The analysis of splices used in large synthetic ropes

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Abstract

The analysis of eye splices used in synthetic rope is considered by categorising splice geometries and then developing the modelling for each type. The three splices considered are those commonly used in wire ropes and applied to six round one aramid ropes; the splices are the long or transmission splice, the Admiralty splice and the Liverpool splice. The geometry of each type is analysed and then applied to determine the load capability for each type. The internal friction and contact forces are also discussed.

Introduction

Large synthetic ropes are being widely exploited in many long time structural environments; to be employed, ropes must be terminated and this can be achieved by a variety of mechanisms; their ends can be cast into in epoxy fittings or terminations, they can be gripped or they can be spliced either to another rope or to themselves forming an eye. While some analysis has been conducted on the strength and life of these ropes, little analysis has been done on the splicing of these ropes. This paper describes three splice geometries and introduces the analysis associated with each.

Modern synthetic ropes are varied in construction and in the selection of constituent fibre materials; the assembly geometries consist of the oldest geometry namely twisting of strands around a core axis, of braiding and plaiting of strands, and of layering of groups of strands. The strands can be assumed to be small ropes or subropes, formed by twisting, braiding or plaiting of yarns; also these yarns are so formed from textile or rope yarns that in turn are assembled from the smallest fibre groups. Thus the development of the rope from the basic component is achieved through a hierarchical tree, in which the geometry of construction or assembly is the link between consecutive levels.

The material components used in modern nonmetal ropes are the polymer fibres, as used in a range of textile materials; these material fibres have a range of properties that can be exploited in rope construction, namely strength, stiffness, creep and relaxation endurance, fatigue life, shock and impact resistance, and surface friction for internal energy absorption, fibre abrasion and rope integrity.

Much has been done in recent years on the analysis of rope performance, fatigue within the body of the rope, and internal heating of cyclically loaded ropes. However, the analysis of termination of such ropes by splicing has not been equally developed.

In this paper the analysis of synthetic fibre ropes is briefly reviewed and the internal forces (inter component contact and friction) are discussed. The candidate splices are then described, and the associated analyses are developed. The effects of friction within the splice is considered as indeed without friction the splice would disintegrate; adversely friction is one of the causes of internal heating and abrasion, thus limiting the rope/splice life. The splices considered are:

The long (transmission) splice for twisted structures is achieved by stagger cutting each strand in the standing end and laying in its path a strand from the joining splice end. This is the simplest splice geometry and the analysis for the splice integrity requires an estimate of the contact friction.

The Admiralty splice uses a braid geometry by weaving the strands from the standing end with those of the splice; contact is enforced at the crossover points and friction again ensures that the splice does not disintegrate.

Finally the **Liverpool splice** is achieved by twisting each strand in the standing end with a corresponding strand of the splice; there is a load transference strand to strand along the transition and again the contact forces ensure that there is no splice disintegration.

Review of the Analysis of Synthetic Ropes

The analysis of the static behaviour of synthetic ropes has been achieved using a hierarchical approach[12-16] ; obviously there are many other references that relate to the modelling of rope behaviour but those quoted here are pertinent to the following development. The hierarchical structure is initiated by firstly considering a helical structure in which a single component is wound to form the helix. The component is assumed to have tensile and torsional stiffness where the developed component tension and torsion are each functions of both the component extension and the twist. These stiffnesses are then used to find the tensile and torsional stiffness for the structure and this structure then becomes the component in the next hierarchical level. For definition purposes, the hierarchical levels considered here are baseyarns, ropeyarns, strands and ropes although there are many others, for example subropes, textile yarns and filaments. In the following, the text will refer to baseyarns within a ropeyarn, ropeyarns within a strand or strands within a rope; Figure 1 illustrates this hierarchical structure.

For many ropeyarns within a strand, each is assumed to behave identically to the others and the total effect is simply an accumulation of the identical components. There are some constructions or assemblies where this is not the case and these will be discussed later.

