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FAILURE MECHANISMS

History of Tension Members and their Behaviour

Historique des membrures tendues et leur comportement

Die Geschichte der Zugglieder und deren Verhalten

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SUMMARY
The restrospective of the historical development and the respective ascertainability of the behaviour of the tension elements includes all important constructive details of a tension element, its manufacture and all available fittings as we use today. The first industrial revolution initiated a great number of inventions and technical developments, especially in the field of steel-wire-manufacture and tension-element-construction. Already 150 years ago cables and bundles have been used in the construction of large bridges. It is explained in which way people became aware of the bending stiffness, the friction, the loadbearing capacity and the axial stiffness and how they started to determine this data.

RÉSUMÉ
La rétrospective sur l'historique du développement des membrures tendues et la saisie des comportements correspondants contient tous les détails constructifs essentiels de ces éléments tendus, ceux de leur fabrication et de leurs ferrures possibles, telles que nous les utilisons de nos jours. La première révolution industrielle débuta par un grand nombre d'inventions et de mises au point techniques, tout particulièrement dans le secteur de la fabrication des fils métalliques et de la construction des membrures tendues. Raison pour laquelle on utilisa, il y a déjà 150 ans, des câbles et des faisceaux en fils d'acier pour édifier les ponts de grande portée. L'auteur montre comment les hommes furent confrontés aux différents phénomènes que sont la rigidité à la flexion, le frottement, la charge limite et la raideur élastique, et comment ils essayèrent d'en déterminer les valeurs.

ZUSAMMENFASSUNG
Der Rückblick auf die historische Entwicklung und die jeweilige Erfaßbarkeit des Verhaltens der Zugglieder enthält alle wichtigen konstruktiven Einzelheiten eines Zuggliedes, seiner Herstellung und den möglichen Beschlägen, wie wir sie heute benutzen. Die erste industrielle Revolution bedeutete einen starken Anstoß für eine große Zahl von Erfindungen und technischen Entwicklungen, besonders im Bereich der Eisendrahtherstellung und der Zuggliedkonstruktion. Deshalb wurden Seile und Bündel aus Stahldrähten schon vor über 150 Jahren im Großbrückenbau eingesetzt. Ausfürhrlich wird dargestellt, wie die Menschen auf die Biegesteifigkeit, die Reibung, die Traglast und die Dehnsteifigkeit stießen und wie sie dieselben zu ermitteln versuchten.

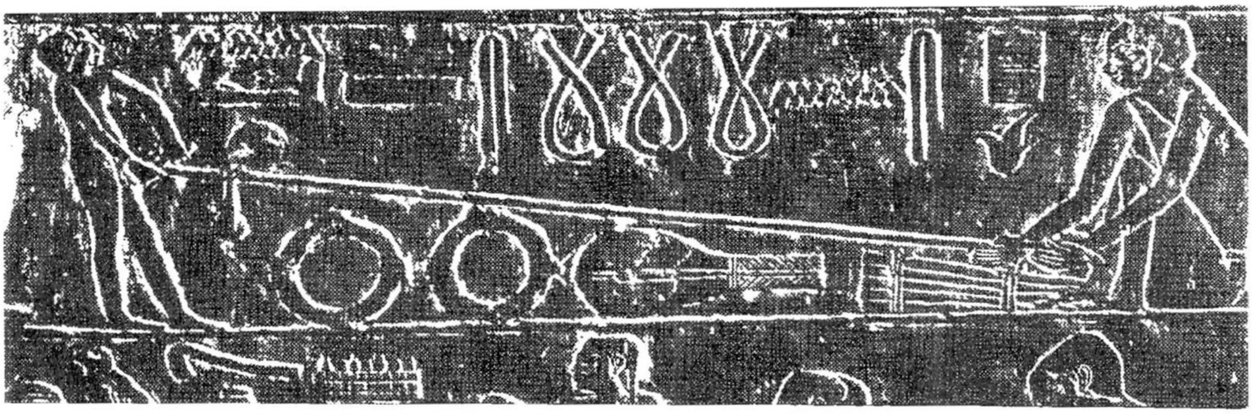


Fig. 1 Papyrus ropery shown on a Egyptian half-relief [1]

INTRODUCTION

The manufacture and the use of ropes is an ancient skill.Half-reliefs found in Egyptian burial chambers show also a ropery (Fig. 1) [1], and already on Assyrian reliefs, exhibited in the British Museum today, cable-stayed tents can be clearly seen. The cables were made out of natural fibres which had to be pre-processed (Fig. 2) [1].

Ancient records and pictures tell us that even in early history there was a great number of various applications of cables, for example
- the lifting- and mining techinque used in the construction of temples or in mines [2]
- in shipbuilding with rigging and loading harnisses [3]
- the sun-protection used in tents, velas, sails and parasols [3] [4]
- in warfare in the case of naval bridges, palisades tied together, tents and catapults [5].

Whereas the Egyptians 3000 years B.C. used leather strips as well as papyrus as a natural fibre to make cables, the Phoenicians used flax, as described by Herodot in Book VII (34 and 37) in connection with Xerxes' army's crossing the Hellespont 480 B.C. In India jute was initially used while the Chinese applied hemp very early on.

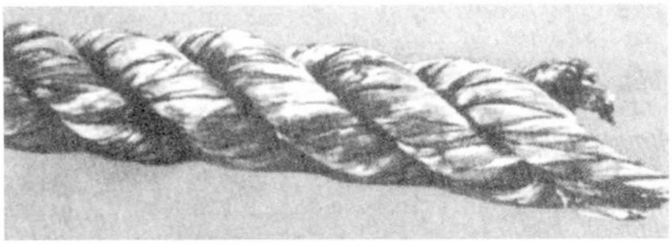


Fig. 2 Early Egyptian papyrus rope, 3 strands with 8-9 threads per strand (about 2900 B.C.), discovered in Sakkara [1]

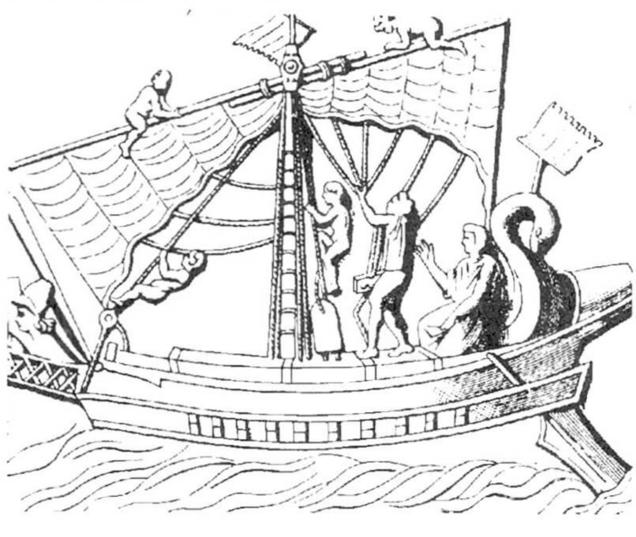


Fig. 3 Relief from Naevoleia Tyche's grave in Pompeji [3]

ROPES RUNNING ACROSS SHEAVES (FRICTION RESISTANCE)

The manufacture of cables did not change very much in the Middle Ages and even the areas of application remained the same. In construction domes and cathedrals required a profound hoisting-/handling- and lifting technique, as did the ever progressing mining industry. But construction was considered an artform heavily favoured by the church whereas mining was subject to purely economical rules. Other natural fibres such as sisal or cotton were discovered and used later. Well-known mechanics and engineers who developped machines by using cables are for example Archimedes of Syracuse (287-212 B.C.) for the defense of Syracuse against the Romans, Fillippo Bruneleschi (1377-1446) for the construction of the dome over Santa Maria del Fiore in Florence and Leonardo da Vinci (1452-1519) for hoisting bronze statues in Milan. They all were familiar with the pulley block, and it was possible to lift heavy loads.

During the Middle Ages people were searching for the "perpetuum mobile", even Claude Perrault (1613-1688) in Paris believed in it when using rolling wheels on the inclined plane and frictionless cable sheaves (Fig. 4). The electoral-palatinate engineer and master builder Salomon de Caus (1576-1630) reports about these frictionless machines without comment [6], while the saxon mathematician and mechanic Jacob Leupold (1674-1727) still shows Perrault's machines in [7] (Fig. 4) but already discussed intensly the influence of friction in [8], which was paid special attention to in 1687 by the French Pierre Varignon (1654-1722) [9]. Guilleaume Amontons (1663-1705), a French, educated clergyman from Paris, dealt not only with sliding and rolling friction [10], but also with friction occuring when cables run over a sheave, as for example in the case of a pulley block or Perrault's machines without "Friktion". In tests with a cable entering a sheave (Fig. 5) Amontons discovered that the resistance force Δ F depends on the cable diameter d, the force F effective in the cable and on the sheave-diameter 2R. In his acknowledged book "Architecture Hydraulique"

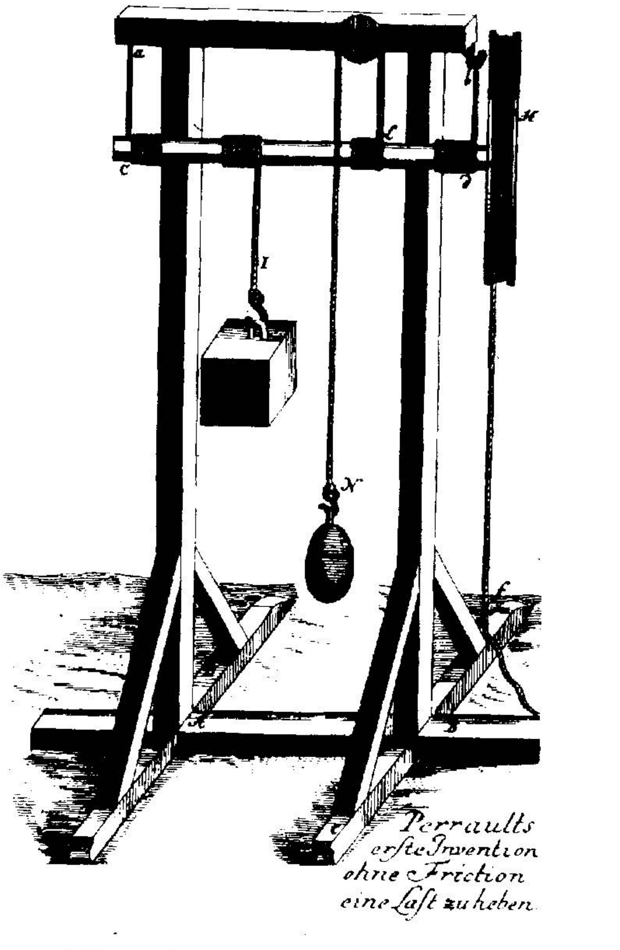
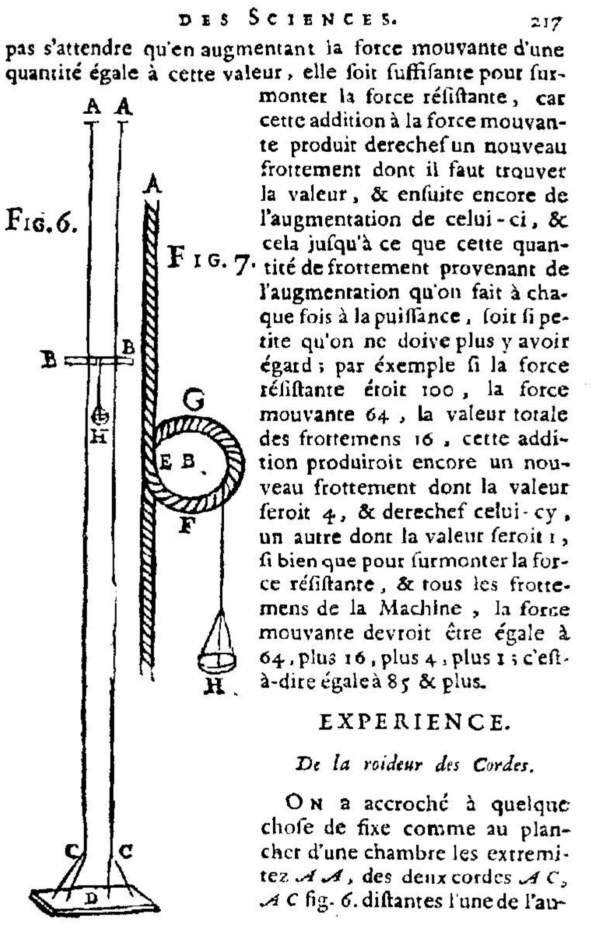


Fig. 4 Perrault's first invention to hoist a load [7] without friction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pas s'attendre qu'en augmentant la force mouvante d'une quantité égale à cette valeur, elle soit suffisante pour surmonter la force résistante, car cette addition à la force mouvante produit derechef un nouveau frottement dont il faut trouver la valeur, & ensuite encore de l'augmentation de celui-ci, & cela jusqu'à ce que cette quantité de frottement provenant de l'augmentation qu'on fait à chaque fois à la puissance, soit si petite qu'on ne doive plus y avoir égard; par éxemple si la force résistante étoit 100, la force mouvante 64, la valeur totale des frottemens 16, cette addition produiroit encore un nouveau frottement dont la valeur seroit 4, & derechef celui-cy, un autre dont la valeur seroit 1, si bien que pour surmonter la force résistante, & tous les frottemens de la Machine, la force mouvante devroit être égale à 64, plus 16, plus 4, plus 1; c'est-à-dire égale à 85 & plus.

EXPERIENCE.

De la roideur des Cordes.

On a accroché à quelque chose de fixe comme au plancher d'une chambre les extremitez A A, des deux cordes A C, A C fig. 6. distantes l'une de l'au-

Fig. 5 Sketches by Amontons to determine the friction resistance of the cables running across sheaves (1699) [10]

[11] Bernard Forest de Belidor (1697-1761) adopts Amontons' ideas, but only John Theophilus Desguillers (1683-1744), Newton's scholar, seriously contradicts Perrault's ideas of the "perpetuum mobile" using cables [12] and firmly states the additional force occuring per sheave in winches with cables made out of natural fibres as follows:

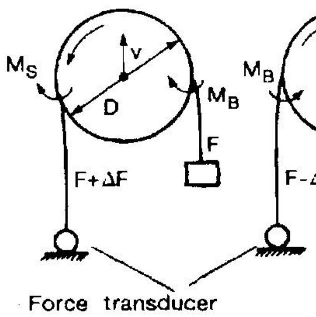
$$\Delta F = 0{,}3125 \cdot \frac{F_c \cdot d_c}{2R_s} \qquad \text{(Eq. 1)}$$

F_c: cable force
d_c: cord or cable diameter
R_s: radius of the sheave

A great number of people dealt with the additional force Δ F occuring when a cable enters a sheave (they called it resistance). In 1781 Charles Auguste de Coulomb conducted his own test with natural-fibre-cables, which are often referred to by his successors because these tests are well documented [13], and he derived the following equation in a purely mathematical way with the

$$\Delta F = \frac{(0{,}5 \cdot d_c)^m}{R_s} (a + b \cdot F_c) \qquad \text{(Eq. 2)}$$

with the constants a, b and m, which in turn could be determined with the results from his test series. Gaspard François Clair Marie Riche de Prony (1755-1839) [14], Johann Albert Eytelwein (1764-1848) [15] and Claude Louis Marie Henri Navier (1785-1836), who in 1819 published a heavily edited version of [11], tried to improve Coulomb's equation for the determination of Δ F. Even Julius Ludwig Weisbach (1806-1871) [28], Ferdinand Redtenbacher (1809-1863) [27] and Franz Grashof (1826-1893) [29] still dealt with the additional force, as clearly shown by M. Rühlmann [30]; but all of them only tried to find the simplest equation possible. The latest research [64] proves that Coulomb was already very close to the exact determination of Δ F (Fig. 6).



$$\Delta F = \frac{1}{R_S} (M_B + M_S)$$

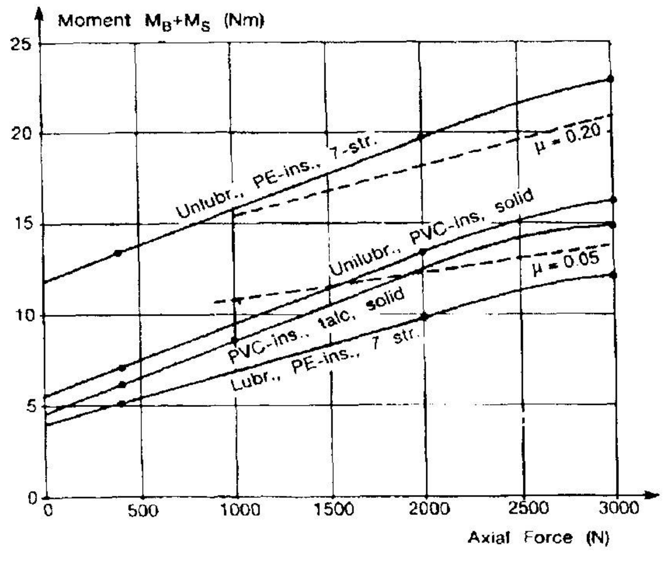


Fig. 6 Representation of the resistance of lubricated and unlubricated cables depending on the axial force in the cables [64] while running across a sheave

EARLY CABLES MADE OUT OF IRON WIRES

The beginning of the industrial revolution, the increasing production of steel-wire (Fig. 7) and the rising demand for tension elements with greater load bearing capacity and durability laid the basis for the fast spread of the first inventions of the wire-cable and the rapid development in this area.

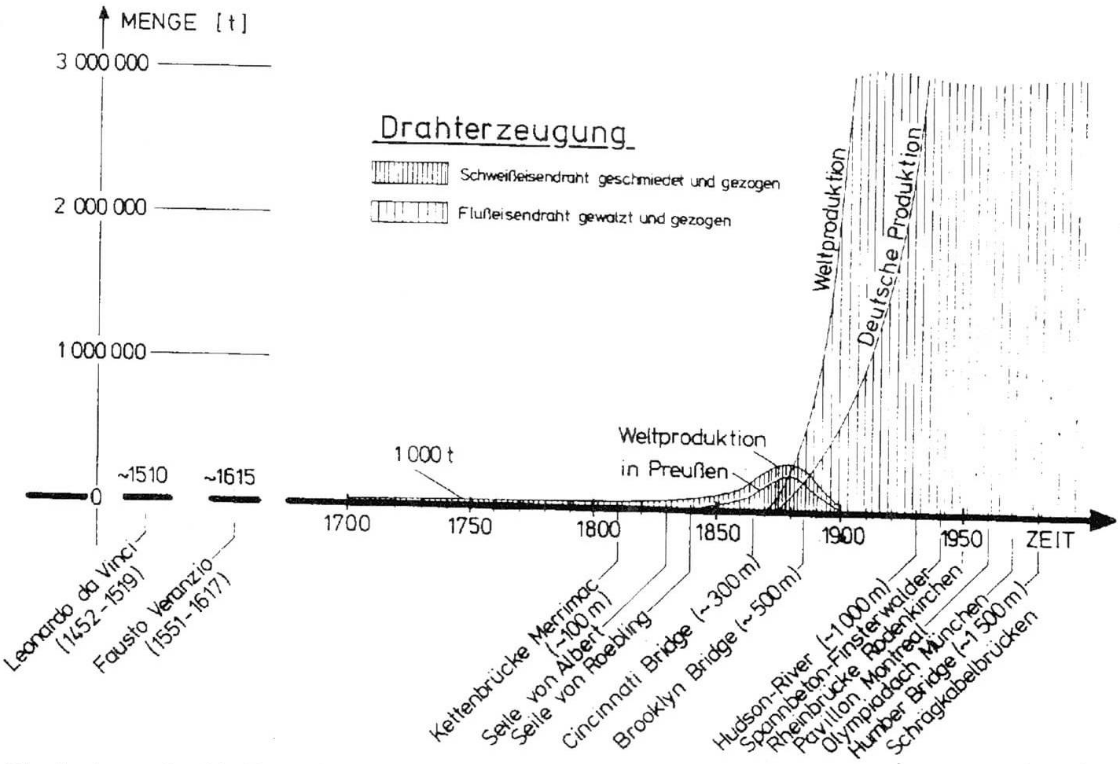


Fig. 7 Steel-wire-output in Prussia resp. Germany and world-wide (forged iron and ingot iron)

Essentially steel-wires were used in the following areas:
- hoisting equipment in mining,
- in the course of channel shipping with inclined planes,
- in bridge construction for road vehicles,
- tending the fields (steam plough) and
- hoisting equipment for the iron processing industry.

In the beginning of the steel wire rope, the most successful "engineers" were:
- Wilhelm August Julius Albert (1787-1846) a Royal Britannic Hanovarian Mining Councilor in the Upper Harz. In 1834 he used a tension element manufactured out of wires for the first time for mining [16] (Fig. 8);
- Marc Seguin (1786-1875) in Annonay, Dep. Ardéche (South of Lyon) and Guillaume-Henri Dufour (1787-1875) in Geneva. In 1822 they were the first to develop and apply cables out of parallel wires and fibre-cable-knot-type fittings used in pedestrian- and road-bridges [18] (Fig. 9 and 10);
- Johann August Roebling (1806-1869). In 1831, after completing his education at Prussian schools, he emigrated to the United States where, while working as an engineer in channel- and bridge-construction, he developped various wire-constructions [19], the round stranded cable in 1842 [20] (Fig. 11) as well as the parallel wire bundle manufacutured by spinning and used as supporting cable in wide-span suspension-bridges [21], [22] (Fig. 12). There were several inventors, as for example the Englishman Andrew Smith, who in the meantime further developped Albert's construction, but none of them was so successful.

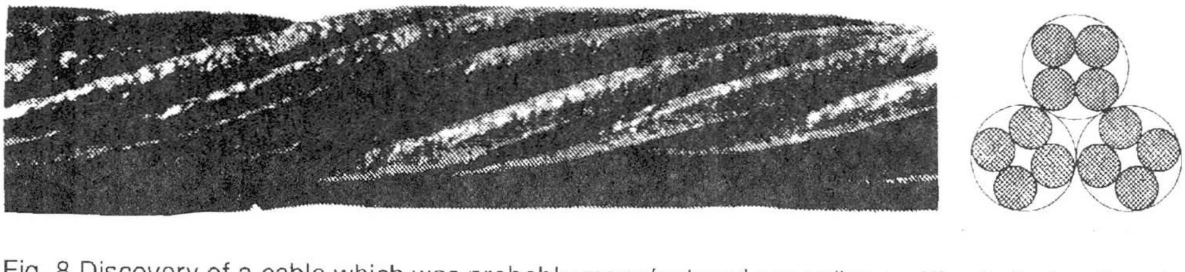


Fig. 8 Discovery of a cable which was probably manufactured according to Albert's instructions in the Harz Mountains (1834) [17]

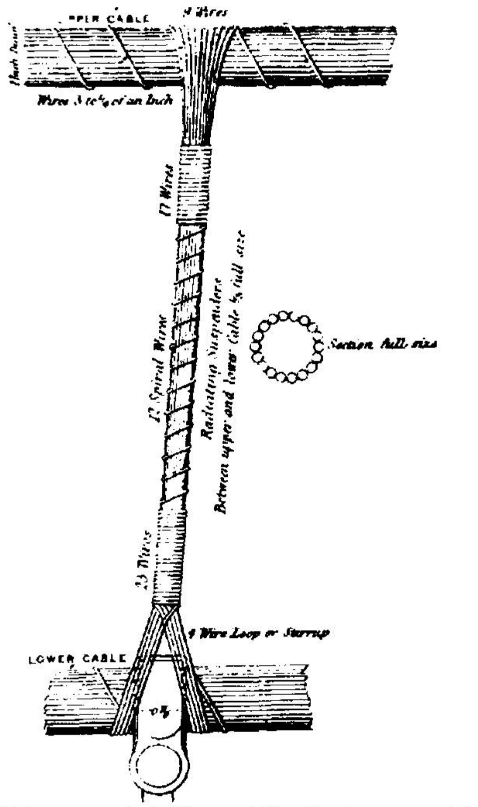


Fig. 10 Hanger-detailing of the first wire-cable-bridges by G.H. Dufour, Geneva (1822) [19]

Fig. 9 Wire knot according to Marc Seguin (approx. 1820) Annonay [18]

Fig. 11 Roebling's first round stranded cable with 7 x 19 regular lay and a diameter of approx. 30 mm, Saxonbourg, Pa. (1842) [21

Well-known poineers of rope-manufacturing were:
- Roebling, Trenton, New Jersey, U.S.A.
- Hazard & White, Philadelphia, Pennsilvania, U.S.A.
- Felten & Guilleaume, Cologne, Prussia
- Binkes & Smith, Grimsby, England

CABLES RUNNING ACROSS SHEAVES (WIRE-STRESS)

With the development going towards the wire-cable, efforts to determine the power-loss in the cable became less pressing, because the ratio of $\Delta F/F$ is a lot smaller in the case of the more balanced wire-cable than that of the natural-fibre-cable. Redtenbacher [27] claimed this already and Hecker [36] later proved it ($\Delta F = 0.015 F$). Instead the necessity of the stress-determination became predominant, since local stress treatment being the major influence on the lifetime of a running cable, it had to be determinable. In continuous operation-tests with chains Albert [17] already came across the phenomena of material fatigue before he discovered the wire-cable. During the 50s and 60s of the past century, the poineering work of August Wöhler (1819-1914) [23], [24] necessitated a pre-determination of the stress-changes in the running cable.

