Interactive Fatigue in Wire Rope Applications

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Abstract: Two technically challenging applications – deep mine hoisting and deepwater offshore mooring – are reviewed in terms of the mechanics of rope response driven by challenges of increasing depth of operation. In both cases, practical and economic solutions lead to a need to understand and quantify interactions between different modes of fatigue loading (simplistically: bending, tension and torsion) which are traditionally segregated in laboratory testing. It is shown that, to assure reliable operation, first a thorough understanding of the mechanics is essential, but also a quantitative measure of the interactions between different modes of imposed loading is required. Some results are presented showing the dramatic effect of such interactions, and an explanation of some these effects is also advanced with supporting experimental data.

Introduction

In the context of past, present and foreseeable technology, it is an accepted fact that, in the great majority of its applications, wire rope has a finite life. The continual processes of degradation associated with operational service, will ultimately lead to failure, and usually a rope must therefore be replaced before the risk of failure becomes unacceptable. The processes of service degradation are complex and different for each category of application, reflecting the interaction between operating parameters and the characteristics of the rope employed.

Serious damage, sufficient to warrant discard, may be induced by single events but in the long run, and in well maintained and operated systems, fatigue will play a dominant role. However fatigue of rope is in practice rather different from, and more influenced by other processes than, the comparatively straightforward “crack propagation” of a single crack in a contiguous metal component under fluctuating stress.

The great majority of safety critical rope applications involve fatigue coupled with other degradation processes such as wear or corrosion, which together determine a finite service life. This combination is reflected in the inspection and discard policies employed on rope systems, as well as in system design and operation.

So for enhanced safety, for improved efficiency in rope utilisation, and for better design and maintenance of rope-dependent systems, a thorough understanding of rope fatigue is desirable. This paper reviews available knowledge of rope fatigue processes, introduces results of recent investigations, and presents the whole in a context of two different applications: deep-shaft mine hoisting and deep-water offshore mooring. The features common to these two applications are the great lengths of rope involved, and consequently the influence of rope weight, as well as issues of twist which can, in the circumstances prevalent, interact with other modes of deformation to bring about unexpectedly dramatic reductions in fatigue endurance.

Fatigue in wire rope

In essence the process of fatigue in metals involves crack propagation from some stress concentrating defect, by mechanisms which involve local plasticity at the crack tip under the influence of a fluctuating load. In practice there are often exacerbating environmental factors, and the “defect” may be some geometrical stress raiser such as a step in a shaft, or some seemingly minor blemish. Very localised surface stresses (fretting) are often linked with the initial stages of fatigue crack propagation.

In the fatigue of engineering components it is unusual to have other than a single crack, and in laboratory experiments it is common to observe very significant scatter in the fatigue endurance recorded in similar fatigue tests. The parameter which dominates the endurance, or number of cycles to failure, is load, or stress, range.

Wire ropes are constructed of a complex assembly of steel wires. Typically the steel used has a very high strength, which may be a factor of five greater than the strength of typical structural steels. This high strength is achieved by using a plain carbon steel with high carbon content and a very fine grain structure achieved through isothermal transformation (patenting), and work hardening by successive drawing. The division of the load bearing capacity between many “parallel” (in the sense of redundant load paths) wires has two essential benefits: it assures the essential combination of high axial strength and stiffness with bending flexibility; and allows the structural use of an essentially brittle steel at very high stresses by subdividing the structure to isolate local fractures in much the same way as a fibre composite achieves toughness. The latter point is important in ensuring that a wire rope is “tough” in the sense that it is tolerant of local damage, particularly in the form of broken wires.

Wire ropes operate at high stress levels and are almost invariably subject to fluctuating loads. In the running ropes of a mine hoist (as well as cranes, elevators and other machines) one source of stress fluctuation is the repeated bending and straightening as ropes run over sheaves, and on and off drums. Axial loads also fluctuate in a mine hoist as the payload changes and as the conveyance accelerates and decelerates; and in a friction or Koepe hoist a key factor is the effective inversion of the rope twice every full hoisting cycle, discussed below. In a mooring system tension fluctuations due to motions induced by environmental loading on the floating structure, are the dominant source of fatigue stresses. Given time and a sufficiently high fluctuation in stress range, fatigue is inevitable. However in a wire rope, due to the loose coupling between wires, complete failure of the rope requires that many wires are broken in fairly close proximity. But the fatigue of a single wire in the rope is invariably more than a simple matter of fluctuating stress; there is usually some other process which exacerbates and accelerates the fatigue, and which focuses the process to specific locations. This process might be fretting between wires, or be linked to another degradation mechanism such as wear or corrosion.