The principle of virtual work has been employed to find the total rope behaviour; in essence it is an energy balance principle where the balance is applied to individual deformations. The direction cosine is the essential link between the levels in the hierarchical tree; the direction cosine relates the direction of the component axis to the direction of the structure axis. It thus connects the structure strain (and twist) to the component strain (and twist) and it also resolves the resulting component force and torque along the structure axis. Thus the emphasis in this paper will be on determining the direction cosines of the components in the splices.

Friction in Synthetic Ropes

Friction in ropes arises from relative slips between components within the rope structure and where there is a contact or bearing force normal to the slip; two categories of friction exist, namely inter, where relative deformation occurs between two contiguous components and intra where relative deformation occurs within a component.

The following slip modes are identified and illustrated in Figure 2:-

a.Mode 1, slip between contiguous yarns and strands in the same layer due to rope stretch and to rope twist. This acts axially along the components, but in opposite directions on opposite contact faces. On the component it will produce a shear or couple whereas on the structure it will oppose the extensional motion.

b.Mode 2, slip in rotation of a strand/yarn in a rope/strand; the torsion developed within the strand is resisted by the friction torque at the end of the strand. This action opposes the unwinding of a twisted strand from its end. The degree of slip is length dependent since the friction(torque) developed is proportional to the strand length.

c.Mode 3, scissoring where the relative angle between crossing strands changes, due to rope stretch and is most applicable in braided/plaited ropes, rope flexure and in splices.

d.Mode 4, sawing due to the action of one yarn over another as they slide due to rope stretch. This is not significant in geometry preserving deformations but since it results from flexure and since geometry preserving deformations are accompanied by flexure at the component level, it is present.

e.Mode 5, dilation, occurring as a result of change in area of a strand as it is stretched in the helix and bears against contiguous strands.

f.Mode 6, distortion, due to a change in strand shape as it is squashed towards the final wedge geometry.

These deformation modes can be classified into **Inter** modes (1 to 4) since these act between components and **Intra** (modes 5 and 6) since they act within a component.

Modes 1 is most dominant for twisted structured rope loading and for the estimation of hysteresis losses induced; mode 2 acts at a rope termination, break or join, or in the development of a splice. Mode 3 is probably the next most important but only for braided/plaited ropes and mode 4 is very important in rope flexure. None of these modes can account for the set induced in ropes due to repeated loading because when the load is removed, the contact forces are zeroed and the rope returns to its original length. The modes 5 and 6 could account in part for this set since dilation and distortion could result from near zero loads. Mode 6, distortion is probably most significant since area changes are relatively smaller than those incurred in changing from cylinder shapes to wedges.

Contact force

The friction force is given by the friction coefficient x contact force, and this latter force (expressed in N/m) will depend upon direction of the contact action; for circumferential contact, between components in the same layer,

$$\text{Contact Force} = \frac{4n\pi(p+t)^2 r}{(1+\epsilon)\sqrt{1+(2\pi pr)^2}} \times \text{Component Tension}$$

where p is the pitch (turns/m) of the component about the structure , r is the helix radius, t is the increased twist of the structure, ϵ is the extension of the structure, and n is the number of components in a layer.

For contact between components in contiguous layers, the contact force is radial and there is no slip, and is given by the following,

$$\text{Contact Force} = \frac{4\pi(p+t)^2 r}{(1+\epsilon)\sqrt{1+\left(\frac{2\pi(p+t)r}{1+\epsilon}\right)^2}} \times \text{Component Tension}$$

Splice Types

Splices are used for joining two ropes and for closing the eye of a loop; both configurations are similar the eye being ‘half’ the join. Three splice configurations are considered here, and are illustrated on a six round one rope, that is the rope has a core subrope component, and around this are wound six subropes with a specific pitch. The first splice is the long splice, the second and most significant is the Admiralty splice, sometimes called the locktuck splice and the third is the Liverpool splice. These splices will be considered separately as their actions are quite different. However, all use an existing rope, since both in real life and in modelling the splice can only be achieved on a rope structure; consequently the analysis and modelling will assume the existence of a rope model and all its hierarchical components.