During the 1850s Franz von Reuleaux (1829-1905), while living in Bonn and being closely connected to Felten & Guilleaume, Cologne, established the stress in a wire of a cable entering a sheave [25] to

$$s = \sigma_B = \frac{\delta}{2 \cdot R_s} \cdot E \qquad \text{(Eq. 3)}$$

δ = wire diameter
R = radius of the sheave

He based this on the formulations to the technical bending theory by Eytelwein [15] and Navier [26]. Reuleaux gives a modulus of elasticity of 200.000 N/mm^2 and limits the maximum stress to 1800 N/mm^2. Famous mechanical engineers such as F. Redtenbacher [27], J.-L. Weisbach [28] and F. Grashof [29] adopted Reuleaux's formula, which - although correct in the case of a simple, bent wire - does not explain the behaviour of the wire in the cable. Basically the size of the bending variation of the wire is overestimated, but compared to this the friction is neglected. The fact that the mechanical correlation in the cable was not worked out, led to far-reaching controversies when Julius Carl von Bach (1847-1931) gave a lower definitive stress [31]:

$$\sigma_B = \frac{3}{8} \frac{\delta}{2R} \cdot E \qquad \text{(Eq. 4)}$$

He was supported by Josef Hrabák [32]. G. Benoit and R. Woernle fought this [34] and they knew that for example J. Isaachsen was on their side, but the ensuing work, [35], [36] etc., did also not lead to a formula closer to reality. This resulted in Theophil Wyss (1890-1971) still quoting Reuleaux's formula in his book as being essential and proving it with test-results, but they showed considerable scattering.

The treatment on a single wire in the cable due to a variation in bending of the cable consists of
- a variation in the bending and winding of the wire
- an alternating change in the axial force due to friction and
- friction between wires

and has not yet been conclusively calculated. When entering the sheave the fact that the sheave pushes the deviations of the single wires ahead has also to be considered [63] [65].

Other problem-areas where the "bending stiffness" of the cable is important for the determination of tl stress-fluctuations are the standing cables bent by the wheels of the cable car and the stay cables of bridges at the anchor-point when the entering angle changes. Nowadays there are formulae availabl solid bars being bent and axially tensioned:

$$M_{(x)} = P \cdot l \cdot \frac{1}{\varepsilon} \frac{\sinh\left(\varepsilon \frac{l-x}{l}\right)}{\sinh \varepsilon} \cdot \sinh \varepsilon \cdot \frac{x}{l} \quad \text{with} \quad \varepsilon = l \cdot \sqrt{\frac{F}{E \cdot J}} \qquad \text{(Eq. 5)}$$

If $x = l/2$ and $J = F \cdot \frac{d^2}{16}$ the formulae change to

$$M_{(l/2)} = P \cdot l \cdot \frac{1}{\varepsilon} \frac{1}{2} \frac{\sinh^2 \frac{\varepsilon}{2}}{\sinh \varepsilon} \quad \text{with} \quad \varepsilon = 2 \cdot \frac{l}{r} \sqrt{\frac{\sigma_N}{E}} \qquad \text{(Eq. 5a)}$$

If σ_N = 700 N/mm^2 and E = 210.000 N/mm^2 as well as a ratio of l/d = 100/0.10 = 1.000 the value of ε is approx. 60 and the fraction in the expression of the moment going towards 1. This leads to

$$M = \frac{1}{2} P \sqrt{\frac{E \cdot J}{F}} \qquad \text{(Eq. 6)}$$

and the expected bending-stress for a solid cylindrical bar

$$\sigma_M = \frac{M}{J} \cdot r = \frac{P \cdot r}{J \cdot 2} \sqrt{\frac{E \cdot J}{F}} = \frac{P}{2} \cdot r \sqrt{\frac{E}{F \cdot J}} = P \cdot \sqrt{\frac{E}{F \cdot A}} \qquad \text{(Eq. 6a)}$$

Isaachsen already derived this formula in [33] using a different approach. The only difficulty is to determine the stiffness corresponding to the cable. To regard the cable-stiffness in comparison to a bending as the sum of all wire-bending-stiffnesses leads to an unrealisticly small stiffness-value, the value of the solid-like cross-section of the cable is too high.

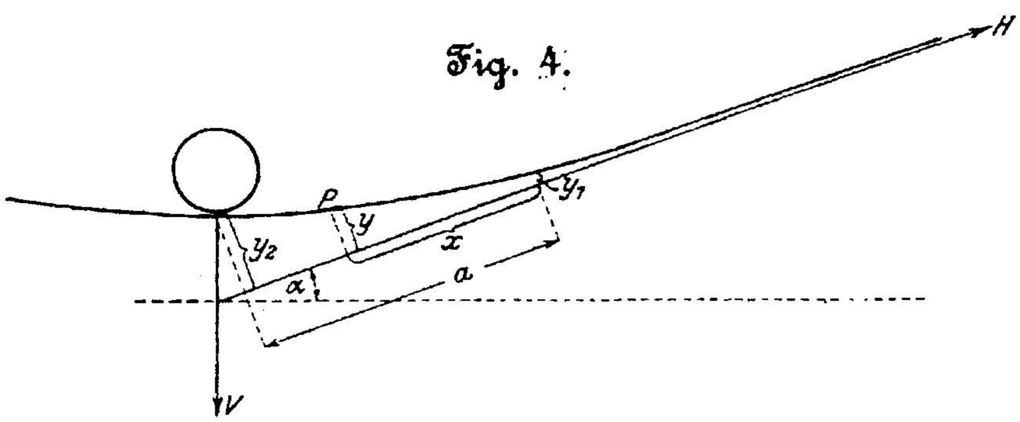
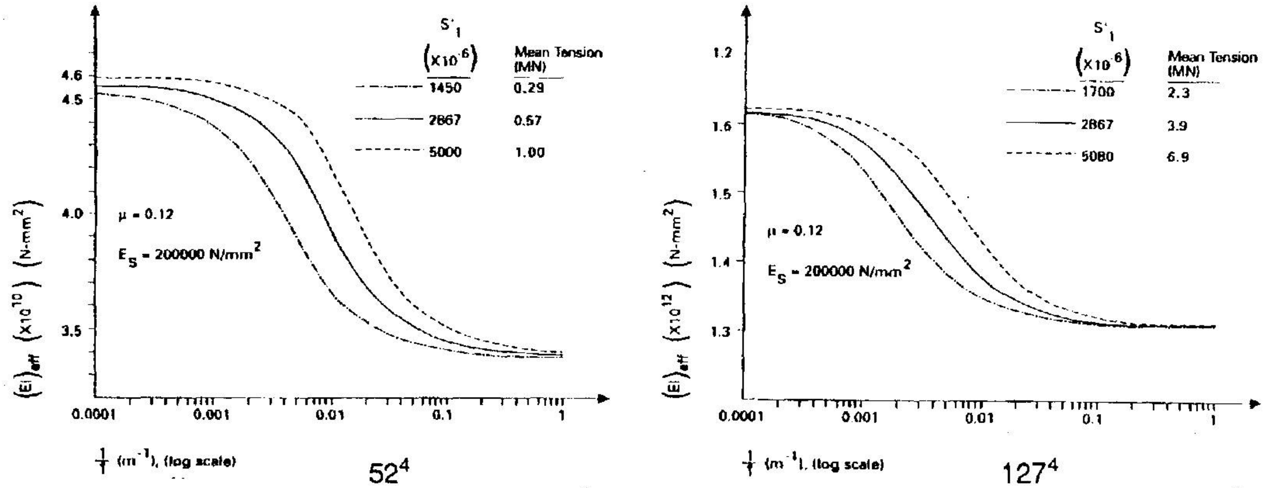


Fig. 11 A wheel riding on a standing cable (cable crane or cable railway) [33]

But at the same time the ratio of 2P/F can be treated equivalent to tg $\Delta\varphi$ according to the relevant vectored component placement whereas $\Delta\varphi$ represents a deviation in the entering angle at the anchorage of a stay cable. This determines the edge-stress in a tension element as being a solid bar as follows

$$\sigma_M = 2 \cdot \mathrm{tg}\Delta\varphi \; E \cdot \sigma_N \approx 2\Delta\varphi \; E \cdot \sigma_N \qquad \text{(Eq. 7)}$$

In connection with the stress-reductions resulting from the assumption of a solid bar Wyss proposes to use the stiffness-modulus of the cables as a value of E and to introduce a reduction-factor of 0.85.
This way the values obtained by Wyss sufficiently close to the results gained by Raoof and Yu [66], who established the values of the bending-stiffness shown in Fig. 11 ($0.85^2 = 0.722$).



$$E_s \cdot J_{solid} = 200\,000 \cdot \pi \cdot \frac{52^4}{64} \cdot 0{,}75 \cdot 0{,}94^3 = 4{,}47 \cdot 10^{10}\,\mathrm{N} \cdot \mathrm{mm}^2$$

$$E_s\, J_{min} = 0{,}75\, E_s\, J_{solid}$$

$$E_s \cdot J_{solid} = 200\,000 \cdot \pi \cdot \frac{127^4}{64} \cdot 0{,}75 \cdot 0{,}95^3 = 1{,}62 \cdot 10^{12}\,\mathrm{N} \cdot \mathrm{mm}^2$$

$$E_s\, J_{min} = 0{,}81\, E_s\, J_{solid}$$

Fig. 12 Bending-stiffness of open spiral ropes ϕ 52 and ϕ 127 depending on the radius of the cable with which it is being bent, shown for three different axial forces [66]

The actual bending-stress of the single wire cannot be determined this way. The deviation of the bending of the wire has to be obtained from the difference between the bending $1/R_c$ at the straight cable and the bending $1/R_T$ at the bent cable [57].

In the case of bundles with parallel wires the effects of angle-changes at the clamps or the anchorages of the main cables of suspension bridges were established by T.A. Wyatt [39].

AXIAL-STIFFNESS OF HIGH-STRENGTH TENSION ELEMENTS

In the course of this century tests were started to establish the wire-geometries in cables and in connection with that also the mechanical characteristics of the cables. The stiffness of stay cables had to become determinable and the factors influencing this stiffness discernible. Hrabák [32] still supports the idea, which, also in the cable puts the elongation in a linear relationship with the reciprocal value of the elasticity-modulus, and, concluding without considering the varying wire-lengths:

$$E_c = E_0 \cdot \cos^2 \alpha \qquad \text{(Eq. 8)}$$

Hudler [48] came to the following result based on works such as [45] to [47]:

$$E_{cp} = E_0 \frac{h^4}{[h^2 + 4\,\rho^2\,\pi^2\,(1+\mu)]\;[h^2 + 4\,\rho^2\,\pi^2]} \qquad \text{(Eq. 9)}$$

Because he places the wire-stresses acting on the section in a standard relation to the cable-axis (ellipse), in today's terminology this means

$$E_c = E_0 \frac{\cos^4 \alpha}{1 + \mu \cdot \sin^2 \alpha} \qquad \text{(Eq. 9a)}$$

Schleicher [52] corrects this hard-to-comprehend assumption and states the following for the cable-stiffness under imposed loads:

$$E_\sigma = E_0 \frac{1}{\sqrt{1+\gamma}\,[\,1 + (\,1 + \mu\,)\,\gamma]} \qquad \text{(Eq. 10)}$$

which means today:

$$E_c = E_0 \frac{\cos^3 \alpha}{1 + \mu \cdot \sin^2 \alpha} \qquad \text{(Eq. 10a)}$$

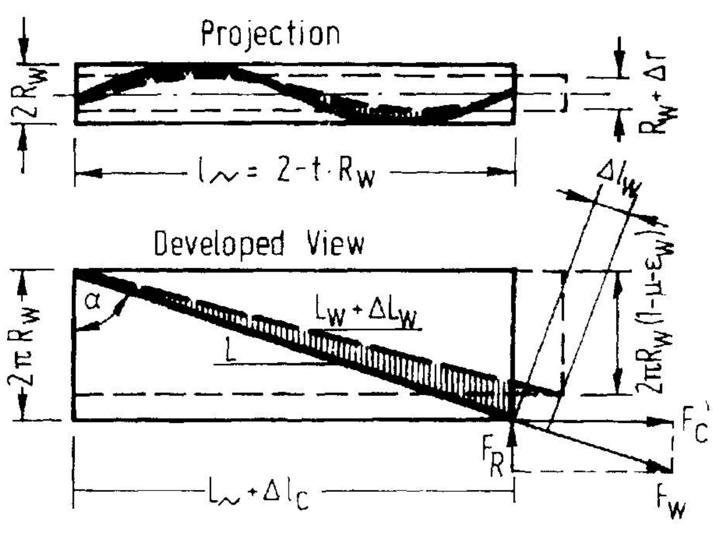


Fig. 13 A wire-layer in a straight spiral cable showing the elongation and the transversal contraction
a) view of the wire-layer
b) the wire-layer spred out in the plane

He also tried to establish the radial pressure resulting from the spiral shape of the wires and the effects this has on the stiffness.

$$\Delta E_c^q = E_0 \frac{2 \cdot \cos^3 \alpha}{\sin^2 \alpha \; (3 \sin^2 \alpha + \mu)} \qquad \text{(Eq. 11)}$$

Schleicher's figures which consider the elongation and transversal contraction of the wire are still valid today, to be used as a rough formula for determining the cable stiffness (see [53] to [61]). The author [58] tried to take the effects, an outer pressure p_c has on the cable into consideration when calculating the stiffness:

$$E_c = E_0 \frac{\cos^3 \alpha}{1 + \mu \sin^2 \alpha + \frac{p_c}{\sigma_0} \cos \alpha \; (\sin^2 \alpha + \mu)} \qquad \text{(Eq. 12)}$$

The formulae neglect the bending stiffness of wires in the cable [52] and the dents occurring locally at the wire-crossings [53], [60] as well as the friction caused by relative movements between the wires [59]. Today's computer applications make it possible to show even these influences [53], [63] and to determine the cable-stiffness depending on
- the period of operation (settling of the wire-structure)
- the filling material (lubrication)
- the radial compression (friction) etc.

Fig. 14 shows how the cable-diameter and the level of load-variations affect the deformation-behaviour and therefore the stiffness.

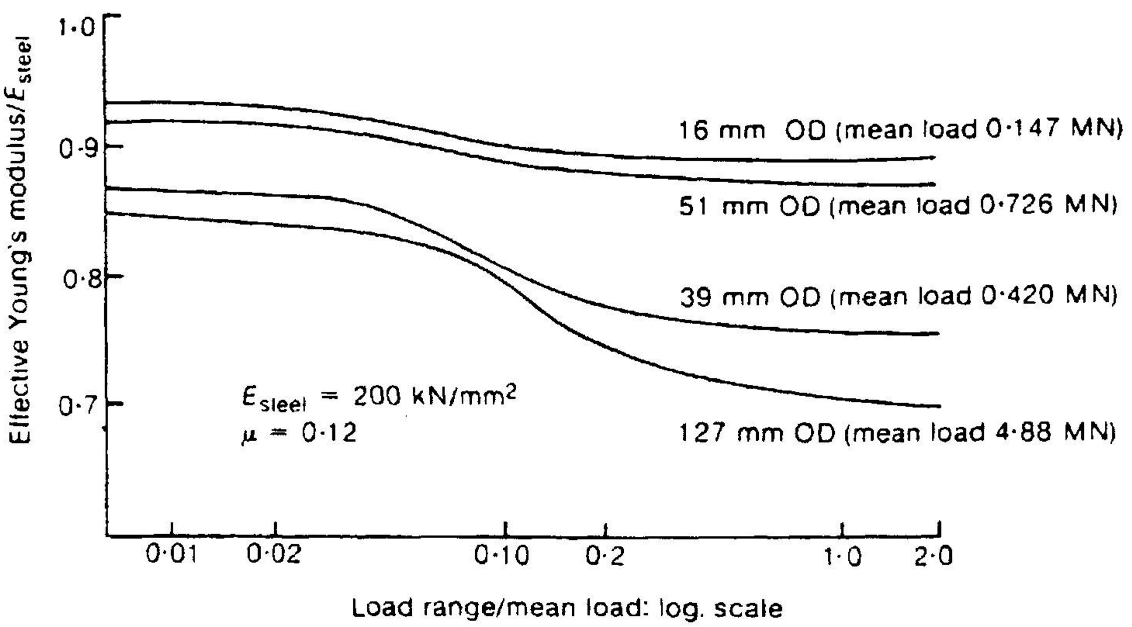


Fig. 14 The theoretical determination of the effective axial stiffness of various cable-constructions depending on the ratio between load-variation and mean load (mean load remains constant) [62]

CABLE-CONSTRUCTIONS

Parallel to these efforts of arithmectically recording cables and bundles, the efficiency of iron and the cable-construction were further developed. Forged iron wires were replaced by ingot wire, which could be rolled and drawn, and the inventions by Henry Bessemer (1813-1896) and Sidney Gilchrist Thomas (1811-1896) led to the mass-production of steel. Within a few years the maximum wire-strength could be increased from 600 to 1.100 N/mm^2, and today in structural engineering it reaches an allowed maximum of 1.800 N/mm^2 (DIN 18 800 T.1), after the rolling- and drawing-process during the production could be coordinated (i.e. was mastered) that the unalloyed carbon steel used in construction contains 0.85 % C. It gets patented cold-drawn and after that it is tempered to be used for examples as prestressing steel or spring steel. Its applicability in prestress-concrete-construction led to a tremendous increase in the output and was one of the reasons why in the post-war-era the iron-industry and the wire-manufacturers paid so much attention to this steel-product in research and development.

With respect to the types of tension-element-construction, which vary mainly in the geometrical detailing of the wire-cross-section and the wire-arrangement within the geometrical structure, a lot of different variations were tried and it is difficult to show them clearly . Roebling developed the "Three Size Construction" as a round strand which is known today as the Warrington-design (Fig. 10). In 1889 James B. Stone patented the Filler-design in the United States, and in 1887 Thomas Seale already received a patent on the Seale-design [21]. The wire-manufacturers Felten & Guileuame commercially introduced the locked coil rope (Germany approx. 1890) (Fig. 16) and, at the same time, French roperies developed the semi-closed spiral rope [40] (Fig. 17).

In the following only spiral ropes are presented.
The spiral rope - made out of round wires, its layers are laid in succession alternately to the left and to the right to show a close tie and to produce only a limited twisting-moment - has relatively great deal of cavities in the wire-structure. In order to decrease the hollow sections of the spiral rope, to defuse the pressure-points of the crossing layers and to produce a mechanical protection against the "outside" various wire-profiles were used.

- Round wires with different diameters which as single wire, triple-strand, as a Lang-lay-wire in Filler-construction or as multiple-layer spiral rope form the core of the cable (Fig. 16 to 18).

- Star-shaped profiles as core-wires did not prove to be worthwhile - they are too expensive (Fig. 16).

- Trapezoid-shaped wedge-type-wires were mainly to decrease the hollow sections and were used until recently. The profile-production during rolling is very sensitive to the formation of cracks and ridges, the final effect (arch) may occur too soon (low load levels) and the layers beneath it are in a cavity which makes their use increasingly risky especially in view of the durability (Fig. 16).

- Waist-shaped wires which, when used alternately with round wires in one layer should also produce a smooth surface and a good seam - which they do - cannot totally escape the above-mentioned disadvantages. In order to form a good seam, they have to be relatively sharp-edged at all four corners of the cross-section, this may lead to difficulties (Fig. 17).

- Z-shaped sectional wires have the most favourite cross-section-detailing and are used as outer-surface-wires. They are largely rounded off, have large cross-sections, they put their "head" on the "foot" of the neighbouring wire when tensioned and their cross-sections can slide on top of each other to avoid arching (Fig. 18) [41].

The state of the early development has been presented for example by Landsberg [42] and de Boulogne [43]. But Mehrtens [40] presented an overall view of the 19th century and then one of his pupils also dealt in depth with the possibilities of close-laid and dissolved bundles [44] (Fig. 19).

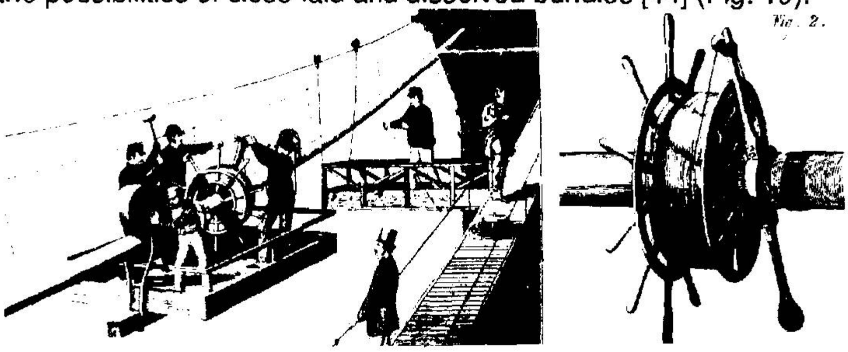


Fig. 15 The apparatus invented by John A. Roebling for wrapping soft galvanized wire around the cables

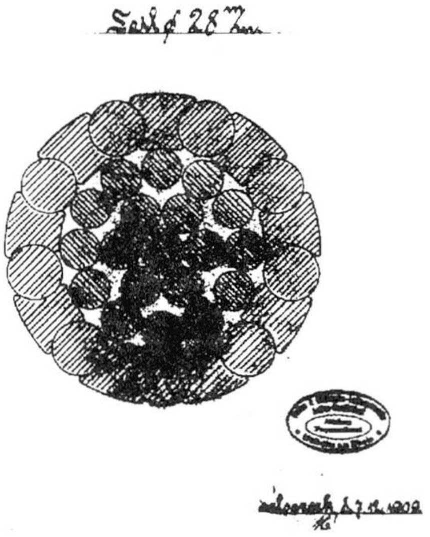


Fig. 17 Semi-closed spiral rope

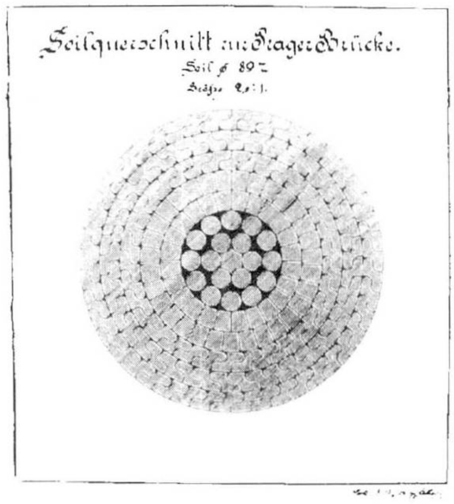


Fig. 16 Locked coil rope with a star-shaped core-wire, round-wire-core, trapezoid- and z-shaped sectional wires

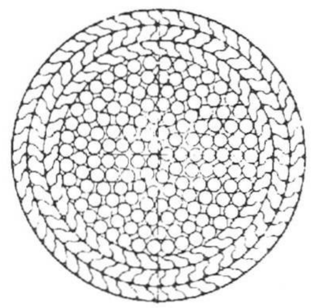
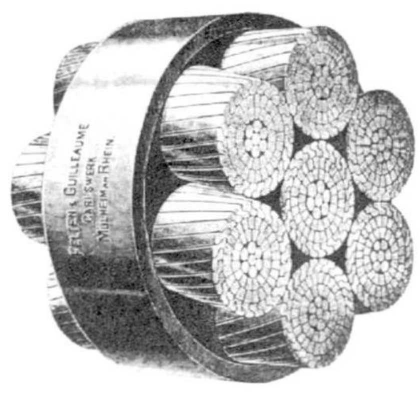


Fig. 18 Locked coil rope consisting only of round and z-shaped wires.
The core is a triple-strand



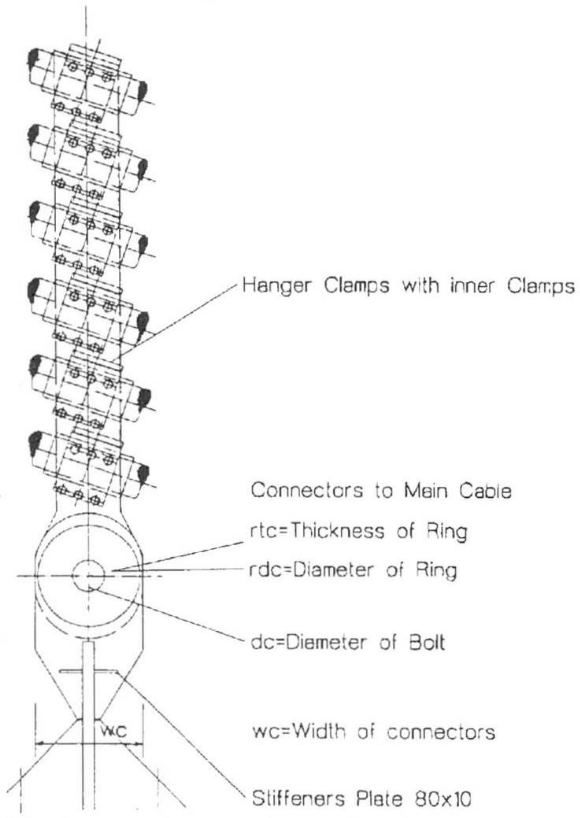


Fig. 19 Detailing of supporting-cables for suspension-bridges
a) as round cable made out of seven open spiral ropes [40]
b) as disolved cable consisting of smaller elements

TENSILE STRENGTH OF TENSION ELEMENTS

During the era of Enlightenment and its thirst for knowledge to further investigate the "resistance" of natural materials towards tensile strength, natural-fibre-ropes proved to be a bad example for determining specific characteristics. Even Franz Joseph Ritter von Gerstner (1786 - 1832) could only give this advice [70]: to determine the failure load of certain ropes (i.e. dry hemp-ropes) according to their length/longitudinal weight, and he had to admit, that the manufacturing procedures used for fibres and ropes would greatly influence their "cohesion".