In practice therefore rope fatigue involves a large number of fatigue processes going on in series (at different locations along each wire) and in parallel (similar processes along each of many wires): rope failure occurs when the accumulation of wire breaks in a locality is sufficient to precipitate total failure. One interesting consequence of this requirement for multiple wire fatigue failures is that, whilst there is a characteristically wide statistical scatter in the numbers of cycles for the isolated failure of a single *wire*, and there must be many broken wires distributed throughout the rope before *rope* failure, there is an “averaging” process that results in strikingly little scatter in the cycles to *rope* failure. The Palmgren – Miner cumulative damage approach to evaluating the combined effect of cycles at different levels of loading also works well with wire rope, arguably for the same reasons [1]. But there are exceptions to this and it is important to be sure when using this approach that the fatigue damage being summed takes place at the same location in the rope and the processes are independent rather than combined[1].

The primary mechanisms responsible for stress fluctuations in ropes can be grouped under four headings: tension-tension, bending-over-sheaves, free bending and torsion. Each of these will be considered in turn, and then in combination in the context of the two applications.

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[1] If two mechanisms each generating similar stress ranges act concurrently to double the stress range the effect is very different from that of them occurring sequentially.

Tension-tension fatigue This category of rope fatigue is probably the simplest, involving stress fluctuations resulting from changes in axial tensile loading. In any fixed rope, such as the stay for a tall mast or for a crane jib, it may be the sole class of fatigue. It is a major consideration for mooring ropes. It is also relevant to any lifting or hoisting application (including mine hoisting) where attached mass changes and accelerations are the primary sources of axial load fluctuation. For this type of fatigue dominant parameters are:

- tensile load range;
- mean load (but note that the requirement that load is always tensile limits this effect);
- rope construction and wire grade;
- environment (including lack of effective lubricant, or exposure to corrosion);
- manufacturing quality.

Of these the dominant parameter is load range, and a good model for tension-tension fatigue performance is provided by a simple power law equation [1], as commonly used for fatigue processes, whereby:

$$\text{number of cycles to failure, } N = (\text{constant/load range})^m \qquad (1)$$

and the power m typically has a value of about five, but may be much higher for rope with small wires.

Note that provided rope temperature is not increased by energy dissipation to a level that affects lubrication, frequency is not a consideration. In addition terminations should not influence rope performance provided a suitable system is used (e.g. resin sockets) and it is correctly applied. The issue of rope quality relates to the variation in load sharing both between wires and along any one wire, which results from the dynamics of the manufacturing process. This can have a very significant influence on the relative performance of nominally identical ropes (from different makers, or from different production runs), affecting fatigue life by as much as an order of magnitude [2]. The quantitative issues of this feature of rope manufacture have now been thoroughly explored by Chaplin, Ridge & Zheng [3] and Evans, Ridge & Chaplin [4]. The mechanism also provides the basis for explaining the beneficial effects of overloads which, by generating a more uniform load distribution, can enhance tension-tension fatigue endurance, especially in a rope of initially poor quality.

Bending-over-sheaves fatigue This is the term traditionally used to describe the process of repeated bending under constant tensile load: it is a topic which has been the subject of considerable experimentation especially at Stuttgart University by Feyrer [5] and before him Muller [6], but also elsewhere, notably by Scoble [7] and Gibson [8]. The primary sources of the stress fluctuations in this mechanism are the local changes in wire curvature as the rope adapts to the radius of a sheave or drum. However the restriction of the source of fatigue stresses to changes in wire curvature requires that wires can slide with respect to one another. Any constraint on this freedom, for example by ineffective lubrication or internal corrosion, can impair fatigue endurance.