During splicing, whether it be a rope join or an eye formation, the first level of hierarchical structure is reformed into the splice using the second and other levels. The modelling thus assumes the subrope/strand/yarn components and re-establishes the rope (now called splice) using these levels. The assumption that has been dominant and that must still be employed is that the structure is geometrically preserving at least locally. It is recognised that whereas in a rope it can be assumed that all stations are repeated identically along the rope although they may be subject to rigid body rotation, in a splice there are different geometries along the development of the splice. However, locally, that is at any axial station in the splice, the deformation is assumed to be geometry preserving, so that points in contact remain in contact. This is quite reasonable in the middle splice but at the end of the splice there will be slip.

The splice

The splicing of these specific ropes is described in two parts; first the core is considered, this being common for the three splices considered and second the detail for splicing the outer subropes by the long (transmission), the Admiralty and the Liverpool splices. In order to describe the geometry of the splices, the following notation is used. The components from the rope are labelled R and those from the splice are S.

The core

Since the rope being considered here is a six round one structure the first point to be considered is the core subrope; for this work the core is assumed to be laid along itself as shown in Figure 3 and the detail is shown in Figure 4. Although there are migrating strands that entrap the incoming S subrope (from the splice) the main mechanism for keeping the two subropes together is friction. The important contribution to this is the contact force initiated by the entrapping strands from the rope R subrope and reinforced by the action of the outer layer on the core. A simplified but adequate theory for this friction splice is developed in the following section on the long splice.

At the crotch of the splice, both subropes are subject to the same load; as the station is advanced to the end of the splice zone, the splice S subrope sheds its load to the rope subrope and at the end of the splice, it carries zero load. Mirroring the structure about the splice crotch generates the splice for joining similar ropes; this is repeated for all the described splices, the eye splice being 'half' the splice for joining two ropes.

The Long (transmission) splice

The subropes in the outer layer from the splice are stagger laid in the spaces that were occupied by those from the rope, Figure 5; each splice S subrope starts at the splice with its full load and sheds this as the station moves to the end of the splice subrope; the subrope is nominally held in place by a fastening ring or collar and is subject to a circumferential contact force from its neighbours. The contact force is responsible for the transmission by friction of subrope axial load.

At the station when the splice S subrope is introduced to the rope, the rope load is shared by n-1 rope R subropes; to sustain this (maximum) rope/splice load, the splice S subrope must achieve maximum load before the next subrope is introduced. The advantage of this splice is that there is no size increase of the splice over the rope size, enabling the splice to be used over pulleys.

Analysis of the long splice

In this splice the S subropes are laid in the place of other R subropes Figure 6. The S subrope that is inserted has zero tension at its end but this is increased by friction contact with the neighbouring subropes until it has the same nominal load as the other subropes at the splice crotch.

The simplest configuration considered is the lap, where the S subrope is in edge contact with both neighbouring R subropes. Define the origin as that position on the S subrope at which it be fully loaded; let x_r be the distance from this station along the R subrope when not loaded and x_s be the corresponding distance for the S subrope. The load carried by the S subrope when fully loaded is P_o, the same load as carried by each R subrope; at the splice the tension in the R subropes has increased to P. The contact force/length is p and the friction coefficient is μ. The stretch of the subropes under load is u(x). The strain in the components is ϵ, and the stress (based on area) is σ. Then it follows that

$$\epsilon_r = \frac{du_r}{dx_r} = \frac{\sigma_r}{E} = \frac{P_0}{EA} + \frac{\mu}{EA}\int_0^{x_r} p(x)$$

$$l\ \epsilon_s = \frac{du_s}{dx_s} = \frac{\sigma_s}{E} = \frac{P_0}{EA} - \frac{2\mu}{EA}\int_0^{x_s} p(x)$$

The end of the S subropes are stress free and the R subropes carry full load P; the distance L along the S subrope end to the fully shared station where the S subrope carries the same as the contacting R subropes is $x_r + u_r(x_r)$ along the R subrope and $x_s + u_s(x_s)$ along the S subrope.