Results of tension-tests with different shapes and production-procedures of wood and iron did not vary as much as published by Pieter von Musschenbroek in 1762, J. A. Eytelwein in 1808, Jean Baptiste Rondelet in 1812, Peter Barlow in 1817, Thomas Telford in 1817, G. H. Dufour in 1824, Samuel Brown, Geroge Rennie in 1829 and C. M. H. Navier in 1826 [70], [72]. While common iron showed tensile strengths of 240 and 480 N/mm^2, wires with a strength of about 650 N/mm^2 were produced and using spring wires strengths of up to 1.860 N/mm^2 could be shown. Even experts could not evaluate the variations occurring naturally - it has to be noted that the products were not standardized as they are today. This is clearly shown by a dispute in 1834 between E. Martin, Director of the Forges de Fourchambault and Louis Joseph Vicat (1786 - 1861), Enginieur des Ponts et Chaussées, about whether the suspension-bridge cable should be a chain or a wire bundle [68], [69]. The wire-strengths measured in tests varied from 490 to 830 N/mm^2 and Vicat assumed a tensil strength of 750 N/mm^2 for calculating the suspension-cable.

There is a long list of researchers who undertook great efforts to determine reproduceable strength-values. In 1834 Karmarsch [72] started in the field of steel-wire-testing and there is no end in sight yet. Also well into the second half of the past century the development of materials (Puddle-, Thomas-, Bessemer- and Siemens-Martin-procedure), the manufacture of suitable profiles (from the forged wire to the rolled wire and from the "Zögersbänke" used in the wire-mills to the disk-drawing and to a faster drawing), the material-fatigue (the work of August Wöhler in Berlin) and the static determination of loadbearing structures (framework-static and graphic static) were more important and decisive in construction than more exact strength-measurements. Only the so-called Bauschinger-Conferences (1884) laid the foundation for the more exact determination of measurements and their standardized registration, the result was the foundation of the "International Association for Material Testing in Engineering" in 1895, which endeavoured in the standardized registration of testing-procedures and with that achieved comparability.

As shown in Fig. 7, the separate wire-production increased dramatically at the turn of the century and becomes an industry of its own [73]. The production-procedures became more scientific [74] and the areas of application increase in number as indicated by the construction of wide-span suspension-bridges. The development of prestressed concrete, which, amongst others, was especially the result of the efforts by Franz Dischinger (1887 - 1953) and Eugène Freyssinet (1879 - 1962), had an even greater influence. Due to this, the research and development of steel wire were tremendously enhanced. Wires with larger diameters (insensitiveness), a higher creep-limit (maintaining the prestress) and a high yield point (allowing high stress) were produced and the exactness of the geometrical form and the eveness of the strength-characteristics were increased.

With the increased use of long tension elements with great loadbearing strength as external tendons and as suspended, wide-span bridges came the desire to determine the influence of the variation, resulting from statical or dynamical tests on short wire pieces, also in the case of the real long bundle. The theorectical research in the area of statistics and probability-theories was that far advanced [75], [76] that those results could be used with test-results and with the safety-philosophy in construction [77] to [82].

The following are the most important results, which are mainly suitable for the more exact evaluation of large-scale-test-results:

- long wires have a smaller, mean tensile strength than short wires
- an increase in the variation of the test-results of short specimens leads to a decrease of the mean-value of long specimens of the same material

- the more wires there are in a bundle, the smaller is the range of strength of the entire cable
- the dependencies in the case of the dynamic strength are subject to the same laws as the ones of the static strength
-just as the dynamic strength is always determined by the quality of its surface, the surfaces of the compared elements can be related to each other
- if the length of a tension element is infinitly increased, the strength reaches a definit, virtually deterministic limit
- correctly applied to the range of the strengths and the extension, as well as their co-relation, of parallel, semi-parallel or of twisted wires, the effect of the first wire-bridge and with that the entire test can be pre-determined.

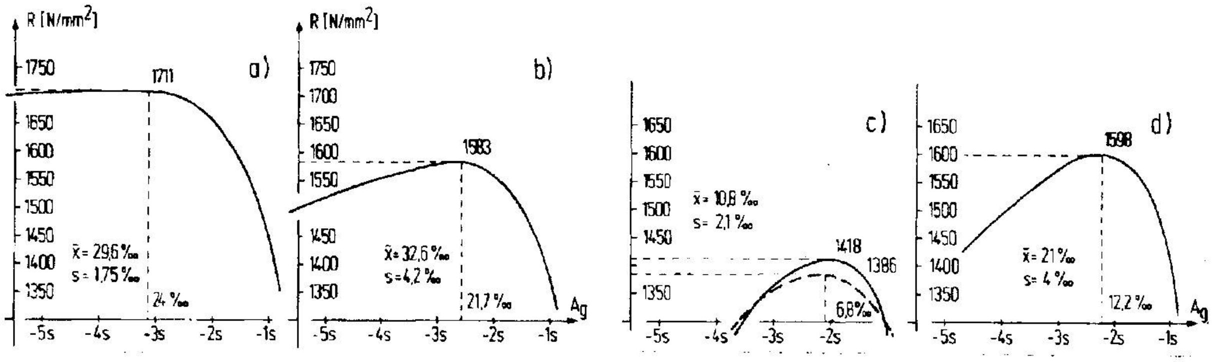


Fig. 20: The strength related to the initial cross-section and plotted as a function of the normal distribution of the uniform elongation before reduction of the tension-member-long individual elements [57]
a) of the realistic stress-strain behaviour of parallel wires, parallel strands and spiral ropes, bundled prestressing wires
b) of bundled strands
c) + d) of twisted bridge wires

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Failure Mechanisms in Rotating Bending Fatigue on 7-Wire Strands

Mécanismes de rupture par fatigue en flexion rotative de torons 7 fils

Bruchmechanismus bei Drehbiegebeanspruchung siebendrähtiger Litzen

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SUMMARY
In order to study the behaviour of prestressing strands subjected to bending fatigue, the authors applied a mathematical model to calculate the stay distortion near the anchorage. They reproduced on an original rotating bending test apparatus such curvatures representative of onsite conditions. Behaviour of non-coated and galvanized strands is given and cracking initiation mechanism by fretting is presented. Influence of corrosive surrounding is also shown.

RÉSUMÉ
En vue d'une étude technologique du comportement de torons de précontrainte soumis à la fatigue par flexion, les auteurs ont appliqué un modèle mathématique pour calculer la déformée d'un hauban au voisinage de l'ancrage puis reproduit sur une machine de flexion originale des courbures représentatives des conditions sur site. Les comportements de torons non revêtus et de torons galvanisés sont donnés et le mécanisme d'amorçage des fisures par fretting est mis en évidence. L'influence d´un environnement corrosif est également montré.

ZUSAMMENFASSUNG
Im Rahmen einer technischen Studie zum Ermüdungsverhalten von Vorspannlitzen unter Biegebeanspruchung untersuchten die Verfasser realistische Krümmungsradien in einem Drehbiegeversuchsstand. Dazu wurden vorgängig mit einem mathematischen Modell die Verformungen von Schrägseilen in der Nähe ihrer Verankerung ermittelt. Berichtet wird von Verhalten unbeschichteter und galvanisierter Litzen, wobei die Rißentstehung unter Reibermüdung und der Einfluß einer korrosiven Umgebung dargestellt werden.

1. INTRODUCTION

Cable stayed or reinforced civil engineering structures use either mono-strand cables (helical or lock-coil) either parallel wires cables or parallel strands cables.

The latter are generally made of prestressing strands clamped one by one. Initially used for prestressed concrete constructions those cables where fully buried inside concrete ; their applications for stay cables are quite new and under fast development for large span cable-stayed bridges (Normandy Bridge ...).

In such structures, in addition to the random sollicitations due to traffic, climatic effects (rain, wind ...) produce alternate and repeated bending deformations at the anchorages level of cables, inducing fatigue phenomena.

It appears, then, useful to know under laboratory conditions the bending fatigue effects on basic strands. After modelling the bending conditions on site and describing the test apparatus, results of first technological tests and fractures analysis are presented using an initial damaging mechanism by fretting.

2. MODELLING THE DISTORTION OF A STAY CABLE

In order to know the actual solicitations on stays and specially the bending amplitude near the anchorages three approaches can be taken :

1) measuring distortions on an actual bridge under traffic. These measures are not reliable enough for giving significant curvature values.

2) measuring in laboratory distortions of a cable under known solicitations. These measures, made on prestressing strands are, to date, determined with quite a large uncertainty (≈ 100%) due to the fact that the expected deformations have small amplitudes and are located near the anchorages.

3) calculation of local deformations of a cable using a model where boundary conditions and parameters are issued from experimental estimations. Such a model has been developped in order to give curvature values consistent with experimental values and with the natural continuous variation of this parameter for actual materials.

2.1 Description of the model

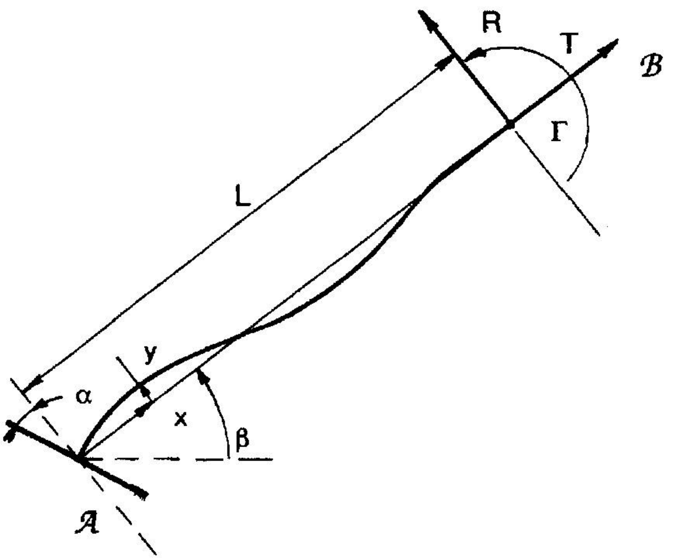

Fig. 1

The cable is modelled as a beam with a constant stiffness modulus, subjected to an axial tensile strength and embedded at each end. The lower embedment $\mathcal{A}$ is rotated with an amplitude α from the acting line of the stay.

The material mass is taken into account in the distortion calculation but its influence on the axial tensile strength variation is neglected (the stay cable being inclined with an angle β from the horizontal line).

Such a model gives results of curvatures slightly greater than those given by the model of semi-infinite cable without mass (Gimsing [1]) and is based on the classical equation (K.G. Mc Connel and W.P. Zemke [2]) :

$$EI \frac{\delta^2 y}{\delta x^2} - T y + \frac{mg \cos \beta}{2} (b - x)^2 - R (l - x) + \Gamma = 0$$

where :

EI	actual stiffness modulus,
T	axial tensile load applied to the cable,
β	stay slope angle,
R	reaction of the embedment (right side) *
Γ	embedment torque (right side) *

* hyperstatic unknown parameters

and for which the solution is given by

$$y\,(x) = L_1 \exp\,(w * x) + L_2 \exp\,(-w * x) + A\,x^2 + B\,x + C$$

with $w = \sqrt{T / EI}$

The L_1, L_2, A, B, C, coefficients are determined from the boundary conditions, taking into account the particular solution giving B and C depending of L_1 and L_2, with $A = mg/2T$.

2.2 Numerical results

Many numerical applications of the above model have been made on cables from 12.6 to 85 millimetres diameter. A good agreement is obtained between experimental and theoritical distortions for the largest cables. On the contrary, as we said, measures on low stiffness cables (low diameter) are not accurate enough for a direct validation of the calculation.

The following results refer to a 7 wire-strand, 12.6 mm diameter, for which the stiffness has been estimated according to the approximations given by G.A. Costello (EI = 21.2 Nm^2, interwires full-slip ; EI = 247 Nm^2, interwires no-slip) [3] and measured on an embedded beam (EI = 107 Nm^2).

Table I gives the maximal curvature radius, calculated at the embedding level $\mathcal{A}$ for anchorage rotation angles consistent with the deck distortions of a bridge and with the construction accuracy of the anchorages alignment with the stay.

	β = 45°	β = 0°		
	EI = 107 Nm^2	EI = 107 Nm^2		EI = 247 Nm^2
α (degrees)	L = 100	L = 100	L = 10	L = 10
- 0.1	(-) 20.2	(-) 13.3	31.7	48.0
+ 0.1	(-) 7.2	(-) 5.6	(-) 17.2	(-) 26.1
+ 0.5	(-) 3.1	(-) 2.8	(-) 4.2	(-) 6.4
+ 1.0			(-) 2.1	(-) 3.3
+ 2.0			(-) 1.1	(-) 1.7
+ 2.5			(-) 0.8	(-) 1.3

Table 1 Curvature radius (metre) calculated for a 12.6 strand under 78 kN tensile load

3. EXPERIMENTAL APPLICATIONS

The execution of bending rotating tests where carried out, reproducing curvatures of the same order of magnitude as those calculated above. These tests allow the determination of an endurance limit for the strands.

A scheme of the apparatus is given in Figure 2 : the sample with a free length L is embedded at each end in anchorages ($\mathcal{A}$ and $\mathcal{B}$) symetrically driven into rotation around the X axis. Bending is obtained by nearing the two anchorages which are free in rotation around the Z axis, perpendicular to the XY plan.

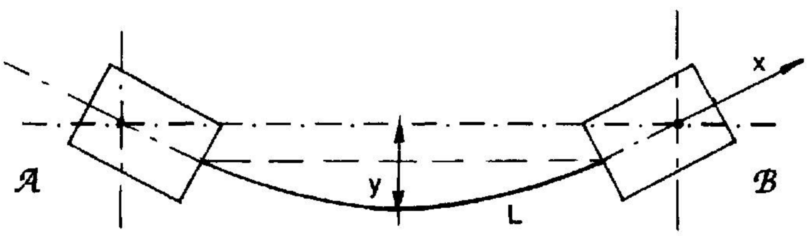

Fig. 2 Scheme of test apparatus

The sample itself bears inside the anchorages so that, in this zone, slipping between the central wire and the six external wires is impeded.

The tests where carried out on non-coated steel and galvanized steel strands, in the open air or with partial dipping in artificial seawater. Test frequency allowing the conjugate action of the mechanical fatigue sollicitation and of the surrounding corrosiveness was 0.26 Hz.

Results obtained with the "K non-broken samples method" [4] (with K =3) are shown in Figures 3 and 4. The "curvature radius" parameter is choosen in order to make easier the application of the results to in site checking operations on bridges.

Notice that the new strands (non-coated or galvanized) show an endurance limit. The oxidized strands (pits deepness around 2/10 mm.), under the same experimental conditions, also show an endurance limit. But conjugate action of fatigue and corrosion does not reveal the existence of this threshold.

It is noted a large scattering for the galvanized strands behaviour when in corrosive surrounding A3 and, for the lowest lifetimes (700 000 cycles) a lack of difference in lifetime with or without this surrounding.

4. PRESTRESSING STRANDS BEHAVIOUR ANALYSIS BY ROTATING BENDING FATIGUE

Experimental behaviour described in the above chapter, particularly the better behaviour of galvanized steels for long lifetimes involves the knowledge of cracking initiation mechanisms under rotating bending, all the more so because galvanizing does not bring any improvement in fatigue behaviour for high strength steels [5].

Analysis of "corrosion" products extracted from strands after tests, macrographic investigation on fractures and surfaces of strand wires and study of the wires behaviour under fretting enabled a justification for the observed behaviours.

4.1 Fatigue fracture of oxyded strands

Investigations of strands fractures subjected to fatigue after corrosion by a storing in natural atmosphere show that the external wires are the first to be harmed by cracking and fracture. Fatigue cracks are initiated on corrosion pits, the measured deepness of which is $2.7\ 10^{-3} \pm 0.2\ 10^{-3}$ millimetres.

4.2 Fatigue fracture of non-coated and galvanized strands

The first peripheral wire breaks are sometimes preceded by the central wire break. For the tests with a fatigue lifetime around two millions cycles, the central wire is always broken.

Strands fracture is preceded by production of oxyded powders, red for non-coated strands, black for galvanized strands. The analyses of powders by X-Ray diffractometry (or Mossbaüer spectrometry) show out :

- for red powder

Iron	Fe
Iron oxide	Fe_2O_3 (hematite)
Iron oxide	FeO (wüstite) - traces

- for black powder

Zinc	Zn
Zinc oxide	ZnO
Iron oxide	Fe_2O_3 (hematite)

Those powders are typical of a fretting wear phenomenon producing metal particles with large reactive surfaces, inducing fast oxidation and oxides presence in the collected powders.

The investigation of wires surface (figure 5) well shows metal tearings at interwire contacts, and especially at central wire/peripheral wires contact. Fracture initiations themselves correspond geometrically to interwire contacts (figure 6), this allowing to state that frictions are the source of fractures (fretting fatigue).

4.3 Fracture under conjugate action of fatigue and corrosion

The common characteristic of all tests carried out under these conditions is the multiple fractures obtained on a same wire and the very close cracking observed at the interwires contacts (figure 7).

For galvanized strands, cracking and fractures are preceded by zinc dissolving and/or complete wearing.

Analysis of corrosion and wearing products by X-Ray diffractometry does not clearly exhibit any presence of iron or zinc under metallic form. The identified crystallized products are :

- for non-coated strands

Goethite	α FeOOH
Akaganeite	β FeOOH
Magnetite	Fe_3O_4

- for galvanized strands

Carbonate "Type 1"	$2ZnCO_3,3Zn(OH)_2$
Carbonate "Type 2"	$ZnCO_3,3Zn(OH)_2,H_2O$
Chloride	$ZnCl_2,4Zn(OH)_2$
Nickel-Iron basic carbonate	

Lack of iron and zinc detection is due to :

- either diffraction lines superposition for these metals and their corrosion products,
- or corrosiveness of the A3 surrounding, inducing complete oxydation of particles teared from friction zones.

5. INTERPRETATION

Fractures of prestressing strands subjected to rotating bending fatigue tests with or without corrosive surrounding are inititiated, for the least hard solicitations, at the interwires contacts (central wire/peripheral wires or peripheral wires/peripheral wires).

Analysis and investigations show that fretting wear and fatigue mechanisms initiate fatigue cracks inducing fracture.

Zinc favourable effect on fatigue behaviour is connected to this fretting mechanism. It has been earlier demonstrated [6] that galvanizing zinc delays wearing of basic steel at interwires contacts, and then initiation of surface damages inducing fatigue fractures.

For galvanized strands subjected simultaneously to fatigue solicitations and to A3 surrounding corrosive action, the same process due to zinc action delaying surface damaging can be kept in mind. It explains the equivalent lifetimes with or without corrosive surroundind observed for the hardest mechanical conditions shown on figure 4 (700000 cycles for fracture). This mechanism explains also the scattering observed for tests under less hard conditions ; zinc dissolving phenomena are indeed miscontrolled during long time tests (temperature, surrounding concentration, corrosion products disposal ...) so that destroying kinetics of galvanizing zinc is not the same from one test to the other.

Multiple cracks and fractures under the action of fatigue coupled with corrosion are simply explained by comparison of defects and surface cracks density on figures 5 and 7. Cracks initiations are directly related to short cracks due to fretting mechanisms. In fretting phenomena wear or fatigue begins by surface short cracks development [7,8]. These ones, inclined around 45°, grow inducing :

- either surface chipping (wear),
- or, under corrosive surrounding and overall fatigue solicitations, cracks perpendicular to the main stress direction.

Action of corrosive surrounding being mainly strong on the new metal surfaces created at the short cracks level helps these fatigue cracks to grow (dissolving, embrittlement, mechanical effects of corrosion salts on cracks opening ...).

6. CONCLUSIONS

The rotating bending fatigue behaviour of prestressing strands near the endurance limit is related to interwire friction phenomena (fretting). Wear results in surface defects inducing cracks initiation. The action of corrosive surrounding helps cracking.

Favourable zinc action is also related with fretting phenomena. This material acts in interwires contacts as a third-body (wearing material) which delays basic steel damaging.

From this study it appears also that the curvature radius, calculated for on site anchorages misalignment or rotations of one or two degrees, are of the same order of magnitude as those corresponding to the endurance limit of strands constituting stays. Particular attention to stays installation should minimize fatigue fracture risks.

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ANNEXE

<u>A3 Reagent</u>

6 g/l	MgCl	Magnesium Chloride
30 g/l	NaCl	Sodium Chloride
1,9 g/l	Na_2HPO_4	Phosphate of Sodium
12,5 g/l	H_3BO_3	Boracic Acid
pH 8	Na_2CO_3	Sodium Carbonate Q.S.P.