The principle parameters are:

- D/d ratio, the ratio of sheave diameter to rope diameter;
- tensile load;
- angle of wrap (arc of contact);
- bending length (or bending stroke);
- fleet angle;

- groove geometry and material;
- rope construction and wire grade;
- environment;
- lubrication;
- rope quality.

Of the parameters listed above, for a well designed and maintained system, the first two are normally the most important. However very short bending lengths or low angles of wrap can lead to a significant increase in life because the rope does not fully conform to the sheave curvature. Adverse combinations of fleet angles and groove geometry can cause additional degradation which in turn compromises bending fatigue performance, causing wear, or inducing twist.

Rope construction can be a significant issue in bending fatigue particularly because of the response to transverse loading on sheaves or drums. In ropes with “equal lay” constructions and a single layer of outer strands, forces are transmitted between wires by line contacts, whereas with compound strands or multi-layered rotation-resistant constructions the transmission involves point contacts between wires. In the latter case this tends to induce internal wire fatigue failures which are not externally visible: a feature which must be considered very carefully when defining inspection methods and discard policy [9, 10].

The rope quality issues described in the context of tension-tension fatigue are also relevant in bending but their effects are less significant due to the predominance of the *D/d* bending ratio in this mode.

Where bending is induced as rope runs on and off a multi-layer winch drum, life may be expected to be significantly reduced in comparison to that found when running over a sheave which has a nominally similar *D/d* ratio. Recent work at the University of Stuttgart by Weiskopf [11], simulating winding on and off drums on cranes, indicates endurances may be reduced by factors as high as 50. But this comparison is somewhat simplistic: in addition to the far more severe contact situation when supported by rope in the layer beneath, which Weiskopf recognises, there is also the issue that at the cross-overs, which typically occur twice per turn, and where the *D/d* ratio is effectively reduced to a much lower value [12]. Furthermore the *D/d* ratios investigated by Weiskopf are quite severe in comparison to mine hoists (cranes typically <35, whereas mines >80), and the cross-overs typically more abrupt.

Free bending fatigue Free bending fatigue involves fluctuating bending deformation of the rope but without contact with another body, and which is typically excited by system dynamics. A useful qualification is that the curvatures developed are seldom as severe as those typical of ropes running over sheaves, or on and off drums, although frequency might be high. In fixed rope applications this type of bending often takes place adjacent to a termination which introduces additional local problems, and life may then be a concern. Lateral oscillation of the cables of cable-stayed suspension bridges is an application where this category of fatigue can be significant [13].

Torsion fatigue The construction of a typical wire rope, with a large number of wires combined so they share the tensile load, results in overall properties that combine axial strength and stiffness with bending flexibility. An unintended consequence of such a construction is that the rope also has a low torsional stiffness in comparison to structural components of similar axial properties. A further consequence of the geometry of most commonly used categories of rope is that they are torsionally active, generating a torque in response to the tensile load when the ends are constrained against rotation, or conversely twisting about their axis when one end is not constrained.

There are of course rope constructions designed to minimise this tendency to rotate, but often these have other disadvantages which might include being less robust, having a propensity to break up internally [9, 10], and high cost. However it is also the case that in many applications a combination of fixed ends and absence of significant variation of tension along the rope means that even for torsionally active ropes there is no rotation. But in some applications, especially where components with different torsional characteristics are connected end to end, torsional oscillations can be induced in response to tension fluctuations. An application where such problems arise is in the moorings of floating offshore systems with hybrid mooring lines combining polyester fibre rope and torsionally reactive, six-strand wire rope [14]. Under these conditions the wire rope may experience a torsional mode of fatigue for which the dominant parameter seems to be twist amplitude [15].

Little is known about this kind of fatigue, and recent work at the University of Reading has investigated the quantitative role of different parameters. The majority of tests performed at Reading to date have combined torsional oscillation with tensile fluctuations, the coupling being achieved by attaching the six-strand wire test rope in series with a torque balanced polyester fibre rope. By adjusting the relative lengths different combinations of twist were obtained. The full details of this work still await publication, but the salient features are indicated in Figure 1 for ordinary lay ropes with IWRC. The primary location of wire breakage seems to be the contact between outer wires of the outer strands and the core of the rope, and broken wires become apparent as they loop out of the construction.