It thus follows that

$$P = P_0 + \mu\, \overline{p_r}\, x_r$$

$$\text{and } 0 = P_0 - 2\mu\, \overline{p_s}\, x_s$$

for the R and S subropes respectively and where the average contact forces/unit length are defined,

$$\overline{p_r} = \frac{\int_0^{x_r} p_r(x)\,dx}{x_r}$$

$$\text{and } \overline{p_s} = \frac{\int_0^{x_s} p_s(x)\,dx}{x_s}$$

and are assumed constant.

The length of the S subrope to fully established loading is $L = x_r + u_r(x_r) = x_s + u_s(x_s)$ or

$$L = \left(\frac{P_0}{EA} + 1\right) x_r + \frac{\mu}{2EA}\overline{p_r}\, x_r^2$$

$$= \left(\frac{P_0}{EA} + 1\right) x_s - \frac{\mu}{2EA}\overline{p_s}\, x_s^2$$

The lengths x_r and x_s that are required for the full load P_o to be developed in the S subrope are

$$x_r\,\overline{p_r} = \frac{P - P_0}{\mu}$$

$$\text{and } x_s\,\overline{p_s} = \frac{P_0}{2\mu};$$

The distance x_s thus defines the minimum length required for each S subrope to be integrated in the splice and the total minimum splice length would be the accumulation of this value for each S subrope. The maximum splice load is thus defined by the number of active R subropes (which is one less than the total R subropes) times the maximum working subrope load and the maximum splice efficiency for the n outer subropes is thus 1-1/n.

In a 6 round 1 rope, a contact force of 10kN/m, a subrope load of 30kN and a friction coefficient $\mu = 0.5$, the minimum x_s for load development is 3m; since there are six outer subropes to be spliced in the total length for complete load development would be about 18m. In order to reduce this length the contact force can be increased by substantive binding, and/or the friction coefficient increased by surface treatment. It is well known that this type of splice whilst geometrically optimum, with no accompanying increase in diameter, is inefficient in the load/strength sense, typically quoted as 85 to 90% or less.

This is because the distance required for the subrope to reach full load is large, and depends on the friction coefficient and the tightness of the twist (pitch).

Various references give rules for the splice length for the long splice; these are summarised

Reference	Rope type/dimension	Splice length
Air Cadets of Canada, (1941)	d diameter	$7\pi d$
Davis, P. and Van der Water, M. (1946)	13mm diameter	1.5m
Day, C. (1953)		20 turns
Cordage Group, (1977)	synthetic rope	35-40 turns
	20mm diameter	5m
	50mm diameter	13m
Klust, G. (1983)	d diameter	50d
Jarman, C. (1984)		16 turns

Because of the loss in load capacity in using a long splice and of the splice length required, the Admiralty or Liverpool splices are preferred.

The Admiralty Splice

The geometry of the Admiralty splice is shown in Figure 7, and in detail in Figure 8; the rope is at the bottom and the splice is evolved by progressing up the figure. Shown shaded at the bottom is a R subrope and this is twisted in the clockwise (Z) sense about the axis of the rope and progressing into the splice; as it encounters the splice S subropes, it is woven over and under these in succession developing a braided structure, in this case a twelve component braid. The S subropes come from the top in a anticlockwise (S) sense and a typical component is shown shaded.

Also indicated in this figure is the tapering of these S subropes as they progress to the rope end of the splice; this is a common practice as near the start of the splice they have not acquired their full load and consequently they do not need their full size. It is also a geometrical sensible design as it allows the rope size to grow gradually to the full splice size, which now contains twice the components initially in the rope. The encounter of a R subrope with the S subropes is called a tuck, and the usual number of tucks in the Admiralty splice is about 4-5 for each R subrope.