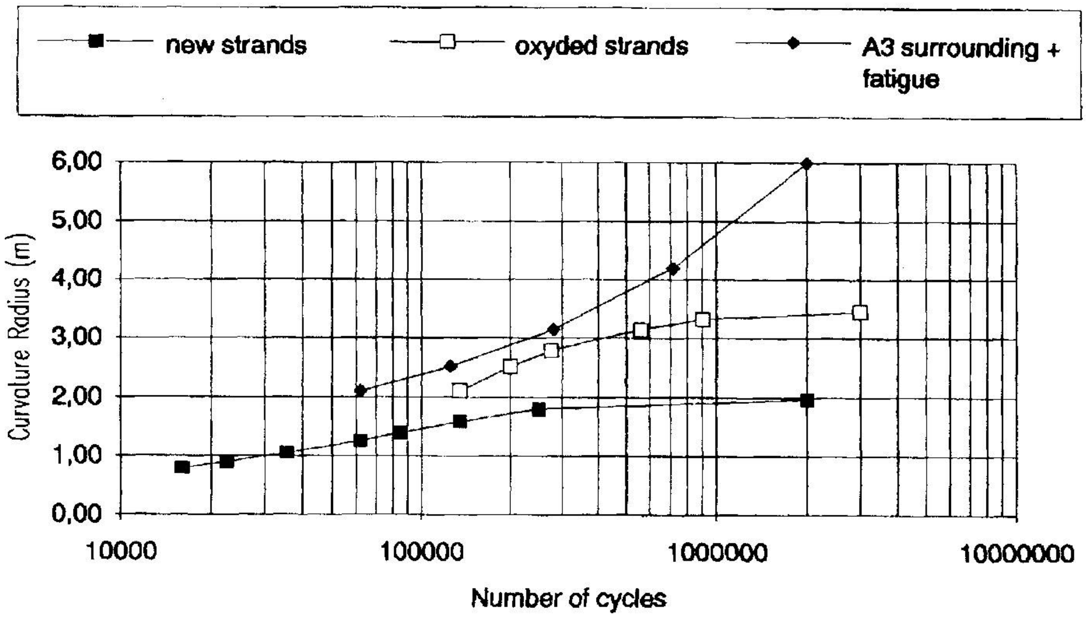

Fig.3 Results on non-coated strands 12.6 mm diameter

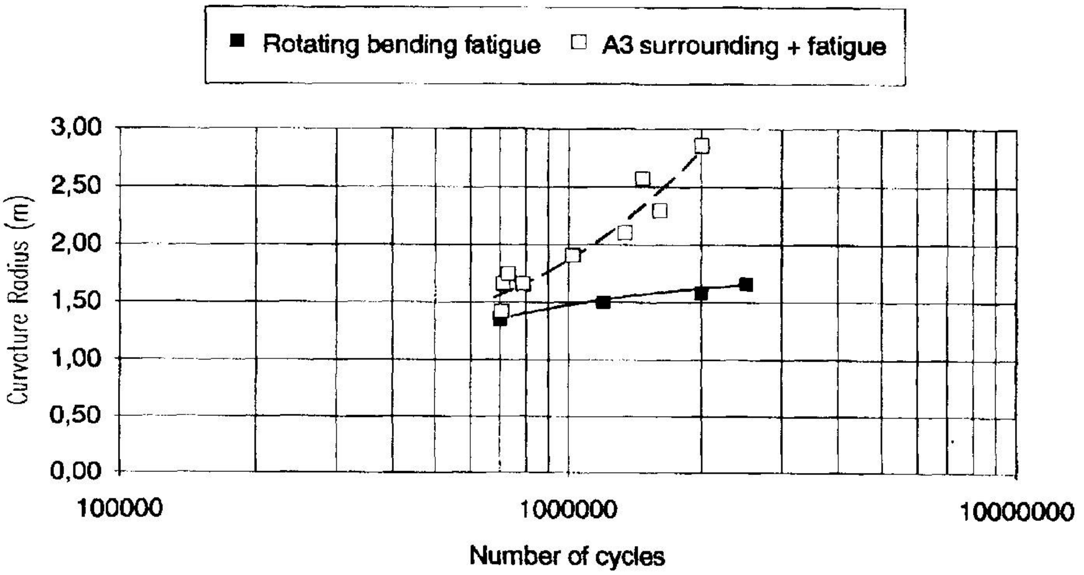

Fig.4 Results on galvanized strands 12.6 mm diameter

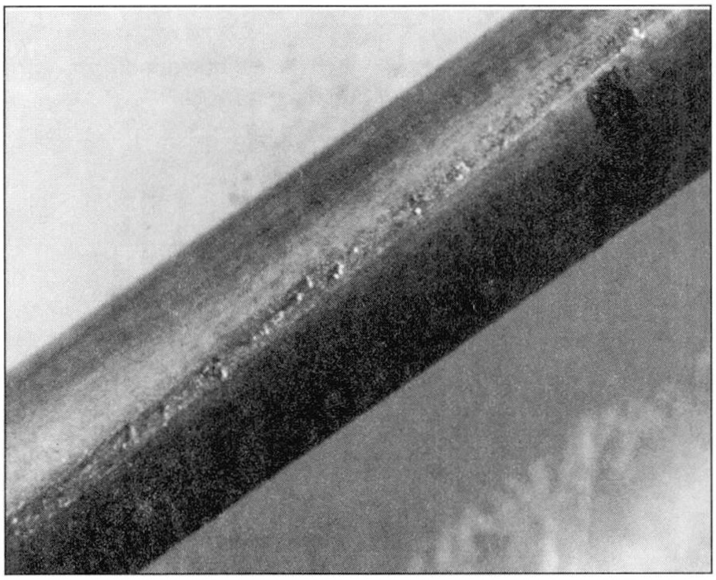

Fig. 5 Particles tearing at interwire contacts (500000 cycles)

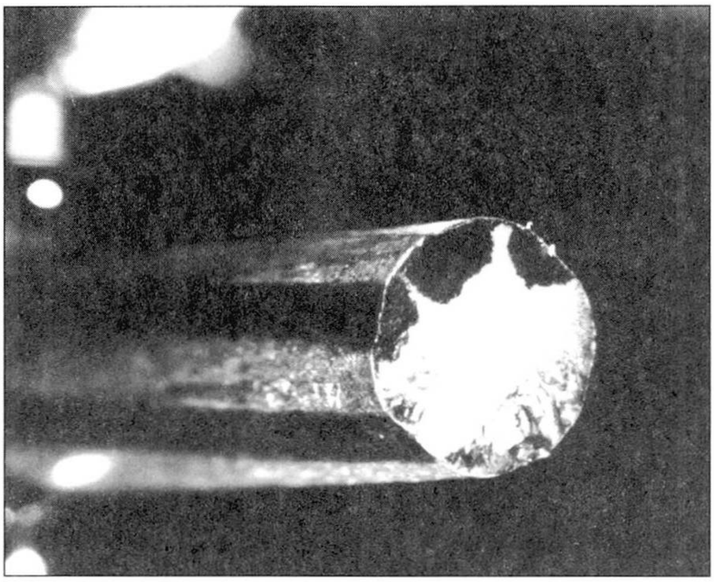

Fig. 6 Correspondance between interwire contacts and cracking initiation (strand core)

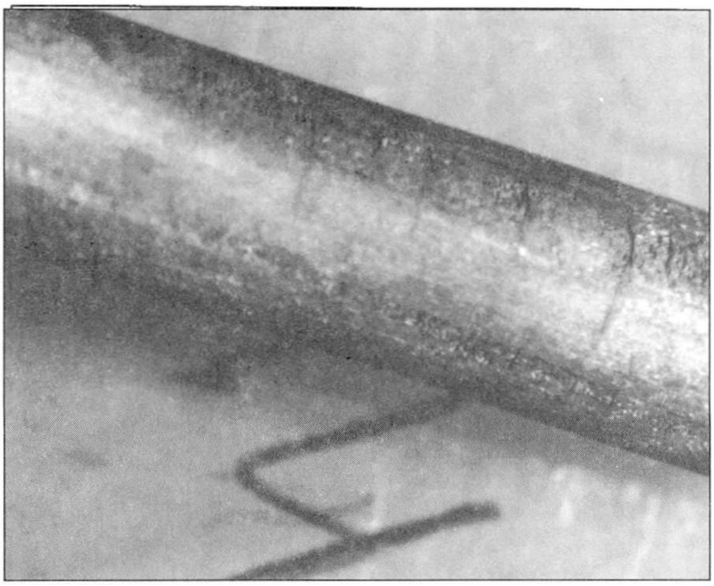

Fig. 7 Cracks under interwire contacts with conjugate action of fatigue and corrosive surrounding

Fretting: a Failure Mechanism in Fatigue of Strands

Fretting: un mécanisme d´endommagement en fatigue des câbles

Fretting: ein Schadensmechanismus des Ermüdungsverhaltens von Litzen

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SUMMARY
Several aspects of fatigue properties of strands can be explained through the fretting behaviour of constitutive steels. This paper gives indications about the fretting behaviour of steels through the effects of slip amplitude and normal loadings. Fretting maps are discussed from which cracking domains are identified.

RÉSUMÉ
Le comportement en fatigue des câbles est souvent associé à la resistance au fretting des fils métalliques. Ce papier présente quelques données relatives à la résistance au fretting d'aciers en insistant sur les effets spécifiques de l'amplitude de glissement et du chargement normal. Les cartes de fretting permettent de bien identifier les domaines à risques dans lesquels s'amorcent préférentiellement les fissures de fatigue.

ZUSAMMEMFASSUNG
Die Lebensdauer von Litzen steht häufig im engen Zusammenhang mit dem Reibungsverhalten der einzelnen Drähte. Diese Arbeit befaßt sich mit den Auswirkungen der Parameter Normalkraft und Reibungsamplitude auf das Reibungsverhalten von Stählen. Sogenannte Reibungskarten erlauben die Identifizierung von Risikobereichen in denen bevorzugt Ermüdungsrisse auftreten.

1. INTRODUCTION

The mounting of metallic wires or strands is widely used in many industries because of the good compromise achieved when taking into consideration ductility, stress to failure, fatigue strength or cost. These industrial applications which include the cables used in mines, aerial tramways, ship moorings, ski tows, fibres in tyres and break cables, require good resistance to fatigue loadings.

Many efforts have been made to try to increase this fatigue strength by means of thermomechanical treatments of the wires, by superficial coatings or by modifying the assembly architecture so as to diminish the local mechanical loading.

When considering the data in the available literature, fatigue results appear to be very scattered and any explanation remains very hazardous due to the great number of test parameters [1]. Furthermore, it is difficult to run fatigue tests with the actual cables and extrapolation of short time duration testing to industrial lifetimes of more than fifty years is still under discussion.

Both theoretical and experimental aspects have been considered as presented in this workshop. It is clear that any attempt to describe the fatigue strength from the ultimate stress or to set predictive models requires further knowledge of the fatigue mechanisms [2]. However results are now available on the effects of the loading (tensile, bending, torsion) and on the first failures especially of the wires in the internal layers [1,3]. More and more friction between the wires appears to be a major mechanism which can initiate notches and thus fatigue cracking.

With the hypothesis of a friction effect in the fatigue failure mechanism, fretting is increasingly seen to be the main cause of the fatigue life reduction [1, 4, 5]. Waterhouse has analysed the influence of heat treatments and decarburising on the fatigue behaviour of .7 carbon steel wires. The initiation of fatigue cracks was seen at the limit between the central sticking zone and the peripheral ring in which sliding occured [7, 8]. Several coatings (copper or silver) were then considered as good anti-fretting palliatives [9].

Because of the increasing interest in the fretting effect to describe the fatigue drops, this paper deals with an analysis of the degradations which can be observed in all the contacts submitted to small displacements. The risks of fatigue crack initiation will be particularly discussed using the new interface tribology concepts.

2. INTERFACE TRIBOLOGY CONCEPTS

Many industrial parts can suffer large drops in their fatigue lifetime whenever local contacts exist. Indeed secondary loadings can induce small displacements between quasi-static assemblies and thus give rise to wear (matter loss) or fatigue (cracking) processes.

Very harmful for industry, this specific degradation is known as fretting-wear, fretting-corrosion or fretting-fatigue. The word fretting is in fact related to small displacement amplitude movement occuring between contacting surfaces and the second word is used to describe the mechanism which induces the damage. However these terms can lead to misconceptions and we would first like to provide a basis for wear aproaches. Indeed, contacts can induce the stopping of machine elements by function loss, fracture or the appearance of nuisances (noise,...).

Materials submitted to contact loadings suffer local stress and strain fields. These fields are related to many parameters which depend on mechanical, material or surface properties and which can vary in time due to the velocity accommodation mechanisms. The knowledge of these fields throughout the contact life is required to determine the material behaviour but it is often difficult to calculate or at least estimate the local stress and strain. Due to local overstressing or overstraining, the material can fail by crack initiation or plastic deformation and brittleness. This first damage is defined as the first wear step. For well-controlled stress and strain fields, this material response is not to be considered totally as dispersive and, moreover, its prediction is possible.

The classical dispersion of wear results found in the literature is a consequence of the so-called second step related to the "use" of the first material response by the contact so as to accommodate the imposed velocity. This behaviour can be illustrated by two examples :

- if the material first fails by debris detachment, the wear regime can explain matter loss. A source and sink approach of the third body justifies the scattering of the results from their possible protective role. For instance, the protection depends on whether the debris are recycled or not during continuous friction (scraping or snow plow effect), whether they are trapped or not due to the displacement amplitude for alternative friction, whether the contact is opened or closed,...

- if cracks are formed, the propagation path depends on the failure mode at the crack tip. Thus the nature of the friction regime can cause the same initial crack to form spalls, to propagate up to the fracture of the part or to arrest.

Without going into the details of recent developments, it can be said that friction and wear have moved :

- from the tribology of volume [10], where body A was rubbed againt body B and wear rates and friction were monitored ;

- through the tribology of surfaces [11], where surface science brought to this domain a solid scientific base ;

- to the tribology of interfaces which focuses on the role of the interfaces or third bodies, whether natural (debris) or artificial (solid lubricants).

The tribology of interfaces is concerned with two basic problems : (i) third-body formation, composition and role, and, (ii) third-body kinematics.

Modelling for wear or durability considers each element of the triplet "mechanisms, first and third bodies" englobing dimensions which go from to the nanometer up to the meter scales [12].

- Mechanisms are gear boxes, bearings, brakes, cables, etc. Mechanisms transmit loads from one machine component or "first body" to another and first bodies only function properly when they are at least separated by an efficient "third body". Running conditions (configuration, loads, speeds, temperature, environment, etc...) imposed by a given mechanism on the rubbing first bodies have to be either calculated or estimated (either theoretically or experimentally) as they govern wear and life.

- The first bodies are the rubbing surfaces and the subsurfaces in which the displacement is to be accommodated. They are homogeneous, coated or have a functional property gradient.

- The third bodies separate the two first bodies partly or fully under the conditions imposed. Oil films, solid lubricants, debris beds are third bodies. Bulk and screen properties govern the type of load carrying mechanisms.

Recently, the velocity accommodation mechanisms have been analyzed [13, 14]. All mechanisms combine a site and a mode. The five sites are the two first bodies and the third body which itself includes the two screens and its bulk. Four modes have been identified : elastic, rupture, shear and rolling.

The main guides due to interface tribology concepts are summarized below:

- Wear is not an intrinsic property of materials and extrapolation from laboratory benches to industrial applications is hazardous.

- Adhesion, abrasion, corrosion and fatigue are not wear mechanisms. They govern particle detachment and cracking which is only one of the steps of the wear process.

- A detached particle is a wear particle only when it is lost for the contact and the presence of debris in a contact does not accelerate wear. In most instances, in dry friction, the protection afforded by the debris is greater than the damage caused by its presence.

- A given material cannot be a priori considered as a "good" or a "bad" anti-wear material. Pairings of materials can give good solutions to well-identified wear problems. For instance a hard coating can quickly form debris which then protect the bulk material if the debris can be trapped in the contact.

- The running of accelerated fretting tests can lead to erroneous conclusions.

- A wear law can only be established for a given mechanism if all elements of the triplet are identified.

- Interface tribology promotes simulation rather than the use of wear laws.

These few results are general. In the case of fretting, it is clear that the first bodies can play a more major role than under continuous sliding. The triplet approach appears very basic for fretting problems also.

3. CRACKING INDUCED BY FRETTING

Fretting wear terms suggest that the small displacements mainly result in particle detachment and matter loss. Debris have been shown to often nucleate in a specific superficial area called a Tribologically Transformed Structure (T. T. S.). Once formed, the debris is trapped, crashed and then oxidised. In the case of steels, red powder is classical. The two synthesis books written by Waterhouse are generic documents for all aspects of fretting [15, 16].

Generally, cracking is related to fretting-fatigue and few results describe cracking as a degradation in the case of fretting-wear, i.e. without external loading. Vingsbo et al. [17, 18] have shown that such cracking appears at the limit between the sticking and the sliding zones. Pellerin [19] studied the conditions for crack initiation of aluminium alloys. These approaches refered to wear maps developed below.

Cracking under fretting fatigue was studied by several authors. Chivers and GORDELIER [20] described fretting fatigue as the super imposing of skin stresses due to the contact loading and stresses due to the cyclic external loading. NISHIOKA and HIRAKAWA have taken into account the modification of the friction coefficient values which appear in the very first cycles [21].

Fracture mechanics were used to define the critical crack length which induces failure [22, 23, 24, 25]. At the beginning of the fretting fatigue test, cracking is governed by the two loadings while the fretting loading can be negligible from a given crack length. Propagation laws have been used, including, for instance, crack closure to justify specific behaviours [26].

Many researchers has tried to pinpoint in an accurate way the effect of parameters such as the material strength, the bulk stress, the R ($\sigma_{min}/\sigma_{max}$) ratio, the normal load, the displacement amplitude as well as frequency, hardness, residual stresses, temperature, environment, ... [27, 28, 29]. The results will not be discussed here but a fatigue limit drop up to 70 % can be noted.

All these results refer to delicate experiments. Very often the slip amplitude is not well-controlled despite the fact that it is one of the main parameters which control crack initiation. To rationalize experimental approaches, a good knowledge of contact mechanics is required.

4. CONTACT MECHANICS BASES

It is not possible to explain in only a few paragraphs how and to what extent contact mechanics govern fretting fatigue. The subject is well documented and an excellent review is given in Ref. 20.

Efficient models for stress, deformation, temperature and stress intensity factor maps for homogeneous, cracked, smooth or rough solids now exist.

Based on restrictive hypotheses, Hertz theory permits a good estimation of the pressure distribution p in a contact submitted to a normal loading Fn. In the case of ball/plane contacts, stress calculations from Boussinesq and Cerutti indicate that the radiant σ_r stress (i. e. σ_{xx} in the plane y = o) useful to estimate the crack nucleation risks reaches a maximal value at the limit of the contact :

$$\sigma_{r\,max} = (1 - 2\,\nu)\,Po/3$$

with Po as the maximum pressure at the contact center and ν Poisson's coefficient.

In the case of a tangential loading, gross slip as described by Coulom's law or partial slip (Cattaneo [30] and Mindlin [31]) must be considered.

For gross slip regime, calculations were made by Hamilton and Goodman [32] and then by Sackfield and Hills [33].

σ_r was a compressive stress at the front of the contact and the maximum at the rear is increased by a "tangential term".

$$\sigma_{r\,max} = (1 - 2\nu) Po/3 + (4 + \nu) \pi \mu Po/8$$

in which μ is the friction coefficient. Of course, in the case of a cycling of the tangential loading, this overstress can nucleate a fatigue crack if it reaches the fatigue limit of the material.

The tangential loading strongly modifies the development of the plastic zone beneath the contact. For a normal loading, the plastic zone is obtained when $Po \geq 1.6\, \sigma_y$ (σ_y= yield stress) while it is formed for $Po \geq 0.60\, \sigma_y$ with a friction coefficient equal to 0.5. The cumulative overstraining can induce a material transformation leading to the T.T.S..

Depending on their location in the contact, these overstraining or overstressing phenomena can act in a competitive way to justify the material response.

In the case of a cylinder-plane contact, stress calculations were given by Poritsky [34], Smith and Lin [35] and more recently by SACKFIELD and HILLS [33]. The maximum stress value at the contact rear is now given by the tangential expression :

$$\sigma_{xx\,max} = 2\mu\, Po$$

Partial slips are characterised by two contact zones :

- a peripheric slip zone
- a central sticking zone with a c radius. These calculations are based on elastic hypotheses while plastic deformation is generally proved for fretting experiments. For fretting-fatigue experiments, Bramhall [23] and O'Connor [22], Nowell and Hills [36] have considered a flat specimen with a cylinder pad. The tangential load dissymetry tends to increase the maximum $\sigma_{xx\,max}$ at the rear of the contact.

Crack initiation in the case of fretting without external cycling has not yet been intensively considered. Research undertaken by Bramhall [23], O'Connor, Nowell and Hills [24, 25, 36] has established the effect of the displacement amplitude at the contact edge on the life time.

5. FRETTING MAPS

Our fretting methodology is based on the following experiments which have been described elsewhere [37].

a) Fretting tests are conducted under a normal load Fn fixed in the range 200 to 1000 N and for a displacement range of ± 10 to ± 100 µm. The tangential force is continuously recorded during the N cycles.

b) Friction logs i.e. tangential load versus displacement as a function of the number of fretting cycles, are plotted.

c) After testing, all the samples are cut and polished for optical and electron microscopy examinations so as to detect surface and bulk damages.

Many metallic, polymeric or composite materials have been tested. Tangential force-displacement cycles have been used to define three fretting regimes (a, b, c) which are associated with the three material responses (i, ii, iii) defined from optical examinations.

a) Stick regime : the tangential loads increase with the displacement and then decrease linearly with the same value, during the reverse movement. The cycle is closed (actually a small opening of the cycle may exist, which is below the accuracy of the measurement : Mindlin's description of partial slip may apply sometimes for this kind of cycle) ; no sliding is achieved at the interface ; only elastic deformation of the device and of the sample occurs for the imposed displacement.

b) Mixed regime : in this cycle, after the elastic part, the relation between the tangential load and the displacement is no longer linear. This cycle is called an elliptic cycle. The non-linear part of the curve represents a decrease in the rigidity while the non-reversibility of the curve indicates that sliding occurs in the contact, at least partially. Such elliptic cycles can also be recorded for large cracks which accommodate the displacement by an "opening-closing" process but the Ft-D slope then strongly diminishes.

c) Gross slip regimes : in a parallelepipedic cycle, the tangential load remains quasi-constant beyond a small value of the displacement. This occurs when complete sliding takes place in the contact. The elastic part of the cycle is the same as that observed in the closed cycle and the real displacement is smaller than the imposed displacement.

Concerning the material response, three cases were identified :

i) low damage surfaces only suffered small plastic deformation of some asperities. Very few particles were seen, resulting probably from the initial stages and the microdisplacement on the edge of the contact area. This was considered as a "non degradation" response and mainly related to the stick fretting regime.

ii) two main kinds of cracks have been observed. Deep cracks of some millimeters in length were located at (or very close to) the contact boundary for the stick or mixed regime. For partial slips with sticking and sliding zones the longer cracks were always noted at the boundary while plastic deformation was revealed in the center of the contact. In the case of gross slip, cracks were detected everywhere in the contact [38].

iii) Debris were always seen during the slip regime. For several metallic alloys, we showed that debris are formed from the specific area called a Tribologically Transformed Structure (T.T.S.). This zone reacted differently from the non transformed initial structure (white layer for steels). It is very hard and is formed by a nanometric grains and composed of the stablest phase as described by the equilibrium diagrams. The quick formation of the T.T.S. justifies that a same alloy treated under several thermomechanical treatments exhibits the same fretting behaviour because the debris rheology depends only on the T.T.S. [19, 39].

For wear induced by fretting, the following process is now admitted :

a) the gross slip induces a destruction of surface screens and sets a two-body problem.

b) wear particles are formed following adhesion and plastic deformation. The strain hardened material (e.g. the T.T.S) embrittles, it fractures and metallic debris is detached.

c) once formed the particles crash and oxidize to form the third body layer.

d) the displacement is accommodated by shearing in oxide platelets.

If debris are trapped, the maintenance of a powdered bed governs the subsurface protection and wear. Debris indeed fight wear and are not at all wear particles.

When analysing the friction logs, the Ft-D cycles and the material responses, the concept of fretting map allows for a good control of the wear process. A running condition fretting maps (RCFM) is similar to the maps introduced by Vingsbo and Söderberg.[17] RCFMs describe the various fretting regimes for a given number of cycles when the normal load and displacement are modified. They are related to the contact conditions : stick, gross slip and partial slip. To take into account the friction log shape, a mixed regime is preferred to partial slip since it is generally obtained through several cycle shapes. (parallelepipedic followed by closed then elliptic cycles).