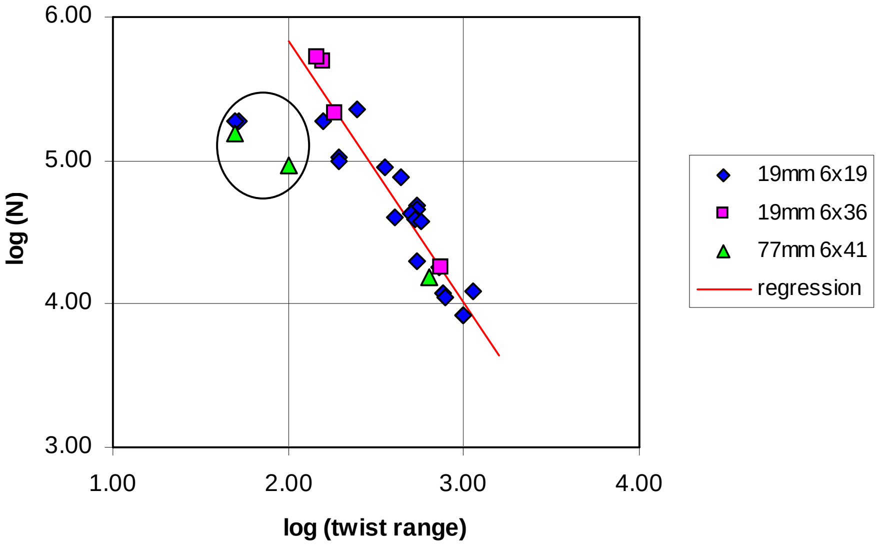

Figure 1: The fatigue endurance in torsion-tension of six-strand wire ropes of different diameters and constructions plotted as a function of twist range. The regression line does not include the four left hand data points (ringed) where the endurance was considered to have been determined primarily by tensile load amplitude. From [15].

It is clear from the investigations to date into this mechanism, that where the torsional oscillations are a consequence of tensile load fluctuations, the endurance can be very substantially reduced from the level associated with tension-tension fatigue. Figure 2 shows results for 19 mm ropes from Figure 1, but with life expressed as a proportion of the tension-tension fatigue endurance at the same tensile loading, in relation to the level of cyclic twist. Whilst at low levels of twist the life tends to that of the sample with full torsional restraint, at high levels of twist, fatigue endurance is reduced in some instances by a factor of as much as 50.

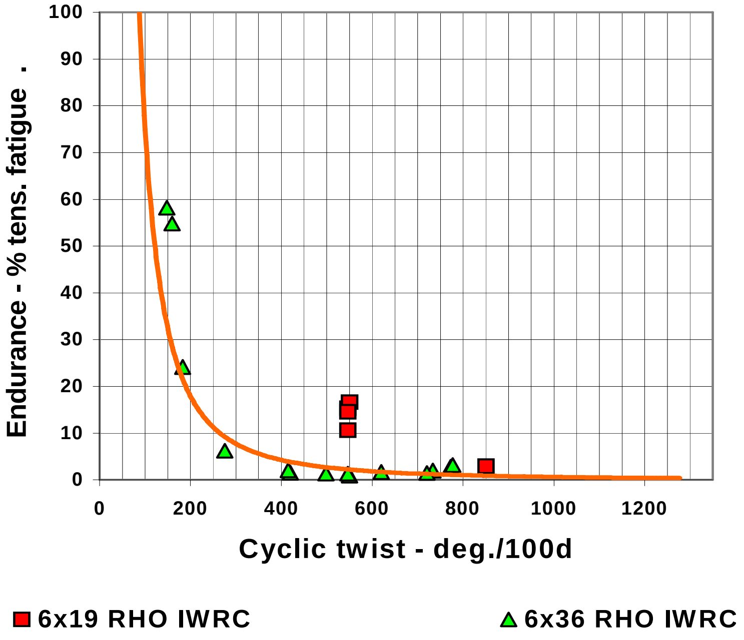

Figure 2: Fatigue endurance of 19mm diameter six-strand wire rope of two different constructions, both ordinary lay with IWRC. The tests involved axially coupled wire and non-rotating fibre rope (different levels of rotation being achieved at different load levels and with different sample lengths). The endurance is expressed as a percentage of the tension-tension life for the same rope at the same axial fatigue load. The abscissa is the range of cyclic twist. From [16].

