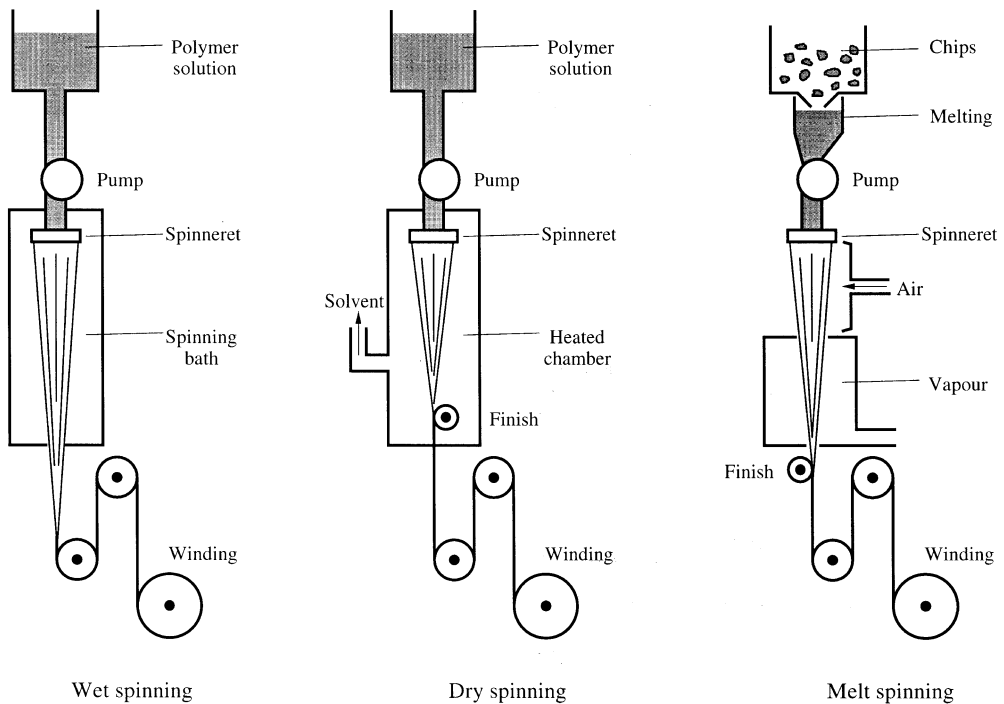


Figure 23: Three types of spinning commonly employed for fibre production [35].

Following spinning, the fibres have poor strength and stiffness since the molecules of the polymer are not preferentially oriented in the direction of the filament. Orientation is obtained by drawing. For fibre such as polyamide and polyester, typical drawing ratios are between 3:1 and 5:1 [38].

After production of the fibres, these are combined as mentioned above into strands and ropes. Some rope constructions (and hence production techniques) are similar to those used for wire ropes and will not be described again here. There are, however, two similar forms of production particular to fibre ropes: braiding and plaiting. Although both these techniques are fundamentally the same, in that they involve weaving of fibres, braiding may be seen as a technique to produce a cover (or series of concentric layers), whilst plaited ropes involve plaiting of the whole strands. Thus a rope made up of parallel strands may have a braided jacket (which may be of a different material with better UV tolerance) to allow it to be operated as a whole with the additional benefit of protection from UV light.

2.4.4 The braiding process

Braiding is a process that produces an interwoven tube of fibres with an equal number of fibres wound both left and right hand. The braiding process involves one group of fibres being wound in a sinusoidal path in one direction, the sinusoidal path thus allowing a second group of fibres to be interwoven in the opposite direction. In order to achieve this, a braiding machine has a number of key components [39]:

- Bobbins and carriers that hold the reels of fibres with a pre-determined tension.
- A deck plate that controls the movement of the carriers by means of two slots and also houses the horn gears
- Horn gears, a number of which are positioned around the centre of the machine, with four slots to hold the carriers. Adjacent horn gears rotate in opposite directions and drive two sets of fibres in their counter-woven path.