The material response fretting maps (MRFM) give the three domains defined on the basis of the microscopic observations (Non Degradation, Cracking, Particle Detachment) in the same kind of normal load versus displacement representation. Generally MRFMs cannot be superimposed on the RCFMs : the Particle detachment domain is associated with gross slip regime but the cracking domain first depends on the number of cycles as in any fatigue problem. The cracking domain first appears in the mixed regime domain and then spreads over the stick domain.

The prediction of the MRFMs requires :

- the comparison of the tensile skin stress to the fatigue limit of the material,
- the modelling of the T.T.S. related to the cumulative plastic strain in the upper layers.

The RCFMs identify the fretting regime and thus permit the calculation or the estimation of the stress and strain fields. If we consider that similar running conditions induce the same fretting regime, two cases can be analysed :

- the RCFM domain is a gross slip regime. Thus the main degradation is particle detachment resulting from overstraining, cyclic hardening and T.T.S. formation. For a same material group, the formation mechanism and the nature of the T.T.S. are very similar. Thus two same based alloys will have very similar tribological behaviours all the more so since the debris will have the same tendency towards oxidation and trapping.

- In the case of the stick or mixed regime, cracking is the main risk which depends on the σ_{xx} value at the contact frontier. Classical fatigue properties govern the nucleation of the fatigue cracks and their propagation. The two previous alloys will have far different behaviours according to their fatigue properties and, for instance, their residual stress levels. These differences increase with the number of cycles.

The definition of the MRFM gives development engineers a tool for the qualitative prediction of material behavior. Indeed, the knowledge of the displacement in the structure and of the local loading allows for the prediction of the major risk in terms of durability (fissuration) and of loss of function (debris formation). Even if the character of the step is too qualitative, it is a new and useful method. To give an example, the MRFM allows for the situation of the maximum risk of fissuration which is not necessairly associated with exterior maximum loading.

The two maps that we propose here have, in our opinion, the principal interest of displaying the critical area called cracking which corresponds to the criteria of crack propagation. Different measures can be adopted for industrial purposes taking these two maps into consideration.
The mixed and sticking areas of the RCFM can be diminished in order to limit the maximum value of the constraint σ_{xx}. Thus the use of sliding varnish can bring about the diminishing of the risk of σ_{xx} going beyond the fatigue stress . As a second possibility, the use of the MRFM map shows the interest of increasing the fatigue strength of materials : this increase is of little usefulness if the contact is in total sliding. It is significant in the mixed regime. Here a shot peening is an excellent way to fight against cracking in small displacement. The user disposes of a third method, not developed here, which consists in the use of a third body or a film in which the difference in velocity can adapt between the two first bodies.

The use of maps and velocity accommodation mechanisms seems to us to be the means to rationalize the seeking of solutions. This same approach has been used to justify the corrosion action in fretting.

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Fretting Fatigue of Galvanised Steel Roping Wire

Fatigue au frottement des câbles métalliques en fils d'acier galvanisés

Reibermüdung galvanisierter Stahldrahtseile

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SUMMARY

Both hot-dipped and drawn galvanised wire show a marked increase in fatigue strength under fretting conditions in air and artificial seawater. In air the zinc layer accomodates the fretting movement due to its capacity for plastic deformation. The drawn galvanised wire is superior to the hot-dipped beause the final drawing operation closes up porosity and other defects. In seawater the cathodic protection provided by the zinc is the operative factor.

RÉSUMÉ

Les fils d'acier galvanisés à chaud aussi bien que ceux zingués retréfilés font preuve d'une résistance à la fatigue nettement accrue, dans des conditions de frottement à l'air et dans l'eau de mer artificielle. Dans l'air, la couche de zinc absorbe le mouvement de friction grâce à sa capacité de déformation plastique. La supériorité des fils zingués retréfilés sur ceux galvanisés par trempage à chaud provient de la fermeture des pores et d'autres défauts de surface pendant le processus d'étirage. Dans l'eau de mer, la couche de zinc assure une protection cathodique déterminante.

ZUSAMMENFASSUNG

Sowohl heißgetauchte als auch gezogene galvanisierte Drähte zeigen eine deutlich gesteigerte Ermüdungsfestigkeit unter Reibbedingungen an der Luft und in künstlichem Meerwasser. An der Luft nimmt die Zinkschicht die Reibbewegung mittels plastischer Verformung auf. Die Überlegenheit gezogener galvanisierter Drähte gegenüber heißgetauchten ist auf den Verschluß von Poren und anderen Fehlstellen im Ziehprozeß zurückzuführen. In Meerwasser ist der kathodische Schutz durch das Zink entscheidend.

1. INTRODUCTION

All steel ropes, whatever their construction, contain multitudinous inter-wire contacts. In stranded ropes and in particular in single strand ropes where the wires are arranged in close-packed layers with succeeding layers wound in opposing sense, the inter-wire contacts are of two distinct types. Between wires in the same layer the contact is a line contact, but between wires in adjacent layers the contact is angled and is usually referred to as a "trellis" contact. When such a rope is under tension and subjected to fluctuating stresses, there is the possibility of oscillatory relative motion of small amplitude at such contacts resulting in fretting damage. Fig. 1 shows a fatigue failure resulting from such damage. In the particular application considered in this paper, the rope was a single strand rope containing several hundred wires of diameter 5mm, and its function was as a mooring rope for an offshore oil rig. Although the rope was sheathed in polythene the possibility had to be considered that damage might be caused to the sheathing and seawater gain access to the steel rope. It is thought that the experience gained with this type of rope could well be of relevance to ropes used in suspension bridges, although it is unlikely that bridge ropes would ever be immersed in seawater, they could nevertheless be operating in severe corrosive conditions in coastal areas or regions of industrial pollution. There is evidence, however, that fretting in bridge ropes has a dominating influence on the extent of fatigue damage [1].

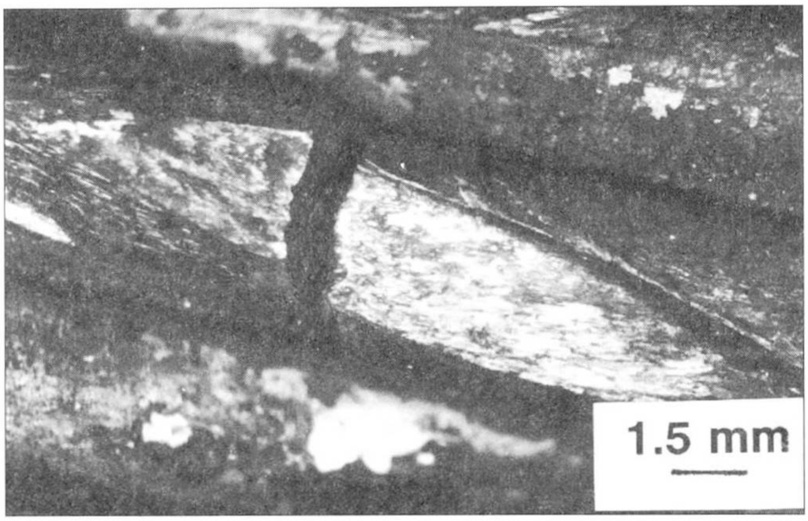

Fig. 1 Failure in a wire due to fretting at a trellis contact.

The mooring rope is under tension but experiences fluctuating stresses resulting from the movement of the surrounding seawater.

In the present work the behaviour of inter-wire contacts was investigated when a single wire was subjected to fluctuating tension. An important factor in such contacts was found to be the location of the contact in relation to the residual stress field in the surface of the wire [2]. In the work described in this paper, the contacts were made at the ends of a diameter of the wire perpendicular to the plane of the coil of the wire, where the residual stresses are the same and have a maximum tensile value. The magnitude of the residual stresses depends on the degree of reduction in the final die in the drawing process. The greater that reduction the higher the residual stresses. However, the heat-treatment experienced by the wire in hot-dipped galvanising, where the wire is passed through a bath of molten zinc, considerably modify these stresses.

2. EXPERIMENTAL

The fretting fatigue tests were carried out using a 20 kN servo-hydraulic fatigue machine. The ends of the wire were gripped in a capstan device to minimise fretting and failure at these points. Fretting was produced by clamping a pair of bridges comprising four short lengths of the same wire as the specimen on to the specimen with a proving ring which allowed the clamping load to be adjusted. The fretting device was surrounded by a transparent plastic cell which allowed the environment to be controlled. In the present case this was limited to laboratory air and seawater, the latter being continuously pumped through the cell. The experimental arrangement is shown in Fig. 2.

Tests were carried out at a frequency of 5 Hz with a constant maximum stress of 950 MPa and a variable minimum stress to give stress amplitudes of the range 120 to 400 MPa. Over this range of stress the slip amplitude varied between 3 and 10μm. The clamping load of 250 N at each contact was maintained constant in all tests.

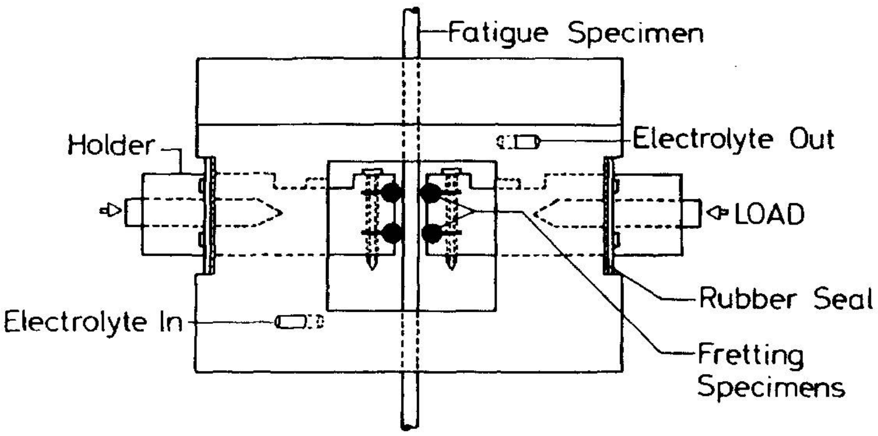

Fig. 2 Experimental rig for testing steel wires under fretting conditions.

For operation in severe corrosive conditions such as seawater it is usual to use galvanised wires. In this work two types of galvanised wire were used. The first was hot-dipped galvanised where the passage through the molten zinc bath is the final stage of production. The second type was where the wire was passed through the molten zinc prior to drawing through the final die. The thickness of the outer layer of equiaxed crystals of zinc in the two cases is 30μm for the former and 5μm for the latter. The underlying Fe-Zn alloy layer and the intermediate layer of columnar crystals is approximately the same in both cases.

The manufacturing conditions were such as to maintain the mechanical properties of the wire at a constant level whether galvanised or not galvanised, as shown in Table 1.

Breaking load N	UTS MPa	0.2% PS MPa	Hardness VHN
34000	1700	1300	520

Table 1 Mechanical Properties of Wire Samples

3. RESULTS

One effect of the galvanising process is to reduce the residual tensile stress in the wire. A specimen of the wire given the equivalent heat treatment of the galvanising process reduced the maximum residual stress from 340 Mpa to 80 MPa. The effect on the fatigue strength of the wire can be seen in Fig. 3 where the increasing residual stresses were produced by reductions in the final die of 5, 12 and 26.5%. Measurement of residual stress on the hot-dipped galvanised wire after removal of the zinc coating was found to be 125 MPa.

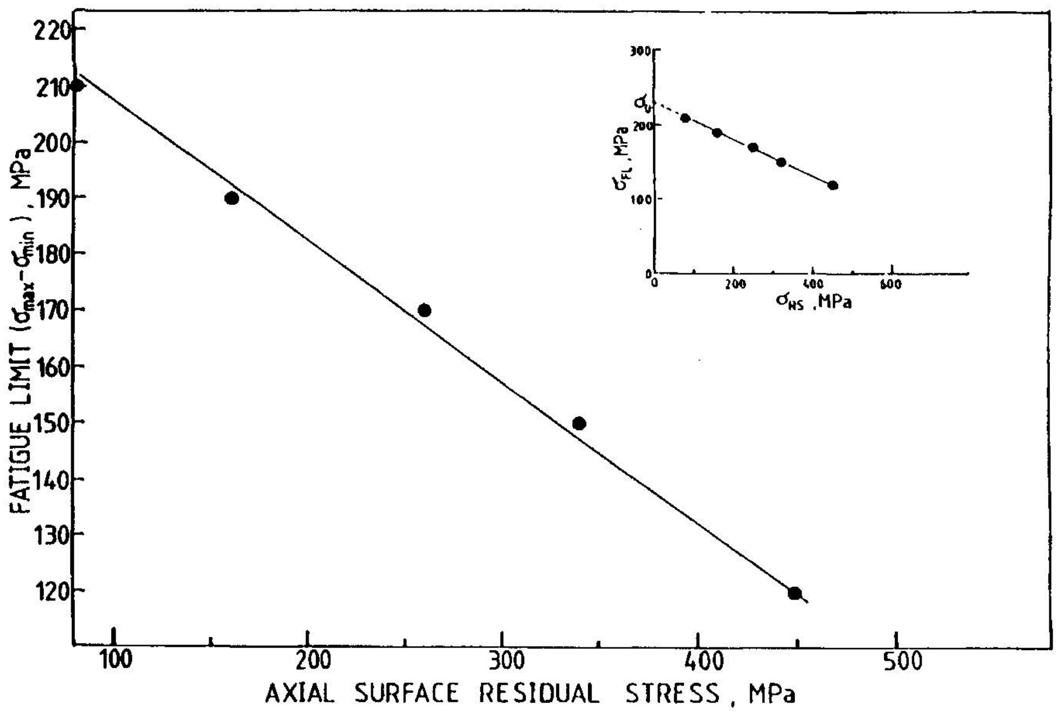

Fig. 3 Effect of axial surface residual stress on the fatigue limit of 5mm dia. steel roping wire under fretting conditions.

The effect of the two types of galvanising on the fatigue curves in air and seawater are shown in Figs. 4 and 5. It is apparent that both treatments produce approximately the same result both in air and seawater. Included in the figures are the curves for the untreated wire in the two environments. It should be noted that the untreated wire in seawater has no fatigue limit.

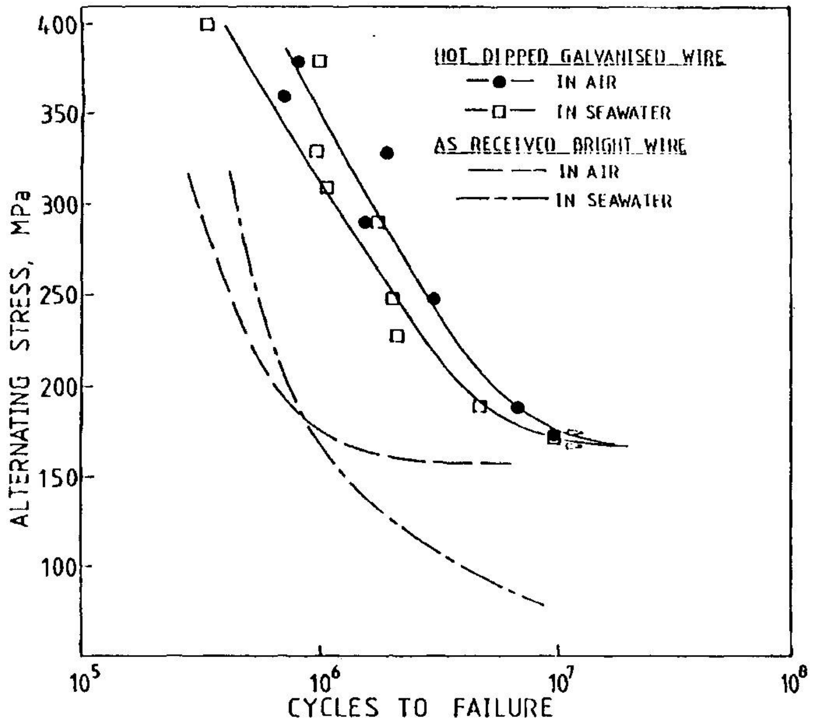

Fig. 4 Fatigue curves for hot-dip galvanised wire in air and seawater under fretting conditions.

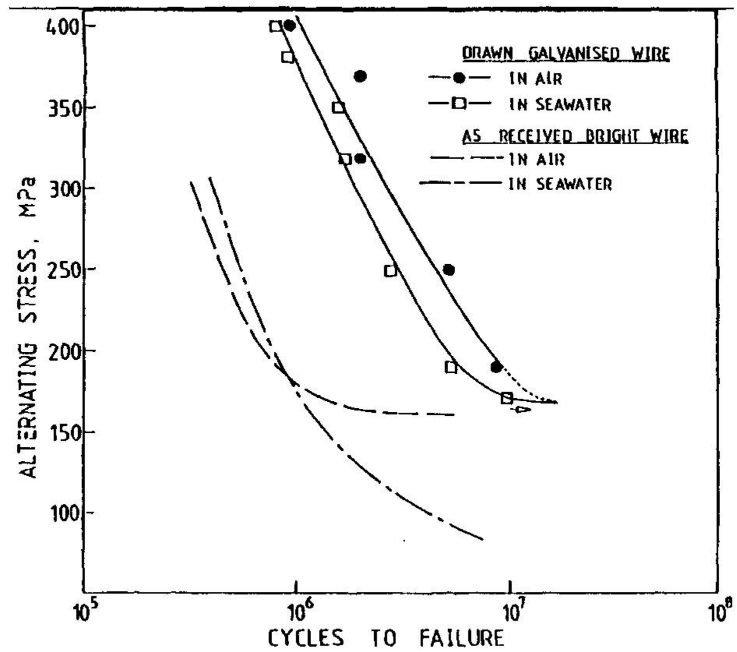

Fig. 5 Fatigue curves for drawn galvanised wire in air and seawater under fretting conditions.

Fig. 6 shows cracks developed in a pair of fretting scars. In all cases they were at the outer edge of the scar.

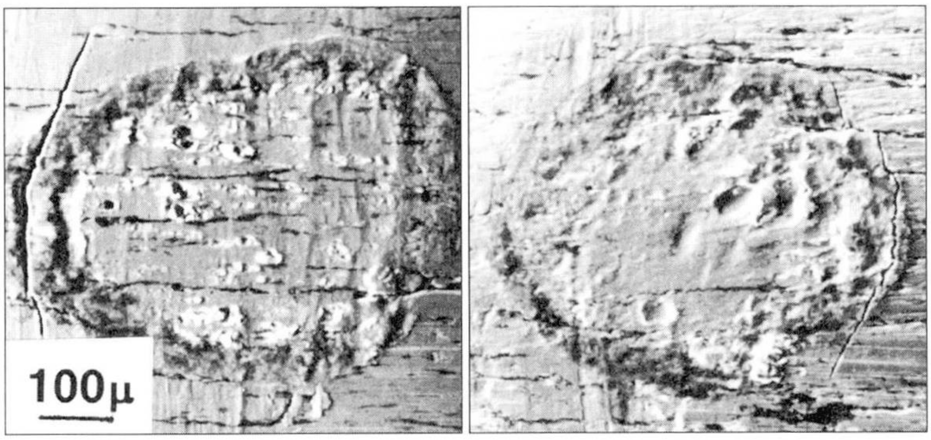

Fig. 6 Pair of fretting scars on ungalvanised wire showing fatigue cracks.

4. DISCUSSION

By making the fretting contacts at the points of maximum residual tensile stress in the surface means that the fretting results in the most severe fatigue damage. In earlier work on 1.5mm dia. wires of UTS 1900 MPa, it was found that hot-dip galvanising produced a reduction in the fatigue limit in air of the as-drawn wire of 7% [3]. This was attributed to the presence of the hard, brittle Fe-Zn alloy layer resulting from the galvanising. Fatigue curves of electrodeposited zinc coated wires showed an increase in fatigue strength depending on the thickness of the zinc layer. This increase was a linear function of the square of the coating thickness [4]. This relationship had been found with other electrodeposited metal coatings on steel [5]. In the absence of the Fe-Zn alloy layer the soft zinc coating has a protective effect against fretting.

In the present case the wires with the two types of galvanised coating both have almost the same fatigue strength as the uncoated wire in air. There is evidence that fretting causes the initiation of fatigue cracks in the Fe-Zn alloy layer which then propagate into the underlying steel. In the 1.5mm dia. wire such cracks would result in rapid failure, whereas in the larger 5mm dia. wires the crack has a much greater distance to propagate to failure. The observation in Figs. 4 and 5 that the fatigue life at alternating stresses above the fatigue limit is considerably longer in the galvanised wires than in the uncoated wire shows that the zinc coating has an appreciable effect on the overall propagation of the fatigue crack. In the case of the 1.5mm dia. wires the fatigue lives above the fatigue limit were the same for the galvanised and uncoated wires [4].

In seawater the two galvanised coatings produce a marked increase in the fatigue strength due to the cathodic protection afforded by the zinc coating. This improvement has been shown to be comparable to that produced by imposing cathodic protection of -950 mV vs. SCE [6]. Above the fatigue limit the fatigue lives in seawater are slightly shorter than in air. It has been shown earlier that cathodic protection is only effective in retarding crack growth up to a crack length of about 30μm [7]. At greater depths the crack will be propagating under the corrosive influence of the seawater and therefore at a greater rate than in air.

At alternating stresses above the fatigue limit the drawn galvanised wires have a somewhat longer fatigue life in both media. This is attributed to the drawing process, while not influencing the alloy and columnar layers, consolidates and closes up defects in the outer equiaxed layer and reducing its thickness.

5. CONCLUSION

The hot-dip and drawn galvanised wires both produce an increase in fretting fatigue life in air above the fatigue limit, but have little effect on the fatigue strength of 5mm steel wires. In seawater the fatigue strength is restored to that in air.

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Interwire Contact Forces and Behaviour of Spiral Strands

Forces de contact entre fils et comportement général des brins en spirale

Kraftübertragung zwischen Drähten in gedrillten Litzen

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SUMMARY
The importance of catering for the effect of interwire/interlayer contact patches on various spiral strand overall characteristics is briefly discussed. Simple guidelines are given for carrying out appropiate single (or thin) wire fretting fatigue experiments for predicting and/or improving spiral strand fatigue performance.

RÉSUMÉ
L'effet de surface de contact entre fils et couche sur l'ensemble des caractéristiques des divers brins en spirale est présenté. Des directives simples sont données pour effectuer des essais fatigue due au frottement des fils simples (ou doubles) permettant de prédire et/ou d'augmenter la performance optimale due à la fatigue des brins en spirale.

ZUSAMMENFASSUNG
Die Verhaltensmerkmale gedrillter Litzen sind stark von den unterschiedlichen Kontaktverteilungen zwischen den Drähten oder Drahtlagen abhängig. Wie gezeigt wird, können nach einfachen Richtlinien Reibermüdungsexperimente an Einzel- oder Doppeldrähten durchgeführt werden, um das Ermüdungsverhalten gedrillter Litzen vorherzusagen oder zu verbessern.

1. INTRODUCTION

Over the last thirteen years, a substantial effort has been put by the present author and his associates into assessing contact forces and the associated relative displacements between individual wires, taking full account of frictional effects, in large and multi-layered spiral strands undergoing a wide variety of loading regimes. This has been achieved by employing the orthotropic sheet concept based on which the individual layers of helical wires in a spiral strand have been modelled as a series of partly self-prestressed orthotropic cylinders which structurally interact. Thus each layer of wires, although discontinuous, has its elastic properties "averaged" in a way familiar in the analysis of stiffened plating for bridge decks and ship hulls. Results from contact stress theory are used to determine the properties of the orthotropic sheets, whose principal axes run parallel and perpendicular to the individual wire axes. The chief advantage of this approach is that its accuracy improves as the number of wires in a given layer increases; i.e. for practical wire sizes, as the size of spiral strand grows. This desirable situation may be contrasted with the decreasing accuracy and increasing complexity as the number of wires increases associated with certain previously available methods of analysis which have primarily been developed for frictionless wires. Space limitations do not permit a detailed review of the available literature on various aspects of wire rope behaviour. The interested reader may refer to fairly recent surveys of Utting and Jones (1), Costello (2) and Chaplin and Potts (3) for further information. For the present purposes, much attention will be devoted to the application of the orthotropic sheet theory to steel cables.

2. MODELS BASED ON THE ORTHOTROPIC SHEET CONCEPT

For a given mean axial load, the orthotropic sheet approach yields estimates of axial (4), torsional (5) and free bending (6) stiffnesses, which are found to be functions of the applied axial, torsional, and free bending load perturbations, respectively. The stiffnesses for small load changes can be much larger than for large load perturbations, because sufficiently small disturbances do not induce interwire slippage. The theoretical models for various loading regimes predict the bounds to the stiffnesses and describe the variation between them.