When a rope is twisted the original construction is upset in various ways. The changes of most significant consequence here would seem to be imposed imbalances in axial strains. This effect will be most noticeable in "ordinary lay" stranded ropes where the effect of relaxing the end restraint on twisting, is to unlay the rope, but twist up the strands in the process since they have an opposite lay. In simple terms, this imposed deformation increases the length of outer wires in relation to the core wires and the inner wires of the outer strands, and so imposing additional tension.

Figure 3: 77 mm rope with strain gauges attached to each of 16 outer wires of one strand.

To evaluate this effect a simple series of tests was performed upon a 77 mm diameter 6x41, IWRC, ordinary lay rope. Strain gauges were attached to 15 of the 16 outer wires of one of the six strands as shown in Figure 3. The rope was then subjected to small numbers of tension cycles between 5%

and 40% of its Minimum Breaking Load (4425 kN). The rope was tested on Reading's Tension/Torsion machine [17] allowing two different end restraint conditions to be applied: fixed and free (i.e. zero torque). This is quite demanding upon the integrity of the miniature strain gauges and just over half survived the free-end tests, but sufficient data was obtained to be meaningful. A mean axial strain range of 2519 micro-strain was observed for the fixed end test but a much higher range of 5877 was obtained for the zero-torque test when cycling between 5% and 40% of breaking load.

Thus for the outer wires of this rope the effect of allowing full rotation was an apparent increase in tensile wire stresses of some 130%. Based on the simple power law tension fatigue model (Eq. 1) with an index of 5, then this could imply an endurance that is $(1/2.3)^5$ times (i.e. about 1.5% of) the restrained value. This is of the same order as results quoted for smaller diameter ropes [17]. Of course the strain range for other wires in the construction must be reduced and this will be most evident in the Lang's lay core: which explains why, in contrast to what is observed in simple tensile fatigue, very little damage is observed in the core in this combined mode even after failure.

Combined modes Laboratory testing inevitably tends to idealise the nature of the fatigue loading imposed upon ropes, and this is helpful in aiding our understanding of the roles of different parameters, but in service things are seldom so simple. The practical operating conditions of ropes are such that not only do different types of fatigue mechanism operate in combination (as above), but also the fatigue parameters are not consistent. Furthermore there are usually additional processes, such as wear and corrosion, introducing degradation that physically alters the rope and its fatigue performance. In some instances it is possible to make simplistic assumptions, as above, which allow a safe (i.e. exaggerated) estimate to be made of such effects, but this should be approached with caution.

Lifting operations typically involve different tensile loads at different stages, as well as running over sheaves and onto drums. Feyrer [5] gives a method for modifying the bending-over-sheaves prediction to incorporate tension changes, but these must be at the same frequency. An alternative is simply to employ a cumulative fatigue damage summation, on the assumption that the fatigue damage induced by the different mechanisms is co-located but independently determined.

A rather more subtle set of circumstances exists when bending length (the movement of the rope on and off a sheave) is very short. Here there is a transition range between a modified bending-over-sheaves regime, with accentuated tensile load, and tension-tension at very small amplitudes [1].

It has previously been suggested that the combined action of the mechanisms of tension-tension and torsion fatigue were essentially independent [18], except for an ill-defined transition at low twist amplitudes. However the more recent experimental work described above suggests the opposite, and that they are closely linked by means of additional tensile wire stresses associated with twisting.

Fatigue damage distribution Different points along a running rope are typically subjected to different levels of fatigue damage. This is best illustrated in the context of a mobile crane. When lifting a given load different parts of the rope will go round different numbers of sheaves, depending on the reeving but also depending on the jib extension and the height of the lift. This results in a very uneven distribution of bending fatigue damage along the rope, though tensile fatigue is typically more uniform. The next lift may be quite different, generating another uneven distribution of fatigue damage which is then superimposed upon the previous damage. A careful review of the spatial distribution of accumulated damage can be informative in optimising the kind of "slip and cut" policy adopted in many offshore applications such as drilling line or riser tensioners [19].