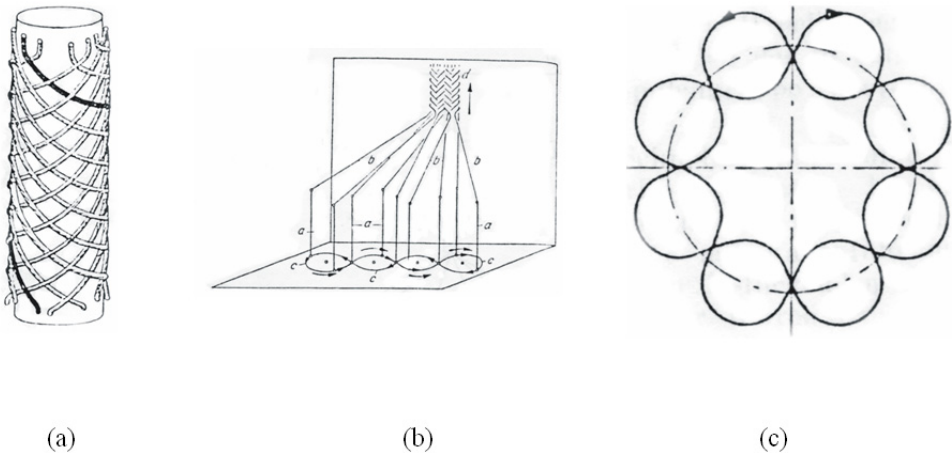


Figure 24: The braiding process, showing (a) a braided tube, (b) an example of the fibre path for a braided sheet and (c) the fibre path for a braided tube (from Matschoss [39]).

3 Description of biological rope-like structures

Tissues within an organism are tailored to their specific functional needs both by the properties of the constituent ‘building blocks’ and their structural organisation. There are many examples

where a long helical (rope-like) structural organisation has been employed and this section gives some examples of this. Two broad groups of building blocks exist as polypeptides in mammalian structures (specifically collagen and elastin), and polysaccharides in plant structures and insects (cellulose and chitin).

As well as the fibrous building blocks of biological tissues, a number of other constituents exist that can be broadly termed as matrix materials, fillers and ground substances. These may have a critical role in the mechanical behaviour by either binding fibres together (in the case of hard tissues) or allowing free slippage between fibres (in the case of soft tissues). Some examples of these are globular proteins or glycoproteins and water, in un-calcified soft tissues; in hard tissues hydroxyapatite (in bone), and lignin in wood, are common examples.

A number of biological systems are discussed in terms of their structure-function relationships. Two building blocks have been chosen – collagen, a polypeptide, and cellulose, a polysaccharide. As mentioned above, there are other building blocks found in nature such as chitin, a polysaccharide, found in crustaceans and insects based on a helical molecule. Thus these examples should be seen as illustrative rather than exhaustive.

3.1 Polysaccharide structures

Plant structures are made up from elongated cells that have helical cellulose macro-fibres within their walls. The structure of these macro-fibres will be discussed and then their role within the organisation of a plant cell wall will be detailed.

3.1.1 Cellulose macro-fibres

The cellulose molecule is a polysaccharide with two glucose molecules rotated by 180° (known as polybiose) as its repeating disaccharide. This molecule is twisted into a microfibril [40], which is in turn twisted into a macrofibril along with pectin, glycoprotein and hemicellulose, which act as a gel-like lubricant or a glue depending on the stage of growth of the plant cell wall. Thus the cellulose macro-fibre has a hierarchy of helical elements, its place within the plant cell wall is discussed in the following.

3.1.2 Plant cell walls

Plants utilise two general mechanisms of structural support within their cell walls [41]. Flexible cell walls that rely on hydraulic ‘turgor’ pressure for bending stiffness and stiff cell walls that are bonded together with a stiff matrix and have stability even when dry. In the case of tree structures both types of structure exist within the development of the plant (Fig. 25). A brief description of these two systems is given.