It is now possible to predict the energy dissipation under continued uniform cyclic axial, torsional and free bending loading by assessing the energy dissipation per cycle on each of the contact patches within the strand: summation yields a value for overall hysteresis of axially preloaded spiral strands (5, 6, 7).

Once fatigue is addressed, the number of variables involved makes effect of mean axial load, and grade of wire have been investigated theoretically.

To extend the present analytical model to cater for the effect of sea-water corrosion, Equation (7a) may be rewritten as (16).

$$S_e = K_c\ K_a\ K_b\ S' \tag{8}$$

where K_c is a parameter defined as the ratio of single wire fretting fatigue endurance stress in air to the corresponding reduced value of stress in sea-water at a fatigue life of $N_c = 10^7$ cycles. For example, for small diameter (1.5-2.5mm) wires, data from Takeuchi and Waterhouse (18) and Thorpe and Rance (19) suggest that $K = 0.7$. Cable S-N curve under sea-water corrosion may thus be estimated by using Equation (8) instead of Equation (7a) which assumes $K_c = 1$ for in-air conditions. Otherwise, the calculation procedure is the same as the corresponding in-air condition. Fig. 2 presents a theoretical comparison of in-air and in-sea-water outer layer axial fatigue lives for a 45mm diameter spiral strand (13). The plots cover K_a values in the range $0.5 \leq K_a \leq 1.0$, while the K_c values for in-air and in-sea-water are 1.0 and 0.70, respectively. An examination of the theoretical results provides an explanation for the previously reported experimental observations (15) in which no marked reduction in axial fatigue life (cf. in-air data) due to the presence of sea-water is reported: the usual degree of scatter in-air fatigue lives covered by $0.5 \leq K_a \leq 1.0$ may easily mask the rather smaller reduction in life due to sea-water corrosion as simulated under laboratory conditions.

For an elliptical contact patch carrying a constant normal force, P, and a monotonically increasing torque, M, the torque causes the spread of an annular region of slip from the outer edge of the contact towards the centre of the patch, until adhesion is completely lost and gross sliding takes place. Raoof (8) has used such results in the field of contact stress theory to determine the ratio a*/a, where a = semi major axis of the individual trellis contact patches which under partial slip conditions possess a no-slip part whose semi-major axis is a*, Fig. 3. This figure shows variations of a*/a of the individual trellis points of contact as a function of cable axial load perturbation for two different levels of mean axial load on a 39mm spiral strand with an ultimate tensile strength of 0.123MN and whose outer layer is layer number 1. Fig. 3 illustrates that for the practical ranges of axial load perturbations, the spread of the partial slip zone over the trellis points of contact is not very significant. Indeed, it is demonstrated that gross sliding is unlikely to occur. On the other hand, theoretical results (backed by experimental observations) strongly suggest that gross sliding over the line-contacts between various wires in any given layer start at much lower levels of range to mean ratio of axial load on the cable (7). The principal source of strand overall hysteresis is, therefore, the interwire

It is not the intention to repeat the often lengthy analytical derivations and/or experimental techniques here, nor, indeed, does space permit such repetition. In view of their prime importance, the following sections give an account of the controlling role of the pattern of contact patches on cable fatigue performance.

3. INTERWIRE/INTERLAYER CONTACT PATCHES

3.1 Background

Full details of the various patch compliances are given elsewhere (4) and it is useful to review some phenomena associated with contact patch behaviour. Two classes of interwire contact occur in a multi-layered spiral strand. The first, which governs the overall axial, torsional, and free bending (i.e. in the absence of sheaves, fairleads, or other formers) stiffnesses, and associated hysteresis under cyclic loading, is the contact within a given layer between adjacent "parallel" wires. In terms of contact stress theory, this case can be regarded as the line-contact of parallel cylinders. The second class, which is less important for the above strand stiffnesses and associated hysteresis but which play a central role in fatigue phenomena, involves the contact between wires in different layers at the "trellis" points.

Taking cyclical axial loading (on a strand whose ends are not allowed to rotate) first, the line-contacts within a layer (class 1) clearly experience a cyclical variation of the direct normal force on the contact as a result of the variation in the clench forces on the layer caused by the changing axial load. Each line-contact patch also experiences a varying shear force which tends to cause sliding of one cylinder parallel to the other, as a consequence partly of the tendency of the lay angle to decrease in association with the increase in cable axial strain, S'_1, and partly due to the induced axial strain in individual wires, S_1, where, it can be shown that (14)

$$\frac{S^i_1}{S'_1} = 1 - 0.00255\alpha_i + 0.000215\alpha_i^2 - 0.000027\alpha_i^3 \qquad (1)$$

$$0 \le \alpha_i \le 25°$$
$$S'_1 \le 0.005$$

where, the lay angle in layer i, α_i , is expressed in degrees, and S^i_1 is the wire direct strain in layer i.

The tensorial shear strain, S^i_{6T} , over the line-contact patches in layer i is given by (14).

$$S^i_{6T} = S'_1 \; F\,[\alpha_i] \qquad (2a)$$

where

$$F[\alpha_i] = 0.0196\alpha_i - 0.000394\alpha_i^2 + 0.0000247\alpha_i^3 \qquad (2b)$$

Using Equations (2a) and (2b), the magnitude of interwire line-contact slippage, u_i, in layer i, whose wire diameter is D_i, is given as

$$u_i = 2D_i S^i_{6T} \qquad (3)$$

The change in the lay angle, $d\alpha_i$, in layer i, as a function of the lay angle, α_i, and cable axial strain, S'_1, may simply be obtained from (14).

$$\frac{d\alpha_i}{S'_1} = 0.0203\alpha_i + 0.000576\alpha_i^2 - 0.0000395_i^3 \qquad (4)$$

$$0 \le \alpha_i \le 25°$$
$$S'_1 \le 0.005$$

where, $d\alpha_i$ and α_i are expressed in radians and degrees, respectively.

The interwire/interlayer relative rotation, $d\omega_i$, over the trellis points of contact between layers i and i+1, is then given as

$$d\omega = |d\alpha_i| \pm |d\alpha_{i+1}| \qquad (5)$$

where, the positive sign holds for the case when the two adjacent layers have opposite lay.

Simple routines for obtaining the magnitude of normal forces on the line and trellis contact patches have, on the other hand, been presented elsewhere (4). However, it transpires that Eq. (19) in Ref (4) should be replaced by

$$X_{Ri} = X_{MSi} - 2P_{Msi} \cos\beta_i$$

Note that all the results presented in various papers of the present author to date are based on the above Equation rather than Equation (19) in Ref (4).

The above information is of direct relevance as an input to interwire fretting fatigue experiments aimed at improving cable fatigue life. Such data should also prove rather useful in the context of tests between individual wires with different types of lubrication in order to determine the relative efficiency of various lubricating compounds under a variety of interwire fretting conditions such as those occurring inside an axially preloaded spiral strand as discussed in the next section.

3.2 Fretting fatigue phenomena and strand fatigue performance

The fretting problem is an extremely difficult one and, in the absence of relevant experimental data, it is not easy to draw any reliable conclusions from purely analytical techniques. Nevertheless, careful examination of the literature in the general field of fretting fatigue, coupled with available contact stress theories and load-displacement values such as those discussed in the previous section, should help to design (and, later on interpret the results of) interwire fatigue tests aimed at predicting and/or improving cable fatigue performance. A fairly recent account of available fretting fatigue results for individual wires such as those reported by, say, Waterhouse and his associates is presented by Chaplin and Potts (15). For the present purposes, a few introductory remarks may give a feeling for the complexities involved and is hoped to provide a few clues as how to tackle the problem of cable fatigue performance.

Fairly recently, the present author reported theoretical models for predicting axial and restrained bending fatigue life of axially preloaded spiral strands from first principles (8, 9). In both cases, it has been shown that it is the state of contact stresses over the trellis points of contact which primarily control cable fatigue life, although the modes of trellis contact displacements in the context of axial and bending loading regimes are very different: this is briefly discussed in the following sections in which the need for further fretting fatigue experiments employing realistic values and modes of contact forces and relative displacements, is emphasized.

3.2.1 Axial fatigue

The orthotropic sheet theory has been used for obtaining estimates of interwire/interlayer contact stresses throughout realistic pre-tensioned multi-layered structural strands. These data have been used to obtain estimates of the maximum Von-Mises contact stresses, σ_{max}, on the individual elliptic trellis (interlayer) contact patches. For each individual trellis contact patch, a stress concentration factor is defined as

$$K = \frac{\bar{\sigma}_{max}}{\bar{\sigma}} \qquad (6)$$

where $\bar{\sigma}_{max}$ is the maximum Von-Mises stress at a given strand mean axial load which occurs at a depth z below the surface of contact patch central axis, and $\bar{\sigma}$ is the corresponding mean nominal axial stress in the individual wires due to strand tension.

Using the so-obtained values of K_s in conjunction with axial fatigue data on single wires, a theory has been developed which predicts the axial fatigue life of strands (under constant amplitude cyclic loading) from first principles (8). The theoretical interlayer slippage over the individual points of contact between various layers has also been addressed which takes interwire friction into account.

The reduced magnitude of the endurance limit, S_e, which takes interwire contact and fretting plus surface conditions and size effects, etc., into account may be defined (8) as:

$$S_e = K_a K_b S' \tag{7a}$$

where (13)

$$S' \approx 0.27 S_{ult} \tag{7b}$$

In the above, K_a = surface finish factor, and $K_b = 1/K_s$, with S_{ult} = ultimate wire stress, and S' = wire endurance limit.

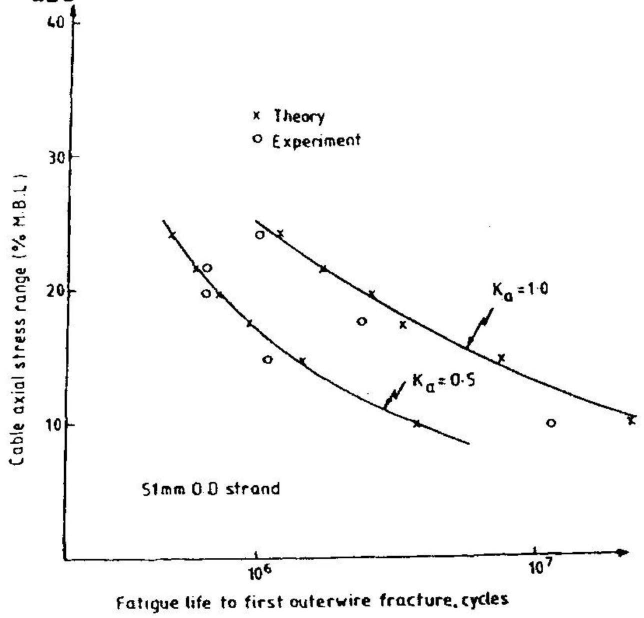

Fig.1 Comparison of theoretical and experimental axial fatigue S-N curves

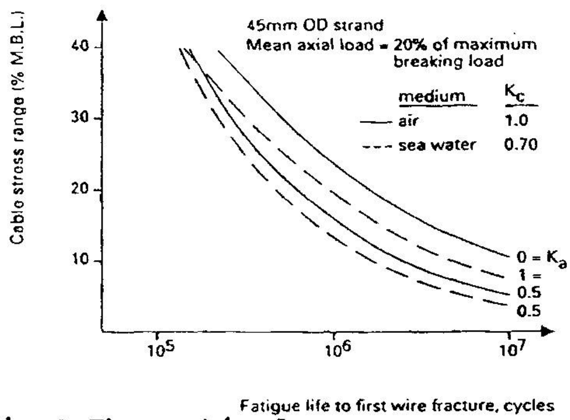

Fig.2 Theoretical comparison of in-air and in-sea-water S-N curves

Figure 1 compares the theoretical axial fatigue life predictions with experimental data on a 51mm diameter spiral strand. The criterion for fatigue initiation has been the occurrence of first wire failure in the outer layer. With epoxy resin end terminations, all the wire failures occurred away from the ends (in the free field). A fairly significant degree of scatter was found in the experimental data which may be covered by empirical finish factor K_a in the range $0.5 \leq K_a \leq 1.0$. similar encouraging correlations using $K_a = 0.5$ have been found between experimental data and theory on a 39mm diameter strand (8) and Tilly's (17) experimental data (16). The theory indicates that internal wire fractures invariably occur prior to external wire fractures. Moreover, other effects such as those due to the effect of mean axial load, and grade of wire have been investigated theoretically.

To extend the present analytical model to cater for the effect of sea-water corrosion, Equation (7a) may be rewritten as (16).

$$S_e = K_c\ K_a\ K_b\ S' \tag{8}$$

where K_c is a parameter defined as the ratio of single wire fretting fatigue endurance stress in air to the corresponding reduced value of stress in sea-water at a fatigue life of $N_c = 10^7$ cycles. For example, for small diameter (1.5-2.5mm) wires, data from Takeuchi and Waterhouse (18) and Thorpe and Rance (19) suggest that K = 0.7. Cable S-N curve under sea-water corrosion may thus be estimated by using Equation (8) instead of Equation (7a) which assumes $K_c = 1$ for in-air conditions. Otherwise, the calculation procedure is the same as the corresponding in-air condition. Fig. 2 presents a theoretical comparison of in-air and in-sea-water outer layer axial fatigue lives for a 45mm diameter spiral strand (13). The plots cover K_a values in the range $0.5 \leq K_a \leq 1.0$, while the K_c values for in-air and in-sea-water are 1.0 and 0.70, respectively. An examination of the theoretical results provides an explanation for the previously reported experimental observations (15) in which no marked reduction in axial fatigue life (cf. in-air data) due to the presence of sea-water is reported: the usual degree of scatter in-air fatigue lives covered by $0.5 \leq K_a \leq 1.0$ may easily mask the rather smaller reduction in life due to sea-water corrosion as simulated under laboratory conditions.

For an elliptical contact patch carrying a constant normal force, P, and a monotonically increasing torque, M, the torque causes the spread of an annular region of slip from the outer edge of the contact towards the centre of the patch, until adhesion is completely lost and gross sliding takes place. Raoof (8) has used such results in the field of contact stress theory to determine the ratio a*/a, where a = semi major axis of the individual trellis contact patches which under partial slip conditions possess a no-slip part whose semi-major axis is a*, Fig. 3. This figure shows variations of a*/a of the individual trellis points of contact as a function of cable axial load perturbation for two different levels of mean axial load on a 39mm spiral strand with an ultimate tensile strength of 0.123MN and whose outer layer is layer number 1. Fig. 3 illustrates that for the practical ranges of axial load perturbations, the spread of the partial slip zone over the trellis points of contact is not very significant. Indeed, it is demonstrated that gross sliding is unlikely to occur. On the other hand, theoretical results (backed by experimental observations) strongly suggest that gross sliding over the line-contacts between various wires in any given layer start at much lower levels of range to mean ratio of axial load on the cable (7). The principal source of strand overall hysteresis is, therefore, the interwire line-contact slippage as has been assumed in the present author's axial hysteresis model (7). However, experimental observations suggest that wire breakages (at least away from terminations) are predominantly located over the trellis contact points which, although invariably experience the partial slip state of fretting, do suffer from much more significant levels of maximum Von-Mises stress compared with the corresponding line-contact patches (16). Indeed, these theoretical and experimental observations have formed the basis of the proposed strand axial fatigue model which assumes the maximum Von-Mises stresses in the interlayer (trellis) points of contact as the primary factor controlling strand axial fatigue life.

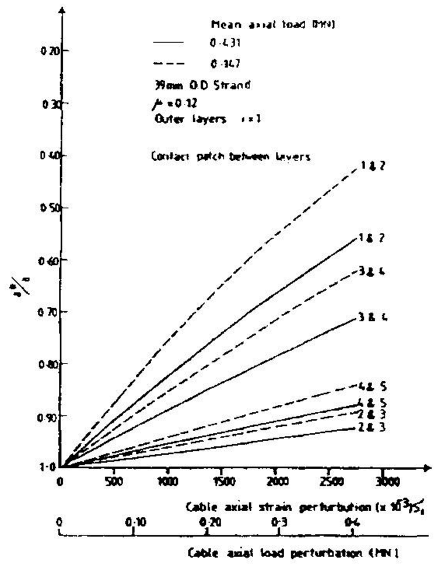

Fig.3 Spread of partial-slip zones in various trellis contact patches in a 39mm O.D. strand

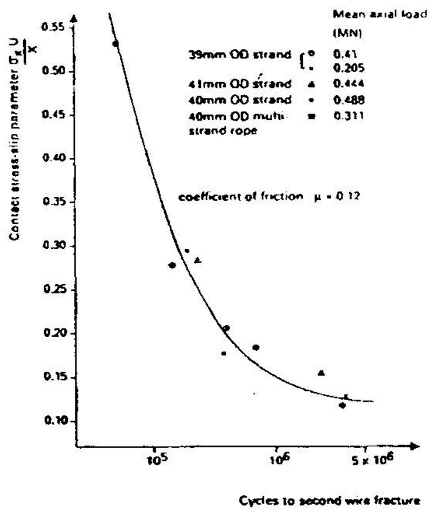

Fig.4 Plot of contact stress-slip parameter against restrained bending fatigue life for a number of steel cables

3.2.2 Restrained bending fatigue

There is surprising little information available on fatigue performance of spiral strands in free bending. The majority of published work concentrates on the influence of pulleys and sheaves as sources of wear and fatigue damage. Turning to the question of bending fatigue close to the termination, some experimental results (20) for a 39mm strand are of interest. In these tests, the initial wire breaks invariably occurred not near the extreme fibre but close to what would be regarded as the neutral axis in a rigid rod. This position can be shown, theoretically and experimentally (21), to be the location where the slip between the outer and penultimate layers of wires is largest. Thus interwire or rather interlayer fretting has been assumed to be the most likely cause of wire breakages, and to be much more relevant to a discussion of fatigue life than the traditionally assumed maximum wire stresses near the extreme fibres (6).

In detail, the life to second wire fracture (the second wire being approximately 5% of the outer layer wires, a popular but by no means universally accepted indication of incipient overall failure) was compared with the maximum wire stresses found in the author's experiments and calculations (22). A weak correlation was found in that it was possible to sketch curves through the data points - but the curves for each mean strand axial load were well separated.

A newly developed alternative, Fig. 4, appears much more promising. Here, the life to second wire fracture is plotted against a parameter linking

(i) the computed maximum tensile stress, σ_x, at the trailing edge of the interlayer contact patch between wires of opposite lay; i.e. at the edge of the so-called "trellis" contact,

(ii) The computed interlayer relative displacement, U, near the neutral axis at a distance equal to the interlayer contact patch spacing along the wire from the assumed ideally fixed end, and

(iii) the trellis contact patch spacing, x, along any individual wire in the outer layer.

The stress, σ_x, computed on an elastic basis, has been chosen in view of its likely role in fatigue crack initiation in the individual wires; cracks are commonly found at this location. The value of, U, near the neutral axis is taken since the slips (in the form of a sawing action as opposed to the rotational movements under the cable axial loading case) are largest there.

It is encouraging that the use of this parameter makes it possible to draw the single curve of Fig. 4 through the experimental data for a number of spiral strand constructions (9).

Finally, in view of the rather complex nature of the theoretical model, extensive theoretical parametric studies have been carried out for developing straightforward design formulations amenable to simple hand calculations (22).

3.2.3 Appropriate factors for realistic interwire fretting experiments

According to the above, the mode of interwire fretting for the strand bending fatigue at points of fixity is one of a sawing action at the trellis points of the interlayer contact patches as opposed to the torsional mode for the axial case. Theoretical studies suggest that for the average strand construction subjected to typical working axial loads, interwire fretting under restrained bending conditions appears to reach a significant level at rather large values of radii of curvature at the restrained socket. For example, for the 39mm diameter strand under a mean axial load of about 33% of the ultimate breaking load, interwire slippage between the outer and penultimate layers can reach the full-slip (gross-sliding) condition (i.e. relative interwire displacement $\approx$ 0.00085mm), well within the operational radii of curvature (of the order of 10-20 meters) at the restrained end. Full torsional slippage over the trellis points of contact is, however, very unlikely to occur in this same strand, once one addresses the axial fatigue problem. The use of the same modes of interwire contact deformation as those occurring inside spiral strands, in any interwire fretting experiment aimed at predicting and/or improving cable fatigue life is, therefore, strongly recommended. The appropriate levels of input parameters, such as the normal loads and relative deformations, for such experiments may now be realistically determined by the straightforward routines recommended in this paper.

Lubrication is an important factor in cable fatigue performance. In a number of previously reported twin wire experiments which have been carried out to identify the significance of various lubricants as regards cable fatigue performance, the range of input parameters such as magnitude of imposed normal forces and/or relative displacements have not been chosen with due regard given to those that are operative within realistic steel cables. Very often, the mode of interwire contact deformations have been determined by the ease of setting-up the testing equipment with little attention paid to adhering to the most appropriate modes of fretting movements as determined by the actual cable loading conditions. Future tests, however, should take such effects into account.

Finally, there is, at present, an ever increasing demand for larger diameter spiral strands outside the traditional range of cable diameters which tend to employ wire diameters up to, say, 8-9mm. There is currently very limited fretting fatigue data available on such large diameter wires. The majority of published axial fatigue S-N curves for bare wires have also been obtained on specimens with often much smaller diameters. Axial fatigue tests on larger diameter wires should, therefore, be carried out in order to identify possible size effects which may also affect the interwire fretting fatigue performance specially under sea-water corrosion conditions.

4. CONCLUSION

The controlling role of different classes of interwire/interlayer contact patches on various spiral strand overall characteristics is briefly discussed. In particular, the central role of interlayer (trellis) points of contact in the context of cable axial and restrained bending fatigue performance is emphasized in the light of the author's recent theoretical and experimental findings using well established results in the field of contact between elastic bodies.

It is suggested that single (or twin) wire fretting experiments should be carried out under realistic modes of interwire movements representative of the conditions inside steel cables. To this end, some straightforward formulations are presented which should prove useful in estimating the appropriate levels of normal loads and relative displacements to be adopted in such fretting fatigue experiments.

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Fatigue Strength of Wires

Résistance à la fatigue des fils

Ermüdungsfestigkeit von Drähten

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SUMMARY
This paper describes the fatigue strength of prestressing wires which have been manufactured by the state-of-the-art. Taking wires for the automobile engine valve spring as an example, measures to enhance the fatigue strength of plain carbon wire are discussed. Finally, fatigue test data are presented for 7 mm diameter galvanized wire manufactured with all possible precautions to reduce flaws in the process.

RÉSUMÉ
Cet article traite de la résistance à la fatigue des fils de précontrainte fabriqués par les procédés les plus avancés. A partir de l'exemple de fils destinés aux ressorts de soupapes des moteurs de voiture, la discussion porte sur les mesures envisagées pour augmenter la résistance à la fatigue de fils d'acier au carbone non allié. Pour terminer, l'auteur présente des résultats d'essais effectués sur des fils galvanisés de 7 mm, pour lesquels toutes les précautions envisageables ont été prises afin d'éviter l'apparition de défauts de fabrication.

ZUSAMMENFASSUNG
Der Beitrag behandelt die Ermüdungsfestigkeit von nach modernsten Verfahren gefertigten Spanndrähten. Am Beispiel der Drähte für die Ventilfedern von Automotoren werden Maßnahmen zur Steigerung der Ermüdungsfestigkeit reiner Kohlenstoffstahldrähte diskutiert. Abschliessend werden Versuchsergebnisse für 7mm dicke galvanisierte Drähte präsentiert, bei denen alle denkbaren Vorkehrungen gegen Herstellungsfehler getroffen wurden.

1. INTRODUCTION

The ISO Standard for steels for the prestressing of concrete (ISO 6934-1,2,3,4 and 5) prescribes that, if agreed between purchaser and manufacturer, the material shall withstand 2 x 10^6 cycles of a stress fluctuating down from maximum stress of 70% of the nominal tensile strength and that the stress range shall be 200 N/mm^2 for plain wires, 180 N/mm^2 for indented and ribbed wire, 195 N/mm^2 for all strands.[1] The valve spring wire for automobile engine is considered to be the most stringent fatigue oriented product in the wire industry. The high tensile valve spring wire, manufactured by the quenching and tempering method with minimal flaws, can withstand more than 1 x 10^7 cycles at a stress amplitude of more than ±600 N/mm^2 in a rotating bending fatigue test.