Allowance for the influence of degradation Degradation such as abrasive wear or corrosion can reduce the load bearing area of a rope. Discard decisions should be based upon a "safe estimate" of residual service life which is obviously affected by degradation. One approach to dealing with this is to calculate the *effective* loss of the cross section, load bearing, area of the rope. This is not quite the same as strength loss, since at normal operating loads the effective area lost will take into account slack wires, for example. The concept embodied in this approach is to estimate the effective increases in operating stresses induced by degradation, whether that be actual area lost or elements which through local deformation no longer share the load under operating conditions. Such a concept must recognize that area loss in one cross section is not the complete picture and losses must be integrated over all wires (e.g. if all outer wires suffer equal loss due to abrasion the effect must be considered as acting over the whole section). The corresponding increase in stress can then be considered as an overall increase in tensile load and thus used to recalculate endurance. This rather simplistic approach does seem to provide a reasonable estimate of reduced endurance, which can form the justification for discard criteria when considered as future (though more strictly "residual") life rather than reduced strength [20].

Applications

Offshore mooring The mooring "spread" for a floating offshore structure, whether a "permanent" production system or a "mobile" unit, entails ropes deployed in a pattern radiating from the moored structure to anchors on the seabed. At the vessel end it is common for the rope path to go via a fairlead sheave attached below water level, up to a deck mounted winch, or alternatively where no length adjustment is required to connect via chain to a fixed point. At the seabed wire rope normally runs to a drag embedment anchor, possibly connected via ground chain. Apart from small bending movements at the fairlead sheave and bending and slippage at the winch, the main loading is simple tension determined by vessel motions induced by environmental loading from waves, wind and current, as limited by the overall station keeping characteristics of the mooring system. System design is typically limited by strength, and would relate to the most extreme environmental loading event considered for the location in relation to service life requirements, usually in a "damaged" state. But fatigue is also a design issue, especially for locations where extreme events are less demanding. Where rope passes around a fairlead sheave just below water level, stretch of the rope between this sheave and the winch can result in bending-tension fatigue and consequent life reduction. Periodic adjustments of the mooring can mitigate this effect by distributing the very localised fatigue damage from this combined mechanism. Corrosion and winch related damage can also compromise fatigue endurance in the long term.

As oil production is required from ever greater water depths the mooring requirements become more challenging, and not only because of more severe environmental loading. The greater lengths of line involved result in greater weight and a catenary which approaches the vessel at a steeper inclination. This reduces the inherent station keeping effectiveness of the mooring leading to a requirement for higher mean tensions, and thus larger heavier mooring lines. To break this circle of diminishing returns the industry has sought lighter components, realised in the form of high strength polyester (PET) fibre rope [21]. Since polyester is almost weightless in water the rope adopts a straight line not a catenary, providing inherently better station keeping performance, and at a competitive cost. The problem has been what to connect this rather less robust PET component to at each end. At the seabed there is the additional requirement of an anchor system to take vertical load components but at the surface it is necessary to connect to a steel component within some 40 m of the surface. In systems based upon mobile drilling units, converted from more conventional all wire moorings, this is most easily achieved by coupling the PET rope directly to the conventional wire rope. Wire rope may also be employed at the seabed as well, though chain is more common.

The consequence of this is that unless the PET rope has been designed to have similar torsional response to the wire rope, there will be rotation at the interface [22] and fluctuating tension will be combined with fluctuating rotation, and the potential loss of endurance discussed above. The alternative would be the use of a torque balanced wire rope, but such multi-strand ropes, invariably with smaller wires, do not generally exhibit the robustness of conventional six strand ropes and so are not considered suitable for operation at high tensions on relatively small diameter winches.

Mine Hoisting There two different categories of hoisting equipment used for operation in vertical shafts: drum winders and friction (or Koepe) winders. These are illustrated schematically in Figure 4.