The geometry developed in the Admiralty splice (locktuck) transforms a twisted (rope) structure into a braided structure. In the zone where the subropes enter the splice, those leaving the rope carry 1/n (n = 6 for six round one) of the total rope load whereas those from the crotch are unloaded. However they disturb significantly the rope geometry. Moving towards the splice those subropes from the rope shed some of their load to those from the splice; the transference is not subrope to subrope but rope to splice since each subrope from the splice meets through the braid many of those from the rope. When the load transference is complete in the zone of the splice, each subrope contributes equally (1/2n) to the rope/splice load and at this point it is a conventional braid structure. Friction due to strands passing over and under each other is the main mechanism of load transference (mode 4,sawing). There is scissoring (mode 3) but this results in fatigue and not load transference. Since the contacts are discrete, the rate of load transference is the result of the contact force at each contact and the number of these contacts.

The path geometry is shown in Figure 9 and shows the R subropes moving in a clockwise direction around the rope/splice core and the S subropes (shaded) moving in an anticlockwise direction as the station moves from the rope into the splice. For all stations along the splice it is assumed that the geometry is the same, although the effect of tapering the S subropes could be included.

Analysis of the Admiralty Splice

If r_{min} and r_{max} are the minimum and maximum radius of the subrope as it moves around the splice axis, the mean radius r_m and radial travel Δr are given

$$r_m = (r_{min} + r_{max})/2$$

$$and\ \Delta r = (r_{max} - r_{min})$$

These two quantities cannot be specified yet but will be determined from the other geometrical quantities including the splice pitch L_o and number of subropes in the rope. The path can be estimated using the following assumed equation.

$$r = r_m + \frac{\Delta r}{2}\sin(n\psi)$$

where r is the radial position of the subrope and ψ is its angular position and n is the number of rope subropes. The subropes coming from the eye move in the opposite direction and out of phase with these. The rate of change of angular position with the axial station (dψ/dz) cannot be assumed constant here, whereas in the rope it has been justifiably assumed constant.

The direction cosine assumption

Referring to Figure 8 at the crotch, and consider an axial load on the structure. For an established splice, at *any* station all the subropes from the rope and eye are at the *same* ($\pm$) angle to the axis, those from the eye at positive angle and those from the rope at the same but negative angle. Thus in the established part of the splice they all equally contribute to the splice load. Now consider a neighbouring station; the splice load is the same and again the subropes contribute to the same load. Since in the developed region the subrope load does not vary and since then the component of subrope load along the splice axis must be the same, then the angle made by any strand with the splice axis must be constant. This angle, the direction cosine of the subrope is thus constant throughout the established splice. If s is the distance along a subrope and z is the distance along the splice, then the direction cosine is

$$\cos\theta = \frac{dz}{ds}$$

and

$$\frac{ds}{dz} = \sqrt{1 + \frac{dx}{dz}^2 + \frac{dy}{dz}^2}$$

or

$$\frac{ds}{dz} = \sqrt{1 + \frac{d\psi}{dz}^2\left(\frac{dr}{d\psi}^2 + r^2\right)}$$

Since ds/dz is constant, then

$$\frac{d\psi}{dz} = \frac{C}{\sqrt{\frac{dr}{d\psi}^2 + \psi^2}}$$

where C is a constant; thus

$$C\int_0^L dz = \int_0^{\Psi}\sqrt{\frac{dr}{d\psi}^2 + \psi^2}\, d\psi$$

where

$$\frac{dr}{d\psi} = \frac{n\Delta r}{2}\cos(n\psi)$$

Over one pitch, $\Psi = 2\pi$ and $L = 1/p$ where p is the pitch (tpm) and hence

$$CL = \int_0^{2\pi}\sqrt{\frac{dr}{d\psi}^2 + \psi^2}\, d\psi$$

At this point r_m and Δr and hence C are unknown; if the direction cosine were known then from the packing of the subrope the helix radius of the subrope at various points could be determined. The direction cosine, $\cos\theta$ is given from above