The central living part of a plant cell (protoplast) synthesises layers of cellulose fibres within an amorphous matrix [42], which are gradually stacked one on another (i.e., the outermost wall being the first formed). The first layer formed (the primary layer) has a low fibre content, around 25%, and is embedded in a gel-like matrix, pectin, which gives a flexible wall structure. The inside of a cell at this stage is under hydrostatic pressure due to osmosis. The gel-like matrix also allows the cell to grow and elongate easily during this stage of development. The next stage of development involves the formation of secondary layers, generally referred to as S1, S2 and S3, which have a much higher fibre content than in the primary layers (gradually increasing to 80% by dry weight). The S1 layers consists of cross-helical fibres at around 80° to the axis, S2 and S3 are about 40° to the axis. At this stage both primary and secondary walls of the cell are impregnated with lignin, which is a complex organic polymer with a three-dimensional configuration [42] and bonds the whole structure,

giving it bending stiffness without the need for hydrostatic support. Plant cross sections tend to be arrays of parallel cells each being helically wound tubes as described.

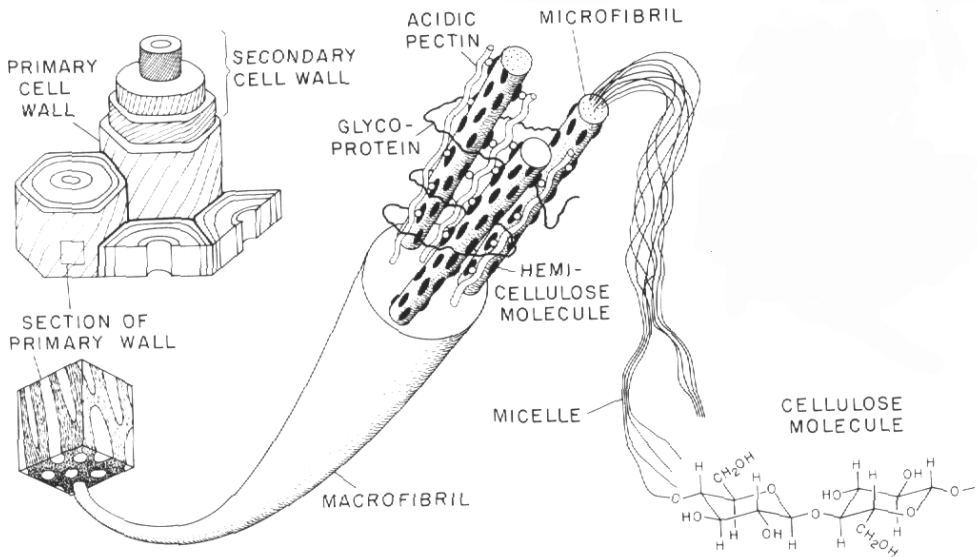


Figure 25: The hierarchical structure of plant cell walls as found in wood, from Esau [41].

Wood structures are able to create pre-stress within their fibres to re-orient branches and trunks that are mechanically displaced from their original position. The same mechanism is employed by the aerial roots of the fig tree once it enters the ground in order to create a tension guy [41]. This type of wood is known as ‘reaction wood’ and the pre-stresses can be tensile or compressive.

Wood has a mechanism of toughness that enables it to absorb large amounts of energy before failure by the pseudo-plastic behaviour caused by the realignment of fibres of the fibre-wound wood cells (known as tension buckling). It has been found experimentally to have maximum energy absorption when fibre angles are around 15° .