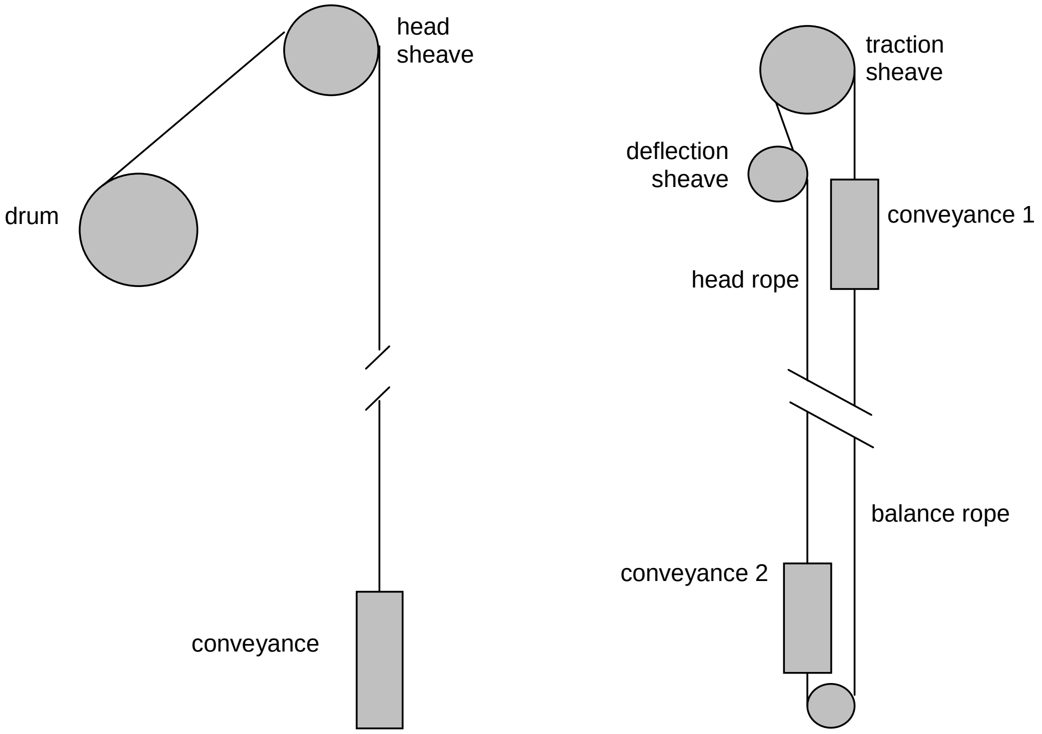

Figure 4: Schematic representation of the two categories of hoisting mechanism with a drum winder (left) and friction winder (right).

As the conveyance is raised the rope on a drum winder is wound onto the drum retaining, almost, the same tension until it is unwound. On a friction winder the head rope passes over the traction sheave, effectively being inverted. Although the high torque on the drum can be offset to some extent by coupling a second drum to the same shaft, with its rope wound in the opposite sense, of the two concepts the overall efficiency of the friction winder is inherently better. However rope considerations render the drum winder more favourable with very deep shafts.

Assuming that the primary fatigue component is the rope tension range, then for the drum winder the range experienced at any point is simply the difference between empty and full conveyance (the payload) with additional components due to acceleration and breaking. For the friction winder the effective inversion of the rope means that the tension range experienced by rope just above the attachment to each conveyance is the payload plus almost the whole rope weight, with additional acceleration components.

For this reason friction winders are not employed for hoisting in very deep shafts. But there are additional considerations. The first concerns the adverse condition of rope resting upon it self in the multilayer winding on the drum, and sliding small differences as the unwinding rope approaches the tangent point. The sliding under the very high local contact stresses results in flattening of the surface wires (called plastic wear) which distorts the local structure and forms surface irregularities from which fatigue cracks initiate, an effect which cannot be easily quantified. The other significant consideration though is the potential rotation of the rope about its axis.

The weight of the suspended rope induces a tension profile from top to bottom of the shaft: rope at the top must support the weight of all below, whilst rope at the bottom has a lighter tension. Considering the static situation of drum winder rope supporting a loaded conveyance at the bottom of the shaft, to obtain equilibrium of rope torque, the rope unlays at the top whilst lay is shortened at the bottom. This state of deformation remains more or less unchanged as the rope is wound onto the drum. Lay lengths fluctuate a little as tensions change, especially when the conveyance is loaded but these are second order effects compared with the static profile of twist.