$$\cos\theta = \frac{dz}{ds} = \frac{1}{\sqrt{1 + C^2}}$$

and must be determined from iteration; the procedure first assumes a direction cosine or an average direction which yields the maximum and minimum radial position (r_{max} and r_{min}) of the subropes; this then enables the calculation of the constant C and this gives an estimate of ds/dz, an improved value for the direction cosine. The estimation of the subrope radial positions and the direction cosines depends upon the type of assembly; assumptions relating to the structure of the component subropes arising from the softness and hardness of the subropes assumptions result in different assembly algorithms; in each case the maximum and minimum radial points lead to the mean radius r_m and the radial travel Δr.

The Liverpool Splice

The geometry of the Liverpool splice is shown in Figure 10, and in detail in Figure 11; the rope is at the bottom and the splice is evolved by progressing up the figure. Shown shaded from the bottom is a R subrope and this is twisted in the clockwise (Z) sense about the axis of the rope and progressing into the splice. As it encounters the splice S subropes, it is twisted against it's own S subrope, in the S direction to form a two component twisted 'strand' so that the twist of the R-S subrope assembly is in the opposite direction to the direction that the 'strand' twists about the rope/splice core. Again it is usual to taper the S subropes to minimum size at the rope end of the splice.

The path geometry is shown in Figure 12; here a pair of S and R subropes are shown moving as a unit in the clockwise direction around the rope/splice core. However within this migration the 'Strand' is seen to rotate in the anticlockwise direction. Within a hierarchical scheme, the subropes are the second level of the rope hierarchy; in the Liverpool splice they are the third level, the second level being the twisted two strand assembly, and this assembly is different at various stations. Figure 13 shows this intermediate hierarchical structure that lies between the splice and subrope.

The Liverpool splice implies a load transference subrope to subrope. It is not a simple twisted structure; the subrope leaving the uniform part of the rope will carry 1/n of the rope load, where n is the number of subropes. At this point it meets the subrope from the splice and since this splice subrope is essentially under zero load, the rope subrope will follow a simple helix and the splice subrope will follow a double helix path. Towards the splice the rope subrope will shed load to the splice subrope, and since the splice subrope is picking up load the its path will no longer be the double helix and the rope subrope will develop into a secondary helix. At some point in the vicinity of the splice both subropes contribute equally and here the two subropes form a two component twisted 'strand'. Load transference is by friction (mode 1) between the two strands.

Analysis of the Liverpool Splice

The detail of the construction of the R-S 'strand' is shown in Figure 13; at the crotch both components are equally loaded and at symmetric positions from the 'strand' axis. Moving away from the crotch and towards the rope, the R subrope becomes more loaded and the S subrope sheds load the R subrope moves towards the R-S 'strand' axis and the S subrope moves away; thus the R subrope spirals in to the 'strand' core and the S subrope spirals out.

At any point between the eye and rope in this intermediate structure, the path can be determined by ensuring contact between the rope and S subropes. The helix radius of the S and rope subropes is given as follows

$$r_s = d \sin^2\left(\lambda\psi + \frac{\pi}{4}\right)$$

$$\text{and } r_r = d \cos^2\left(\lambda\psi + \frac{\pi}{4}\right)$$

so that $r_s + r_r = d$;

a) at $\psi = 0$, $r_s = r_r = d/2$,

b) increasing ψ increases r_s and decreases r_r, and

c) when $\psi = \pi/(4\lambda)$, $r_s = d$ and $r_r = 0$.

This is assumed kinematics, where $0 < \lambda\psi < \pi/4$ and λ is given by the pitch of the lock twist; if the pitch of the S subrope wound around the R subrope is p tpm, and L is the length of the lock twist, then

$$\lambda = \frac{\pi}{4\,(2\pi p L)} = \frac{1}{8pL}$$

Again the direction cosine is

$$\frac{ds}{dz} = \sqrt{1 + \frac{d\psi}{dz}^2\left(\frac{dr}{d\psi}^2 + r^2\right)}$$

where ψ is measured from the crotch station.