3.2 Polypeptide structures

3.2.1 The collagen fibril

Collagen is a collective name for a group of fibrous proteins with similar structures and properties [44] (see Fig. 26). The most abundant amino acids within the basic protein molecule are glycine, alanine, proline and hydroxyproline. These molecules tend to be helical in orientation (α -chain) and grouped in threes, twisted together in the form of a coiled coil (collagen molecule or tropo-collagen), according to the model proposed by Rich and Crick [45]. Between four and eight collagen molecules twist together to form a microfibril [46] and it has been shown that these microfibrils, in turn, twist together to form a collagen fibril. Thus a collagen fibril is a four-level helical hierarchy. The collagen fibre forms the basis for many biological structures such as tendon, arteries, bones and skin, the first two of which will be discussed below. Collagen fibres are often present in materials that exhibit viscoelastic

behaviour. Recent work by Purslow et al. [47] on skin suggests that this behaviour cannot be attributed to re-alignments of the fibres within the matrix. It is suggested that it is more likely to be caused by viscoelastic behaviour of the fibre itself (possibly by realignments of micro-filaments at a lower level within the fibre).

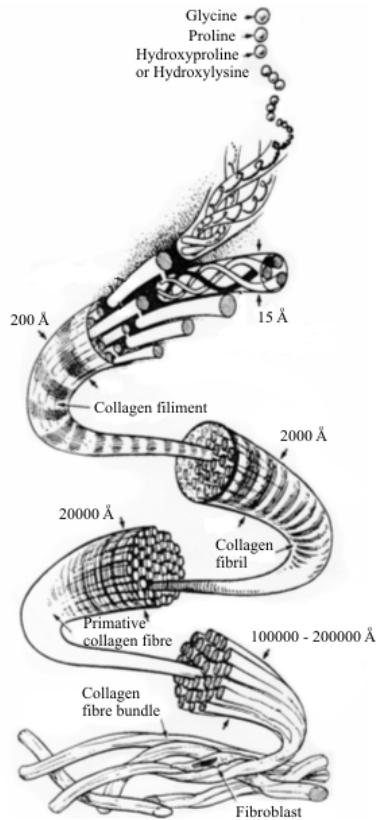


Figure 26: The hierarchical structure of collagen (from [43]).

3.2.2 Arteries

Arteries are relatively high-pressure, cylindrical, thick-walled vessels and the bulk of the load-bearing portion of arteries, the 'Tunica Media', is formed of alternating sheets of helically wound collagen fibres with elastin sheets. Two primary functions of the arteries are to bear the high pressures of the system and to smooth out the pulsatile flow caused by the beating heart. The smoothing of the pulsatile flow is achieved by the highly flexible properties of the arteries close to the exit of the heart. Otto Frank has made the analogy of the aorta being like a 'Windkessel' (air chamber) much as was used in hand-powered fire pumps to provide a uniform outflow with a pulsatile inflow [48]. The ascending aorta has a higher elastin content within the wall so that the vessel acts as an accumulator in this region, where the elastic recovery is 98%

[49]. The elastin content of the ascending aorta is 30–40% and the collagen content is around 20%, then there is a gradual change in these ratios until around the abdominal aorta, where the collagen content is twice that of elastin. Roach and Burton [50] argue that elastin dominates at low tissue stress but collagen provides the strength. This does seem to be particularly true for the higher reaches of the aorta where E_0 (initial, low-load elastic modulus) is 90 kPa at the ascending aorta and 10 kPa at the femoral bifurcation – in line with the elastin content.

Since thick-walled pressure vessels have a maximum tensile hoop stress on the inner radius that decreases on increasing radius (i.e., Lamé's theory, (see [51] for example), optimum load bearing can be achieved by having a residual compressive stress on the inside of the tube. Work by Fung and co-workers [52, 53] has demonstrated that such a pre-stress exists within arteries and to varying levels at different locations in the system.