It may be possible to improve the fatigue strength of plain carbon wires such as wire for prestressing of concrete and galvanized wire for parallel wire cables if we take some measures to reduce, if not eliminate totally, the flaws in the wire during manufacturing process in a manner as it is done for the valve spring wire. This paper describes how wires are manufactured and consideres where the flaws come in or removed during the manufacturing process of wires. An example of the improvement is given for a commercially manufactured 7 mm diameter galvanized wire for the stay cables of a world class cable stayed bridge.

2. PRESTRESSING WIRE

2.1 Specifications for Prestressing Wire

The tendons in the prestressed concrete members are subjected to relatively small stress fluctuations such as 50 N/mm^2 and a high fatigue performance is not a major requirement for the tendons. Few manufacturers, therefore, paid much attention to the fatigue property of the prestressing steels in the past. The prestressing wires, strands and bars are standardized by most national norms. They are now popular tension elements used to fabricate cables for cable supported structures in many parts of the world because they are strong, easily available and relatively economical. Fatigue requirements are gradually recognized by the users of the prestressing steels. Table 1 shows examples of the specifications for typical prestressing wires.

2.2 Manufacturing Method for Prestressing Wire

ISO 6934 "Steels for Prestressing of Concrete"[1] prescribes only the sulfur and phosphorus contents (both of which not to exceed 0.04%) because the chemical composition shall be related to the type of product, its size and tensile strength. ASTM A 421-90 "Uncoated Stress-Relieved Steel Wire for Prestressed Concrete"[2] also limits only phosphorous and sulfur contents, the maximum being 0.040% and 0.050%, respectively. It states that variations in manufacturing processes and equipment among wire manufacturers necessitate the individual selection of an appropriate chemical composition at the discretion of the manufacturer.

JIS G 3536 "Uncoated Stress-Relieved Steel Wires and Strands for Prestressed Concrete"[3] requires to select wire rod from "JIS G 3502 Piano Wire Rods"[4] as the material for prestressing wires and strands, which means that sulfur and phosphorus contents are lower than those prescribed by ISO and ASTM. The selection of the carbon content, however, is left to the discretion of the manufacturer. JIS further requires patenting for the manufacture of prestressing wires and strands.

Fig. 1 shows a diagram for the manufacture of prestressing wires. To take 7 mm diameter prestressing wire as an example, 12 mm dia. 0.77% carbon wire rod conforming to SWRS 77B in Table 2 is selected. The wire manufacturer receives wire rods from a steel mill. The wire rods are transferred from the storage area to the heat treatment area using a folk-lift truck or a hoisting crane, mounted on a pay-off stand, uncoiled and subjected to "patenting" where it passes through a heating furnace and lead bath and then is coiled. The tensile strength is approximately 1,260 N/mm².

Table 1 Specifications for Typical Prestressing Wires

	ISO 6934-2	ASTM A-421	JIS G-3536
Nominal Diameter, mm Tolerance, mm	7	6.35 ±0.05	7 ±0.05
Tensile Strength, N/mm²	1,570 1,670	1,655	1,520 1,620
0.1% Yield Strength, N/mm²	1,255 1,340	NS	NS
0.2% Yield Strength, N/mm²	NS	1,403	1,325 1,420
Elongation, %/G.L. mm	3.5/200	3.5/250	4.5/100
Reverse Bending, R=20mm	5	NS	NS
2 Million Fatigue Str., N/mm²	200**	NS	NS
Curvature (Bow height) mm/m	30/1.0	76/1.524	NS

NS: "not specified".
**: at maximum stress of 70% of nominal tensile strength.

Table 2 Chemical Compositions for Prestressing Wires (by weight %)
(Excerpt from JIS G 3502)

Element	C	Si	Mn	P	S	Cu
SWRS 77B	0.75-0.80	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.
SWRS 80A	0.78-0.83	0.12-0.32	0.30-0.60	0.025 max.	0.025 max.	0.20 max.
SWRS 80B	0.78-0.83	0.12-0.32	0.60 0.90	0.025 max.	0.025 max.	0.20 max.
SWRS 82A	0.80-0.85	0.12-0.32	0.30 0.60	0.025 max.	0.025 max.	0.20 max.
SWRS 82B	0.80-0.85	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.

The patented wire rod is supported with a hairpin hook, pickled in an acid bath, neutralized in a sodium nitrite solution, rinsed in water, dipped in a zinc phosphate solution, and then baked in an oven to dry the coating.

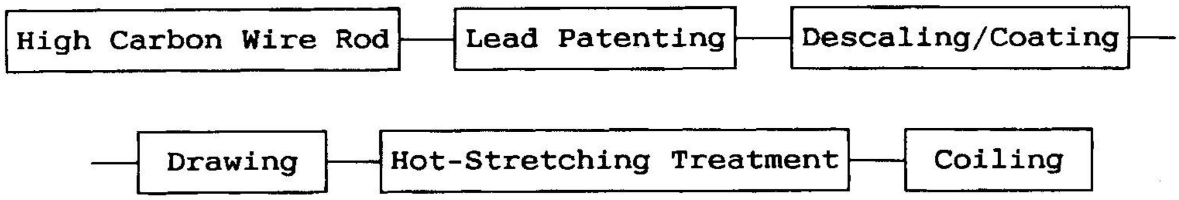


Fig. 1 Diagram for Manufacturing Method for Prestressing Wire

The wire rod is transferred to a drawing shop and mounted on a pay-off stand in front of a drawing machine. The 12 mm dia. wire rod is drawn to 7 mm dia. wire in 5 passes through tungsten carbide dies. The drawn wire is spooled or coiled for handling and is subjected to "hot stretching treatment" where the wire is heated to approximately 400°C and is stretched to yield 1% permanent strain and then wound into a coil of 1.5 to 2.0 meter in diameter. The coil is secured with steel straps. The minimum guaranteed tensile strength is 1,620 N/mm².

2.3 Fatigue Test Data

Many fatigue tests have been done for prestressing wire in the past and the test results are available. However, testing conditions are not necessarily unified and the direct comparison of the various test data is very difficult. ISO 6934-2 calls for a fluctuating stress down from maximum stress of 70% of the nominal tensile strength; many of the specifications for stay cables prescribe a maximum stress of 45% of GUTS; some other tests have been carried out at a minimum stress of 50 kgf/mm², and so on. Fig. 2 illustrates some examples of the definitions of the stress in fatigue tests.

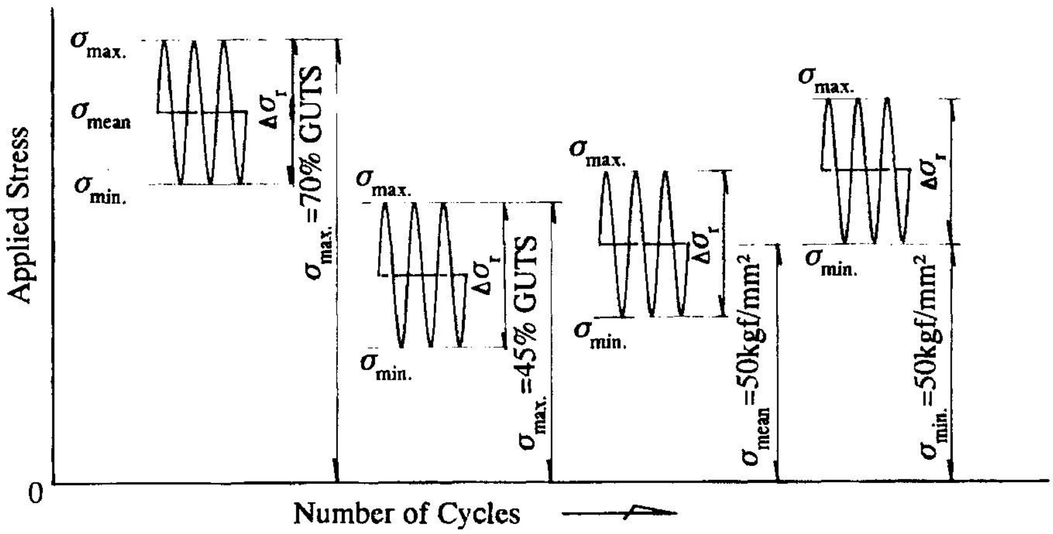


Fig. 2 Examples of the Definitions of Stresses in Fatigue Tests

Fig. 3[(5)] is an example of a fatigue test result for 7 mm dia. prestressing wire at a mean stress of 50 kgf/mm² (490 N/mm²). The endurance limit is determined to be 40 kgf/mm² or 392 N/mm². Combining with other test results, and assuming that the distribution of the data follows the normal distribution, it is reported that a 5% fractile fatigue strength for the wire to be 36 kgf/mm² or 354 N/mm².

The two photographs of Fig. 4 (A) and (B) show a typical example of a fatigue failure of the prestressing wire. It is obvious that the fatigue failure started at a surface flaw that was present before it was subjected to the fatigue test.

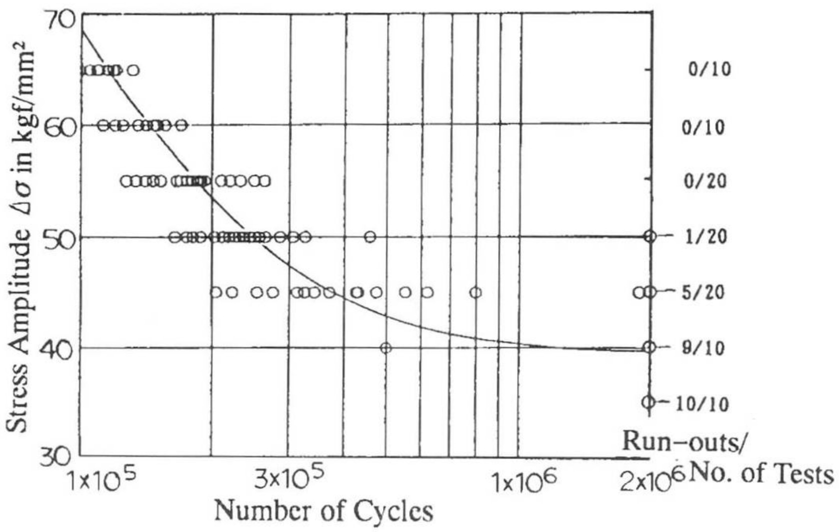
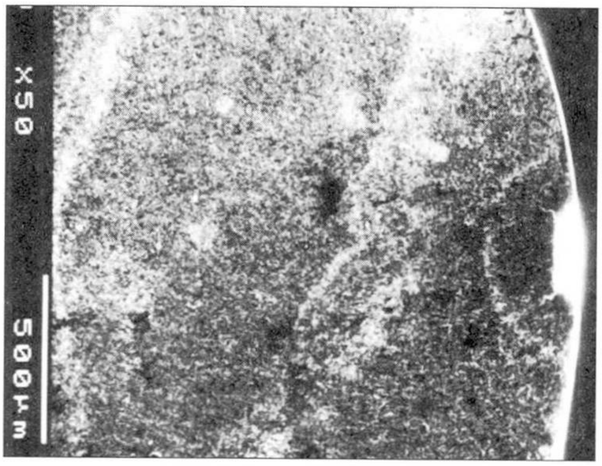
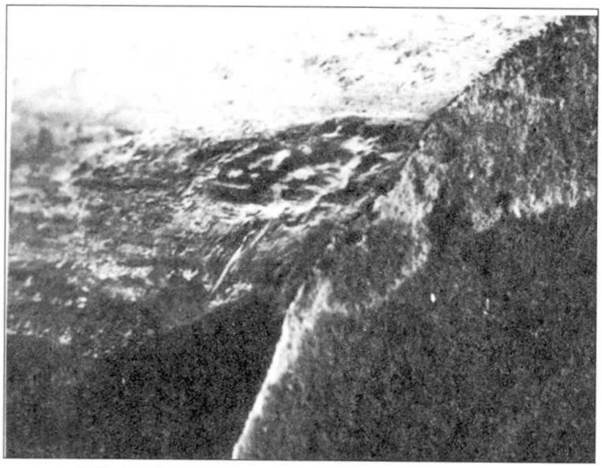


Fig. 3 An Example of Fatigue Test Results for a 7 mm Prestressing Wire



(A) Fatigue Fracture Surface
(50 Magnifications)



(B) Side View of Fracture End
(50 Magnifications)

Fig. 4 An Example of Fatigue Failure of Prestressing Wire

3. VALVE SPRING WIRE

3.1 Requirements

The intake and exhaust valves of an automobile engine are compressed from 250 to 4,000 times every minute (an average of 1,500 rpm) depending on the type of the car and type of operation. The valve springs must not fail during the life time of the car, say about 10 years. They are considered to experience something like 1 to 2 x 10^8 stress cycles at a temperature of about 100°C in service.

3.2 Manufacturing Process

Most high tensile strength valve spring wire is manufactured from the Si–Cr steel or Cr–V steel which is highly refined to reduce inclusions (Al_2O_3, SiO_2, etc.). Two examples of the chemical compositions for Si–Cr steel are given in Table 3. The blooms are subjected to extensive magnetic and ultrasonic flaw detection and any flaws are removed by hot scarfing. The blooms are rolled to billets and flaws are removed by chipping. The billets are rolled into wire rods. Extra cares are exercised to avoid mechanical damage during the blooming, hot rolling and subsequent handling. The wire rods are sometimes protected with a shock absorbing cloth and separating pad for transpiration to the wire mill. The inventories of wire rods are stored flat and are not piled up. Rough handling is strictly avoided.

The surface of the wire rod is peeled off to remove any surface imperfections such as the decarburization which might have been caused during the hot rolling and the mechanical damages which might result from the handling and transportation. For example, 8 mm rod is subjected to continuous eddy current flaw inspection and mechanically shaved to 7.4 mm in diameter using a cutting tool. The peeled rod is drawn to 4.00 mm on a continuous drawing machine. In order to achieve high tensile strength by a fine martensitic structure, the wire is heated to about 900C° and quenched in oil, followed by tempering at about 450C°. Special care is taken to avoid decarburization during the heating process. The oil tempered wire is continuously inspected with an eddy current flaw detector before it is finally wound into a coil. The maximum allowable flaw sizes are agreed between the manufacturer and the purchaser for continuous long flaws and spot flaws.

The HT Steel in Table 3 is an example of the chemical composition for a high tensile valve spring wire that is intended to help car manufacturers to reduce engine weight.

Table 3. Chemical compositions for Si-Cr Steel (by weight %)

Elements	C	Si	Mn	P	S	Cr	Cu	V
Regular Steel (JIS G 3566)	0.50-0.60	1.20-1.60	0.50-0.80	0.025 max.	0.025 max.	0.50-0.80	0.20 max.	- -
HT Steel	0.60-0.65	1.30-1.60	0.50-0.80	0.025 max.	0.025 max.	0.50-0.80	0.20 max.	0.08-0.18

3.3 Mechanical Properties

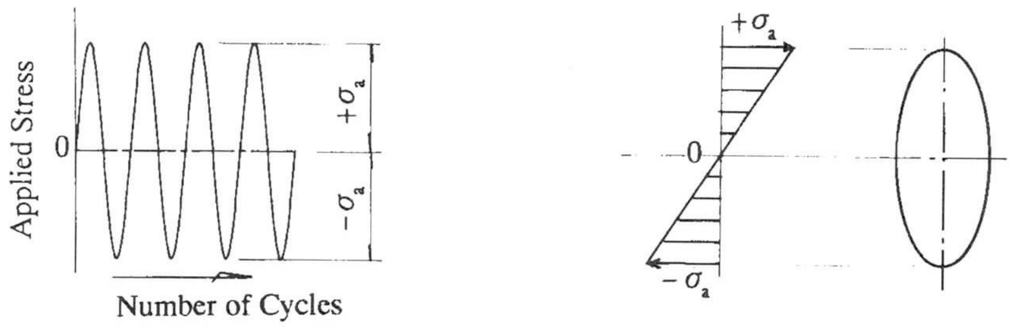
Table 4 shows the mechanical properties of the valve spring wires manufactured by the above mentioned oil tempering process. The yield strength ratio to the tensile strength is about 88% to 90%. The elongation is 4 to 6% in 100 mm gauge length.

Table 4. Mechanical Properties of Typical Valve Spring Wires
Wire Diameter: 4.0 mm

	Tensile Strength N/mm^2	Reduction of Area %
Regular Steel JIS G 3566)	1,810 - 1,960	not less than 40
HT Steel	2,010 - 2,110	not less than 30

3.4 Fatigue Strength

The fatigue tests for valve spring wires are usually carried out by a rotating bending method. Fig. 5 (A) illustrates the stress cycles at the outer fiber and Fig. 5 (B) shows the stress condition in the cross–section of the wire, respectively, in a rotating bending fatigue test. The valve springs are subjected to a shot peening treatment to enhance the fatigue performance. Table 5 shows 10^7 cycle fatigue test results for the wire as oil tempered and the wire subsequently treated by a shot peening. The tests were carried out by a Nakamura's rotating bending fatigue tester.



(A) Stress Cycles in a Rotating Bending Fatigue Test

(B) Stress Condition in a Wire

Fig. 5 Fatigue Test for Valve Spring Wire

Table 5 10^7 Cycle Fatigue Strength of High Tensile Valve Spring Wires (By Nakamura's Rotating Bending Fatigue Tester)

	As Oil Tempered N/mm²	After Shot Peening N/mm²
Regular Steel (JIS G 3566)	620	770
HT Steel	660	840

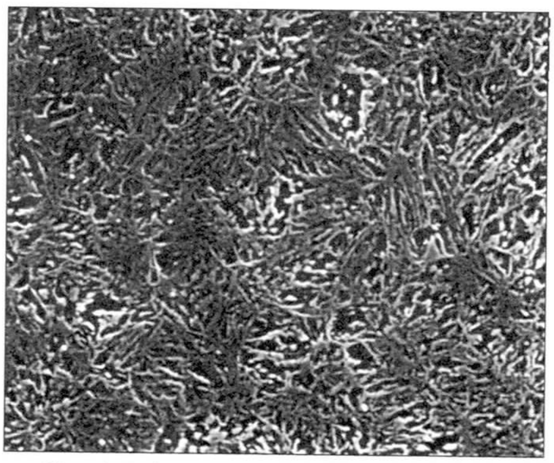


Fig. 6 Micro–Structure of an OT Wire (5,000 Magnifications)

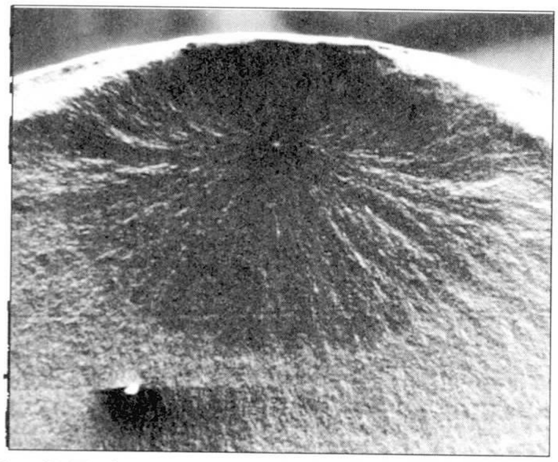


Fig. 7 Fatigue Fracture Surface of an OT Wire (50 Magnifications)

The stress condition of the wire under a rotating bending fatigue test is a tension–compression with a mean stress of zero. If the minimum stress is shifted to zero or higher, in other words, if the wire is subjected to a tension–tension fatigue test at a mean stress of, say, 1,000 N/mm², the endurance stress range will be something like 1,000 N/mm² or higher. Figs. 6 and 7 show an example of micro–structure and a fatigue fracture surface of an oil tempered wire. In most cases, the fatigue cracks of the high quality valve spring wire initiate at an internal flaw such as inclusions because there is less surface flaw.

4. GALVANIZED WIRE

4.1 Specifications for Galvanized Wires

Galvanized wire is preferred for parallel and semi–parallel wire cables even though the hot dip galvanizing process reduces the tensile strength and fatigue strength. Table 6 shows Japanese specifications for galvanized wires for bridge use.

Table 6 Japanese Specifications for Galvanized Wires for Bridge Use

Specification	JSSC JSS-12-1978	HBS G3501-1979	HBS* Special
Dimension			
Nominal Diameter, mm	5.00	5	7.00
Tolerance, mm	0.06	0.06	0.08
Out-of Roundness, mm	0.06	0.06	0.08
Physical Properties	min.- max.	min.- max.	min.- max.
Tensile Strength, N/mm²	1,569-1,765	1,569-1,765	1,569-1,765
0.7% Proof Stress, N/mm²	1,157	1,157	1,157
Elongation in 250 mm, %	4.0	4.0	4.0
Torsion, Turns/100 x d	14	14	12
Wrapping, 8 Turns/3 x d	No fracture	No fracture	No fracture
Zinc Coating			
Coating Weight, g/m²	300	300	300
Increase of Dia., mm		0.12	0.14
Curvature			
Free Coil Dia., m	4.0	4.0	
Up-lift, cm	15	14	
Bow Height, mm/m			35/2.0
Up-lift, mm/m			5/2.0

HBS*Special: a specification for specific bridge projects.

The authors' company has supplied semi–parallel wire (or long lay) cables for more than 20 cable stayed bridge projects using galvanized wire. As can be seen in Table 6, no fatigue requirements are prescribed in the Japanese specifications. However, it is obvious that stay cables are fatigue sensitive and a good wire with high fatigue strength should be used for them.

The following discussions are based on a typical production record. The Higashi Kobe Bridge, a double deck cable stayed bridge with a center span of 485 meter long required 1,300 tons of 7 mm galvanized wire for its 104 stay cables. The largest and longest cables were 357 x 7 mm diameter wires and 220 meters long. The specification for the galvanized wire was identical with the HBS Special Specification which called for the wire rod to be 13 mm diameter SWRS 82B as set forth in JIS G 3502 Piano Wire Rods.

4.2 Manufacturing Method
All possible precautions were taken by the wire rod mill to prevent metallurgical imperfections and the surface damages which might be caused during the rolling and handling. The result of ladle analysis for the chemical composition and metallurgical inspection were as shown in Tables 7 and 8, respectively

Table 7 Chemical Composition of 13 mm Dia. Wire Rod

Elements	C	Si	Mn	P	S	Cu
Spec.:JIS G 3502 SWRS82	0.80-0.85	0.12-0.32	0.60-0.90	0.025 max.	0.025 max.	0.20 max.
Ladle Analysis	0.83	0.24	0.72	0.012	0.008	0.01

The wire manufacturer's precautions started as soon as the wire rods arrived at his stock yard. Any of the sharp edges of the handling equipments were covered with soft materials. The fork-lift truck and crane operators were instructed to prevent hitting the rods against the concrete floor and other coils. The rods were stored on a soft floor in a covered storage area. The received wire rods were carefully inspected for surface flaws. Non-metallic sling was used to hoist the rods and wire. All guides and rollers were made of, or covered with, plastics.

Table 8 An Example of Inspection Results for Wire Rod

	Specification	Test Result	Judge
Dimensions	Diameter 13±0.40mm	T:13.04mm B:13.02mm	Good
	Out-of-roundness 0.4mm max.	T:0.14mm B:0.13mm	Good
Non-metallic Inclusions	Cleanliness 0.1% max.	T:0.03% B:0.02%	Good
Decarburization	Depth 0.07mm max.	T:0.04mm B:0.03mm	Good
Flaw	Depth 0.10mm max.	T:0.00mm B:0.00mm	Good

T and B: top and bottom of a length of wire rod, respectively

The manufacturing method was identical with that for prestressing wire described earlier with the only exception that hot-stretching treatment was replaced with galvanizing process: The 13 mm dia. wire rod with a chemical content as shown in Table 7 was lead patented, descaled in hydrochloric acid and was coated with zinc phosphate before it was cold drawn. The wire rod, which had a tensile strength of approximately 1,255 N/m^2, was drawn in 6 passes to 6.87±0.03mm in diameter and resulted in a tensile strength of 1,620 to 1,815 N/mm^2. The drawn wire was passed through a hot zinc bath to make 7.00±0.08mm diameter zinc coated wire.