This gives the direction cosines for the S and rope subropes as a function of the station along thus two component twisted structure,

$$\frac{1}{\cos\theta_s} = \frac{ds}{dz}$$

$$= \sqrt{1 + (2\pi p d \sin\lambda\psi)^2 [4\lambda^2 + (1 - 4\lambda^2) \sin^2\lambda\psi]}$$

for the S subropes coming from the crotch and

$$\frac{1}{\cos\theta_r} = \frac{ds}{dz}$$

$$= \sqrt{1 + (2\pi p d \cos\lambda\psi)^2 [4\lambda^2 + (1 - 4\lambda^2) \cos^2\lambda\psi]}$$

for those from the rope; ψ is measured from the eye station, and is in the range

$\pi/4 < \lambda\psi < \pi/2$. This gives the direction cosine of the two tuck subropes and from these the strains can be determined, then the stress or subrope loads and ultimately the load of the double subrope.

Splice Results

The results shown following are superficial in that they only illustrate the operation of the above theory; they are only shown for the Admiralty splice applied to a six round one Kevlar rope, nominal diameter 25mm, breaking load 493kN at 0.03 breaking strain. In the first case the splice size and efficiency (splice breaking load/rope breaking load) for various splice geometries (packing factor and pitch). The table shows the best efficiency when the pitch (turns/m) is low and lowest for a high pitch; the splice diameter also is largest for a high pitch, and in general a large splice diameter will accompany an inefficient splice.

Pitch	Packing ratio	Splice diameter (mm)	Peak load (kN)	Strain	efficiency(%)
1	1	33.269	475	0.028	96.3
2	1	33.393	469	0.028	95.1
3	1	33.602	460	0.028	93.3
4	1	33.900	447	0.028	90.7
3	0.8	37.231	456	0.028	92.5
3	0.6	42.664	450	0.028	91.3

Friction in splices

In the long splice, Mode 1 friction acts and is indeed the mechanism for sustaining the splice integrity. In the Admiralty splice the main friction mode is scissoring, Mode 3; to evaluate this, the change in braid angle is estimated and together with the contact pressure it is assumed that the scissor torque = friction coefficient x contact pressure. For the Liverpool splice, the friction modes 1 will be active between the twisted structures, this being the axial slip modes. Mode 3 (scissoring) also acts within the two component ‘strand’ as the two touching components change their intact angle. Mode 2 friction acts at the end of the S subropes in all these splices.

The following table shows the effect of friction when the rope is cyclically strained (0.005 to 0.015); it can be seen that the effect of friction on peak load is insignificant but it is important in the work done over the cycle, this work resulting in heating of the splice and local abrasion and wear.

Friction coefficient	modes	location	Peak Load (kN)	Contact Force (kN)	Work Done (J/m)
0.5	local	rope end	221	0.77	0.3
1.0	local	rope end	222	0.77	12.9
0.5	local	crotch	401	0.77	0.6
1.0	local	crotch	403	0.77	22.8
0.1	global	rope end	222	0.77	12.4
0.1	global	crotch	403	0.77	21.8
1.0	global	rope end	231	0.80	123.7

The local mode (of friction) is scissoring only in the splice between contacting subropes, Mode 3, whereas global modes also account for friction between ropeyarns and textile yarns, Mode 1.

Conclusion

The mechanics of three splices are considered and the associated geometries for the interfacing subrope components are developed. The consequence of friction and the various modes in which it acts is discussed. Some results are shown, the scope of these being curtailed since they are more system specific rather than mechanically important. The accuracy in modelling rope behaviour for load extension is very high for well defined constructions and uniformly selected components. The effect of friction is speculative since the friction theory for advancing contact of contiguous yarn or strand components is not developed; the friction coefficient, assuming Coulomb friction has to be measured for all components and modes within a rope structure. The best that can be done is to establish a qualitative effect and to measure the consequence by the energy loss in a load cycle.

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