3.2.3 Tendon

Tendon transmits the forces developed by the muscle(s) of which they are an extension, to the peripheral bones so as to create moments about the intervening joints over which they course. Tendon is composed of between 70 and 80% collagen by dry weight [54], and has thus been the focus for considerable amounts of basic study on the properties of collagen, the main other components being polysaccharide ground substances (probably acting as a lubricant between fibres) and fibroblast cells for repair. The function of tendon is that of a load transmitter, with a minimum amount of hysteresis but with returnable energy storage with enough flexibility to go around joints. The collagen in tendon is arranged in parallel collagen fibrils. The fibrils tend to have a surface waveform that varies in different tendons from a helix in many tendons, (e.g., human palmaris longus to a planer crimp in rat-tail tendon [55]). It appears that this waveform serves the function of giving the tendon a high compliance at low loads (until it is straightened) and then a high stiffness beyond this point. Tendons also appear to twist to some extent on loading [54], and this is probably a secondary effect of the helical waveform.

3.2.4 Spider's silk

Silks are produced by the more than 30,000 known species of spiders [56]. There is a large variation in the properties of silk not only between species, but also that can be produced by an individual spider [57]. Spider's silk is formed from protein and, like collagen, the majority of amino acid composition is made up of the small helix-forming amino acids glycine, alanine and proline [58]. Spider's silks vary in properties depending on the functional requirement. A typical araneid orb weaver has seven specialised glands, each producing different types of silk for wrapping, webs, hanging on, etc. [59]. Two common types of silk are dragline silk that the spider uses to hang on, which is stiff with some energy absorption at high loads, and viscid silk that is used within the web, and which must have a low stiffness and high hysteresis in order to absorb the impact of the captured fly.

One interesting property of spiders silk is that it contracts on exposure to water; this has the benefit of introducing a pre-stress into a web (it is also one reason why spiders silks are not used in manmade textiles). Recent microscopic work by Vollrath et al. [60] on the dragline silk of *Nephila clavipes* has led to the proposal of a structure for spiders silk as tube helically wound with microfibrils surrounding a less dense amorphous core. They have suggested that the mechanism of super contraction could be that of realignment of the helical fibres of the sheath caused by swelling of the core material.



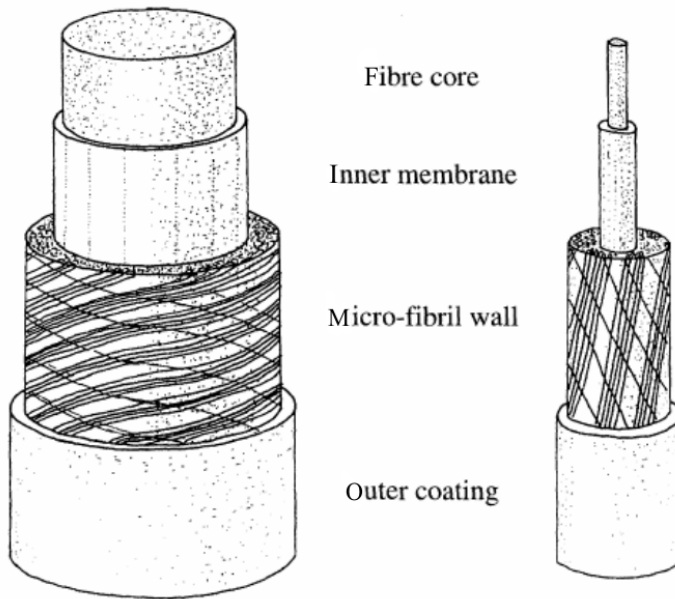


Figure 27: A model for the structural organisation of spiders silk based on light microscope observations. The left-hand image is the state during swelling, the re-orientation of the fibres causing pre-tension in the silk [60].