The position is quite different for a friction winder where the rope is inverted, and so also is the twist associated with achieving equilibrium torque. the position on the rope which just goes across the traction sheave at the tope of the hoist, experience the full twist reversal as well as the high tension range. This combination of cyclic torsion and tension which was described by Macmillan as “torsional fatigue” [23] accounts for the order of magnitude loss of life observed for traditional triangular strand ropes, as shaft depth increased in South African gold mines in the 1960s [24] and. These shorter lives were only overcome in deep shaft friction winders by changing to rope constructions providing a good degree of torque balance [25].

Using Feyer and Schiffner’s model of torsional behaviour [26] with parameters derived from laboratory tests, the effects of depth of hoist on the rotation of triangular strand rope has been estimated and is shown in Figure 5. It is clear that the twist ranges calculated are well above the level at which ordinary lay round strand ropes with IWRC show significant loss of life, but it is reasonable to assume that the combination of fibre core and Lang’s lay construction render the triangular strand rope less susceptible to this combination fatigue mode.

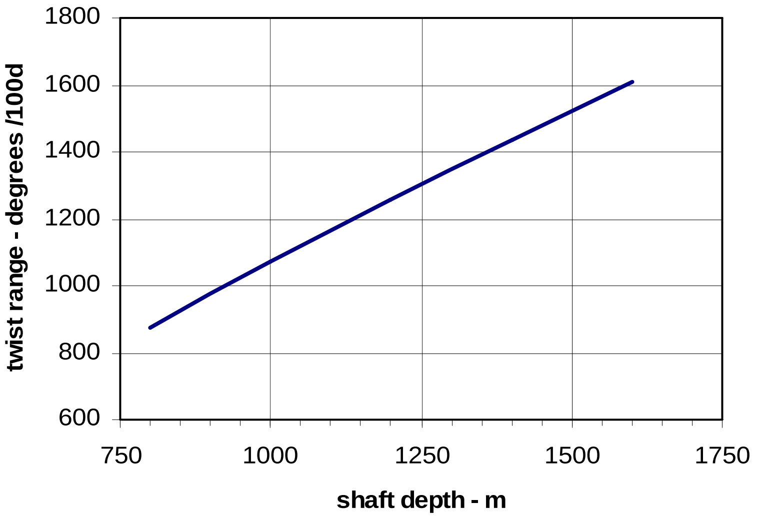

Figure 5: Prediction of twist range in parts of Koepe head ropes close to attachment to the conveyance, but which pass over the driving sheave at the extremity of each wind. An empty 12 tonne conveyance and 44 mm rope are assumed throughout.

Concluding Comments

The fatigue of real wire ropes in real applications is seldom simple and frequently involves combinations of the simple categories of bending-over-sheaves and tension-tension traditionally tested in the laboratory. It is therefore imperative that in trying to understand the degradation mechanisms which prevail in any rope application the interactions between the rope and the overall application are fully understood.

Torsion can become a significant issue, usually associated with tension fluctuations, but may turn out to be a mechanism for enhancing, in some parts of the rope cross section, the effects of tension changes.

An understanding of the mechanisms of rope interactions can inform design changes to obtain life enhancement. So for example the proposal to use synthetic fibre rope as a replacement for steel wire rope on drum winders in deep shafts [27] in addition to failing to recognize that bending-over-sheaves is not the predominant mechanism, also fails to appreciate the way in which rope mass influences fatigue mechanism, and thus rope construction. Since any significant mass reduction would diminish the rope weight related fatigue component in friction winders, then that more efficient hoist system might be used in deeper shafts than previously.

Acknowledgements

Much of what is presented here is a review of previous work some by the Rope Research Group at the University of Reading, the rest by others, but all appropriately referenced. However, as the very productive era of rope research at Reading draws to its close, the author would especially wish to acknowledge the contributions, in the present context, of his colleagues over the years including Andrew Potts, Cesar Del Vecchio, Isabel Ridge, Jill Bradon and Barry Winfield. As regards the new results presented here, special thanks go to John Frew for his meticulous work in attaching miniature strain gauges to individual wires.

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