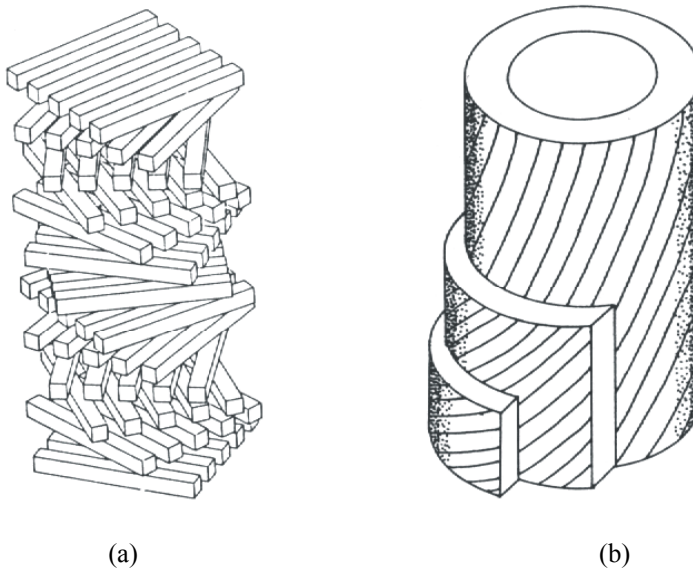


Figure 28: A cholesteric liquid crystal (also known as ‘twisted nematic’ or ‘helicoidal’), (a) in planar form and (b) in cylindrical form, resulting in concentric helical fibres with varying angles, from Neville [61].

3.3 Nature's manufacturing techniques

Many of the molecules that make up compliant structures have a rope-like helical structure – for example the alpha helix, the triple helix and the DNA double-helix molecule. The formation of these helical molecules is by self-assembly: i.e., when the chain synthesises it preferentially forms a particular structure dictated by weak interactions, in particular the hydrogen bond and the interaction of the molecule with neighbouring water molecules.

The mechanism of forming biological 'materials' or structures from molecular subunits is an area of great interest. One school of thought is that biological materials go through a liquid-crystal phase during their formation. Neville [61] has put forward a strong argument for this in insect cuticle and plant cell walls. Wilcox et al. [62] have also put forward evidence for liquid-crystal structure within spider's silk. Fibres form into either a nematic (threadlike) or cholesteric (twisted nematic) conformation. Cholesteric liquid crystals tend to form in sheets of parallel fibres, each sheet being slightly twisted with respect to the previous (see Figure 28). A cholesteric liquid crystal forming on the surface of a cylinder will produce a helical construction with varying angles throughout the layers (as seen in a plant cell wall for example).

4 Discussion

The first man-made rope-like structures utilised biological materials such as hemp, cotton, silk, leather and rubber. It has only been in the last centuries that these materials have been gradually replaced by man-made equivalents. Now, ironically, with the science of 'biomimetics' there is a great interest in going back to the biological structures to see what man can learn from them. There seem to be many parallels between the structure of man-made and biological rope-like structures. Although there is very little evidence that man has copied nature in the past.

One rare example of copying was an attempt to model the structure of wood cell wall to imitate their 'tension buckling' characteristics in order to obtain good energy absorption [63], although this work was in the first instance to make an essentially planar composite material with corrugated layers rather than a helical structure.

We have seen that wire and fibre ropes are formed by combining with different levels of twist the basic elements of wires and fibre. The properties desired of the component may, to a certain extent be engineered by combining elements in multiple-helical sub-structures. Ropes may have excellent wear properties (e.g., locked-coil ropes), be very flexible (eight strands with fibre core), rotation resistant (multi-strand) or a combination of these. The manufacturing variables at the disposal of the engineer include material properties, size, shape, strand structure, direction of spinning, etc.

The helical or rope-like structures that we have discussed, and that are found in nature, share similar performance characteristics, although their scale and method of production is very different (especially in the case of wire ropes and armoured hoses).

One performance characteristic that we have touched upon in Section 1.7 is the effect of imposed twist in a helical structure – a stranded wire rope, particularly a six-strand rope that is torsionally very active. If the twisted rope, that is a rope with twist forced into it from an external source (e.g., see [8]), is unloaded, it will rid itself of some of the twist by forming what is termed a hockle (Figure 29a). If the rope is then re-loaded and the hockle pulled out, serious damage will occur. Compare this undesirable behaviour of the rope with that of the



DNA molecule (Figure 29b). The similarities in performance are obvious, although the scale and materials involved are completely different. Additionally, it should be noted that for the DNA molecule this type of behaviour is necessary for it to pass genetic code to the messenger RNA. Considerable work has been undertaken to model this phenomenon (see for example Thompson et al. [65]).

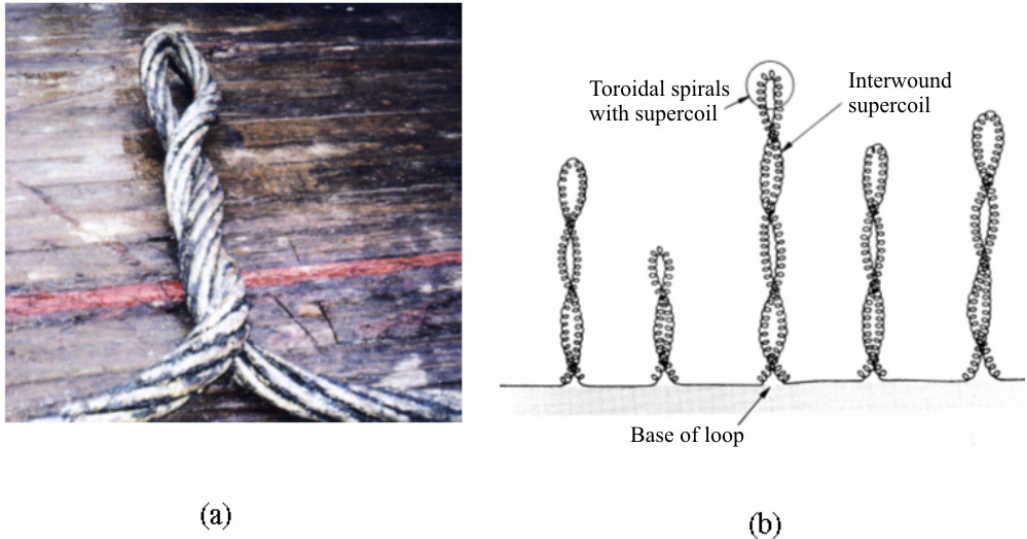


Figure 29: A comparison of hockling seen in a wire rope with a similar effect found in DNA molecules (DNA molecules from [64]).

Wood, arteries and spiders silk all share the ability to develop internal stresses within them in order to adapt or optimise. This idea of pre-stressing thick-walled tubes such as found in arteries has been used in man-made thick-walled pressure vessels (where the vessel is overloaded to cause the inner section to yield and therefore go into compression on unload) and is achieved by a technique known as autofrettage [66]. The mechanism that produces pre-stress in arteries is not fully understood but is unlikely to be caused by such a process. It is possibly more akin to the pre-stressing that is created in the helical armouring of a hose if the wires are spun with sufficient back tension on the bobbins.

Wainwright et al. [67] have suggested that the mechanism by which reaction wood is formed is by the swelling of the fibre-wound cells with fibres other than 55° causing a lengthening or shortening of the cylindrical wood cell (as described in Section 0). A similar explanation has been put forward for the pre-tension in spiders silk by Vollrath [60], involving the swelling of the internal core of the silk through water absorption (see Figure 27).

Some of the properties of silk produced by spiders seem to be analogous to the types of climbing rope in use: viscid silk to the types of ropes used for arresting a fall such as rock climbing and dragline silk to ropes such as those used for rappelling, which must be stiff to prevent too much bouncing. The climbing ropes achieve this variation in properties through helix-angle variations, but the mechanism by which the spider produce these properties in the silk still needs further investigation.

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