4.3 Mechanical Properties

An example of test results for a batch of the 7 mm dia. galvanized wire is given in Table 9.

Table 9 Example of Test Results for 7 mm Dia. Galvanized Wire

	Specification	Test Result			
		Max.	Min.	Mean	n
Dimensions					
Diameter	7.00±0.08mm	7.03	6.99	7.01	68
Out-of-Roundness	0.08mm max.	0.05	0.02	0.04	68
Physical Properties	min.- max.				
Tensile Strength	1,569-1,765N/mm²	1,657	1,608	1,638	68
0.7% Proof Stress	1,157N/mm²	1,294	1,285	1,286	8
Elongation	4.0%/250mm G.L.	6.4	5.8	6.2	8
Torsion	12 turns/100 x d	27	26	27	4
Wrap	8 turns/3 x d	No fracture			4
Zinc Coating					
Weight	300 g/m² min.	388	371	380	4
Adhesion	2 turns/5 x d	No flaking off by nail			4
Dia. Increase	0.14mm max.	0.11	0.11	0.11	4
Straightness					
Arc Height	35mm/1.5m max.	25	17	21	4
Up-lift	5mm/1.5m max.	0	0	0	4

n: number of tests.

4.4 Fatigue Test

To establish S-N diagram for the galvanized wire, fatigue tests were carried out using 200 mm long specimens on a 10 ton capacity electro-servo type fatigue tester. Fatigue test results are given in Figs. 8 and 9 for the mean stresses of 50kgf/mm² (490 N/mm²) and 100kgf/mm² (980 N/mm²), respectively.

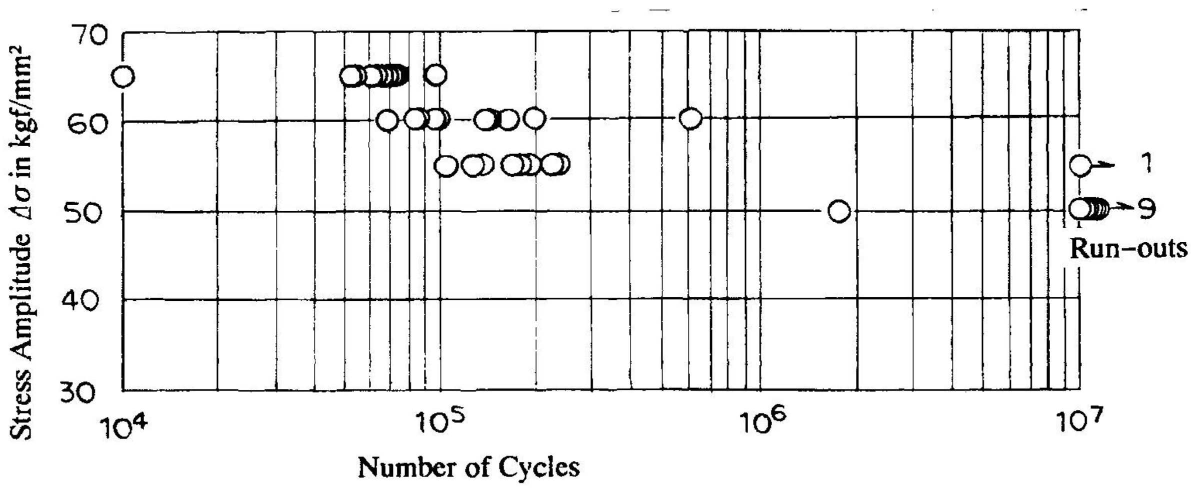


Fig. 8 Fatigue Test Result for 7 mm Dia. Galvanized Wire at a Mean Stress of 50kgf/mm² (490N/mm²)

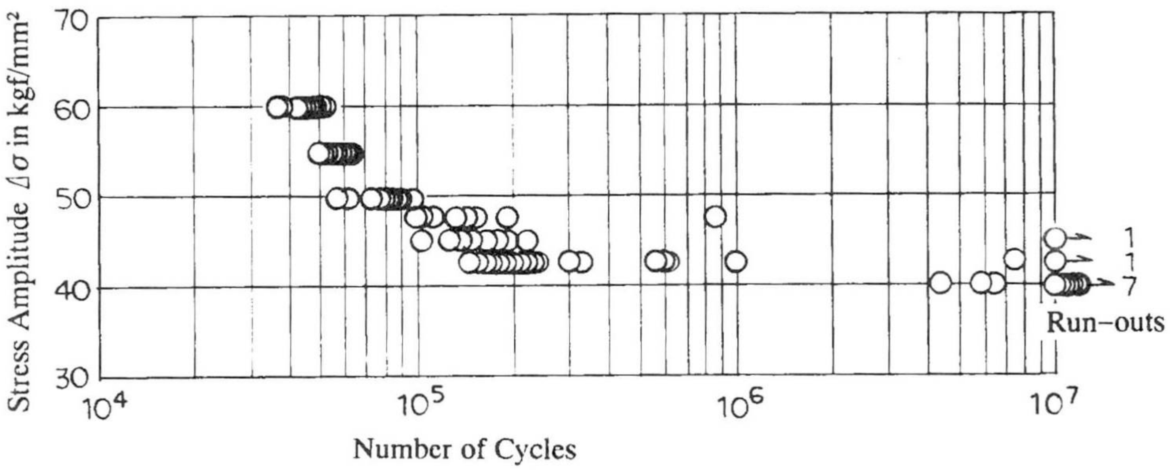


Fig. 9 Fatigue Test Result for 7 mm Dia. Galvanized Wire at a Mean Stress of 100 kgf/mm² (980 N/mm²)

The fatigue tests are still under way to establish a statistical analysis. However, the number of the test data available to date is not enough to permit a statistical calculation of the fatigue values and so we have to guess the endurance limit from the S–N diagrams. It is considered that the endurance limits are 50 kgf/mm² (490 N/mm²) and 40 kgf/mm² (392 N/mm²) for the mean stress of 50 kgf/mm² (490 N/mm²) and 100 kgf/mm² (980 N/mm²), respectively.

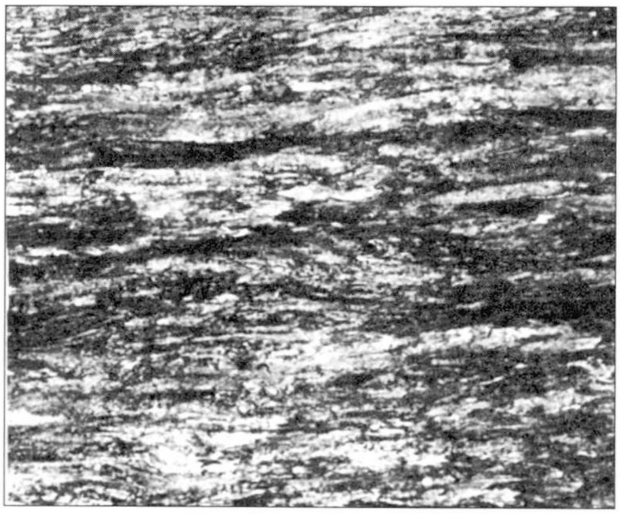


Fig. 10 Micro–Structure of a Galvanized Wire (400 Magnifications)

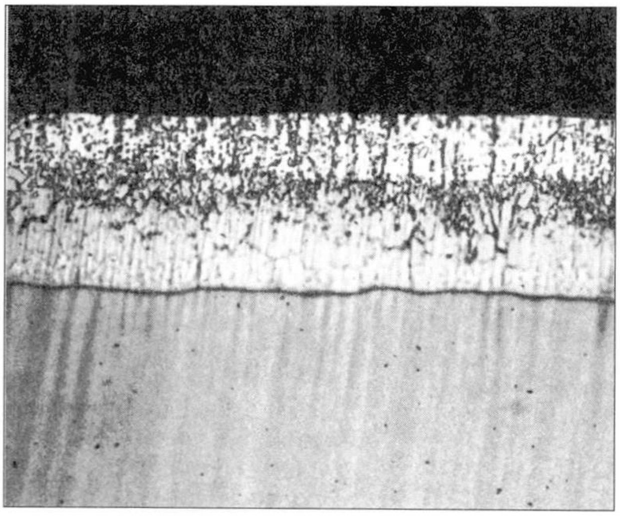
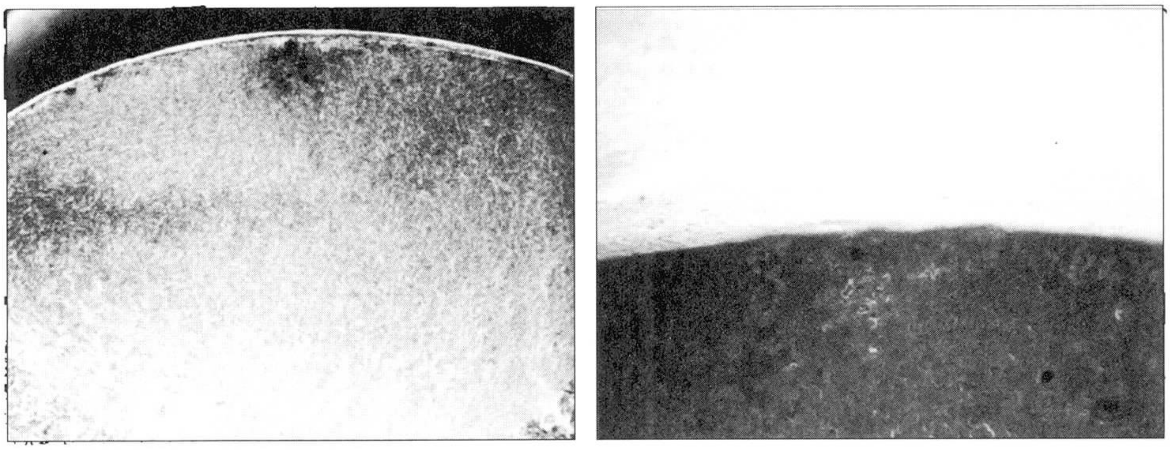


Fig. 11 Micro–Structure of Zinc Coating (400 Magnifications)

4.5 Microscopic Observations

Fig. 10 is a micro–structure of the galvanized wire. This is a typical fiber structure and is identical with that of the prestressing wires. Note that the micro–structure is entirely different from the one shown in Fig. 6 for oil tempered wire. Fig. 11 is a micro–structure of the zinc coating.

Fig. 12 (A) is an SEM photograph of a broken end of a 7 mm galvanized wire after fatigue test. The fatigue failure obviously started at a surface flaw of the steel. The surface of the wire was exposed by resolving the zinc coating in an acid and was observed: a small indentation was found at the initiation of the fatigue crack as shown in Fig. 12 (B).



(A) As Broken
(35 Magnifications)

(B) After Zinc Coating Removed
(100 Magnifications)

Fig. 12 SEM Photographs of a Fatigue Failure of a 7 mm Galvanized Wire

For a comparison, the zinc coating was removed from the galvanized wire specimens in an acid and the specimens were subjected to fatigue test. The bare wire withstood 1 x 10^7 at a stress range of 55 kgf/mm^2 (539 N/mm^2) at a mean stress of 100 kgf/mm^2 (980 N/mm^2). Therefore, the galvanizing reduced the fatigue strength by about 15 kgf/mm^2 (147 N/mm^2).

5. DISCUSSIONS ON THE POSSIBLE SOURCE OF FLAWS

Almost all of fatigue failures of wires, whether a wire for valve spring or a wire for stay cables, are associated with some kind of flaws. It is not possible to determine where such flaws exist before the wire fails in a fatigue test or in service.

There are flaws that originate at the steel mill such as segregation, non-metallic inclusions, decarburization, and the like. There are also external imperfections such as nicks and corrosion. At modern steel mills, molten and refined steel is continuously cast into blooms. Each length of the blooms is hot scarfed to remove surface imperfections. The blooms are rolled into billets. Any external flaws are chipped off. The billets are subsequently rolled into wire rods. The wire rod is laid into coil and secured with steel straps for handling. The wire rods may be stored a concrete floor for a few days to several months at the rolling mill's warehouse or open yard. Corrosion may take place during storage at the rod mill and wire mill. During the transportation and storage, the wire rods are in direct contact with other wire rods and may suffer abrasion indents and scratches during the transportation.

In most cases, flaws in the wire rod are carried through the wire making process. In addition, there are sources of the flaws at the wire mill that may be attributed to the mechanical damages and corrosion of the wire rod or the wire in process. There is a possibility that mechanical damages may be caused whenever the wire touches with any metallic tools, guides and rollers in handling, processing, packing and storage. Steel straps, hoisting hooks and rope slings are also suspected.

We know that oil tempered wire cannot be used for prestressing tendons and stay cables because of its high susceptibility to stress corrosion, and that the steel grades and manufacturing methods are different for valve spring wire and prestressing wire. However, the difference of the carefulness during the manufacture of the valve spring wire may indicate a way of improving the fatigue strength of the plain carbon wires for structural cables. In fact, high fatigue performance was achieved for 7 mm diameter galvanized wire which was manufactured on a commercial production basis with some precautionary measures in the wire production.

6. CONCLUSIONS

(1) The fatigue strength of prestressing wire available on the market place vary widely and an example of 5% fractile fatigue strength of a prestressing wire was reported to be 354 N/mm^2 at a mean stress of 490 N/mm^2.

(2) A valve spring wire for automobile engine, which is manufactured by the quenching and tempering method with the utmost care, can withstand more than 1 x 10^7 cycles at a stress amplitude of ±840 N/mm^2 in a rotating bending fatigue test.

(3) There is a possibility to improve the fatigue strength of plain carbon wire if some precautions are exercised in the wire manufacturing process.

(4) The fatigue strength of the 7 mm diameter galvanized wire, which was manufactured with care and used for an actual bridge, was determined to be 490 N/mm^2 and 392 N/mm^2 at the mean stresses of 490 N/mm^2 and 980 N/mm^2, respectively.

7. ACKNOWLEDGMENTS

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Fatigue and Length Effects in Fibre Ropes

Effets de fatigue et de longueur pour des câbles en fibre

Ermüdungserscheinungen und Längeneffekte in Faserseilen

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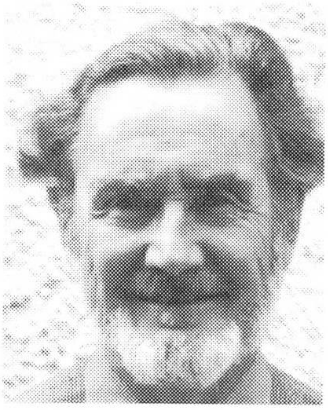

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SUMMARY
The advances in high-performance fibres and their potential for use as tension members in bridges and other structures are outlined. The general length effect problems, which involve the weak-link effect and load sharing, are discussed in terms of limitations of understanding in theory and practice. Six fatigue mechanisms in fibre ropes are described, and their influence in length effects on parallel-lay and structured ropes illustrated by examples of analysis of the mechanics.

RÉSUMÉ
Les progrès réalisés dans les fibres à haute performance et leur possible utilisation en tant qu'éléments de tension dans les ponts et autres structures sont esquissés. Les problèmes généraux d'effet de longeur incluant l'effet de maillon faible et celui de partage des charges et ses limites de la compréhension à la fois théorique et pratique de ces effets sont dicutées. Six mécanismes de fatigue de câble en fibre sont décrits, ainsi que leur influence sur les cordes structurées ou en couche parallèle dans le cadre des effets de longueurs - le tout illustré par des exemples d'analyse du mécanisme.

ZUSAMMEMFASSUNG
Die Fortschritte in der Entwicklung von hochleistungsfähigen Fasern und deren Potential zur Zugkraftaufnahme in Brücken und anderen Bauwerken werden umrißen. Allgemeine Längenprobleme, insbesondere das Auftreten von Schwachstellen und eine ungleichmäßige Verteilung der Lastaufnahme der Fasern, werden unter Berücksichtigung der begrenzten theoretischen und praktischen Kenntnisse erörtert. Sechs Ermüdungsmechanismen in Faserseilen werden beschrieben, und deren Einfluß auf Längeneffekte in parallel liegenden und geflochtenen Seilen wird anhand mechanischer Analyse erläutert.

1. INTRODUCTION

1.1 Development of fibre ropes

From the time of the ancient civilisations, man has fabricated ropes from natural fibres, such as sisal, hemp and cotton. These were used as cables in primitive bridges and for many other structural purposes. However, the advent of steel wire ropes in the 19th century displaced fibre ropes from any serious uses in structural engineering, though they continued to be used for many marine and other applications. The situation has changed in the second half of the 20th century with the invention and production of high-performance man-made fibres. The first synthetic fibre, nylon, was introduced into rope manufacturing in the 1940's and led to stronger ropes. However nylon has a relatively low modulus and high extensibility, which makes it very suitable for uses where stretch and energy absorption are needed, but not for structural members. The stimulus for the development of fibre ropes for stays and cables came partly from the development of parallel-lay (®Parafil) polyester ropes and, more strongly, from a second generation of synthetic fibres with strengths more than double those of nylon and polyester.

The need to bind short natural fibres together led to twisted rope structures, such as the common three-strand rope, but the use of continuous filaments, effectively infinite in length, has removed this requirement. Consequently, new rope constructions have been introduced. The situation is now very complicated, with the number of combinations of fibres, blends and constructions available to rope designers running into millions. What follows is a brief outline of the main features as an introduction to the problems of fatigue and length effects.

The main fibres used in ropes today are listed in Table 1, with those of most concern for this paper shown in bold. Important properties of these fibres are compared in Fig. 1.

cheaper fibres with adequate performance for common uses		
regular melt-spun polyethylene (PE)	polypropylene (PP)	
intermediate performance fibres		
polyamide (PA): nylon 66 and nylon 6	**polyester (PET)**	glass
high performance fibres fibres formed by liquid crystal processing		
aramid (®Kevlar, ®Twaron, ®Technora)	**LCAP (®Vectran)**	**polybenzoxazole (PBO)**
other high modulus, high strength (HMHT) fibres		
HMPE (®Spectra, ®Dyneema)	carbon	

Table 1 Fibres for ropes

Although polyester does not compare well with the newer high-modulus high-tenacity (HMHT) fibres in strength and stiffness relative to bulk or weight, the special forms of yarn designed for engineering uses must be considered when high strength and stiffness is needed at low cost. However for maximum strength and stiffness at minimum weight, the prime candidates are the highly oriented linear polymer fibres formed from liquid crystals. These are represented in Fig. 1 by the aramids, but LCAP and PBO have somewhat similar properties, and the technology is still developing.

Because of their creep properties, the gel-spun or super-drawn HMPE fibres are unlikely to be suitable as load-bearing members in permanent structures. Carbon and glass fibres are too brittle in bending for use as independent fibres in ropes; and their use as pultruded composite rods has more mechanical similarity to wire ropes than to fibre ropes.

The main categories of fibre rope construction, with approximate strength conversion efficiencies, are: *parallel-lay (®Parafil), 50% ; multi-rope, 40%; low-twist "wire-rope" constructions, 40%; braided and plaited ropes, 25%; traditional twisted ropes, 25%.* Generally, the effects of introducing more structure, in the form of twisting or braiding, are, as with wire ropes: (1) to reduce strength and stiffness, due to obliquity effects; (2) to allow movement of yarn from the compression to the tension side of a rope in bending, and so reduce bending stiffness; (3) to bind components more closely together.

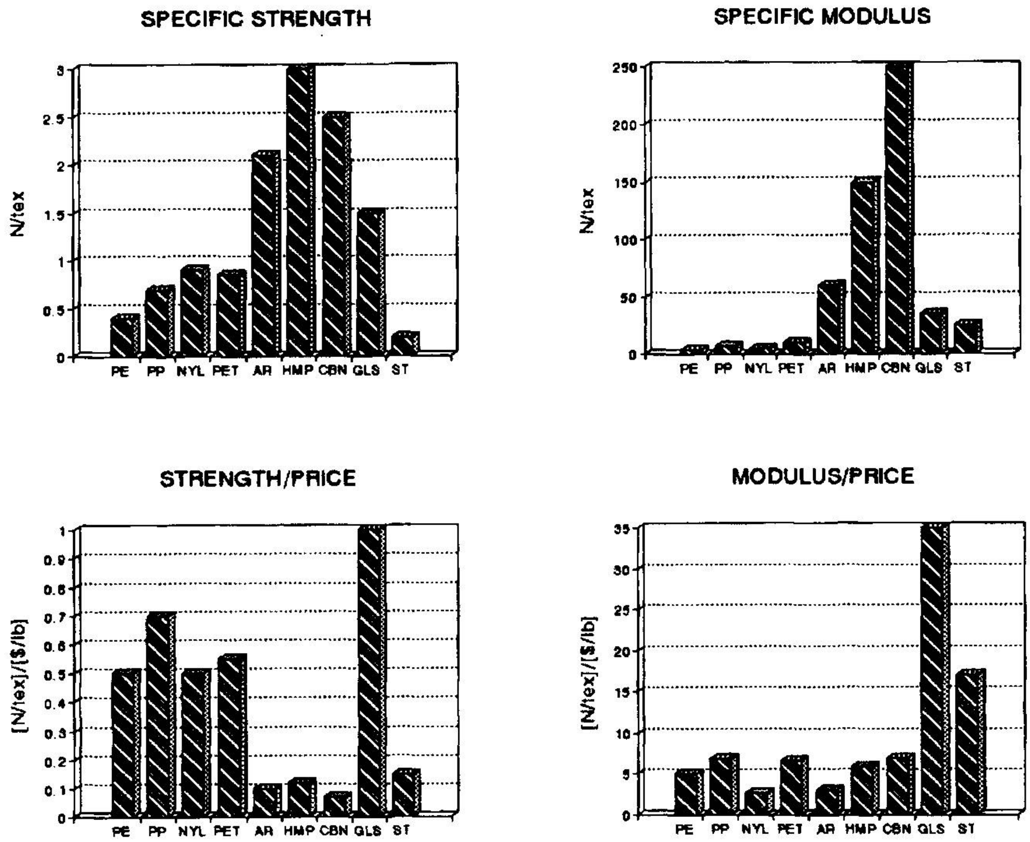

Fig. 1 Fibre property values: indicative only (all values cover a range for different types)
PE=polyethylene; PP=polypropylene; NYL=nylon; PET=polyester; AR = aramid; HMP=high-modulus polyethylene; CBN=carbon; GLS=glass; ST=steel
Unit of specific stress: N/tex = GPa/(g/cm^3)
Unit of linear density: tex = g/km

1.2 Potential of fibre ropes in bridges and other structures

Fibre ropes offer distinct advantages over steel wires in some structural applications. An example of a building structure is a bus station recently erected in Cambridge with the roof supported by aramid Parafil ropes. However, the most important use is in bridges, and three particular examples are most clearly defined.

Tendons in prestressed concrete are normally made from 7-wire spiral steel strand, with a low lay angle. These tendons are protected from corrosion by the high alkalinity of the concrete, which passivates the steel. The tendons are placed in ducts in the concrete, which are filled with grout after tensioning. However, in recent years, there have been growing concerns about the effectiveness of this grouting, which leads to worries about corrosion, and some bridges have collapsed due to tendon corrosion [1]. Replacing the steel with aramid, glass or carbon, which are inherently resistant to attack by water or most chemicals, is attractive, and a number of structures have already been built. Several use pultrusions of fibres with a resin matrix, which can be bonded to concrete, but there are concerns about the wisdom of bonding these brittle materials and also about the long-term effectiveness of the resin. This leads to the idea that unbonded, parallel-lay ropes will prove, in the long run, to be the most suitable form for the use of new materials as tendons [2]. The Department of Transport in the UK is expected, in the near future, to insist on the use of inspectable, removable and replaceable tendons, and the added costs of providing corrosion protection to steel tendons will negate the cost differences in the basic materials. In addition to problems of corrosion, there is a loss of tendon prestress due to creep and shrinkage of the concrete, which has been greater than expected in many bridges in the UK. Tendons encased in grout cannot be restressed, and the only prospect for repair is to use external tendons, for which aramid parallel-lay ropes are strong contenders. Their lower modulus, compared with steel, is an advantage, since it reduces the loss of prestress due to the contraction of the concrete.

Suspension bridges are used to provide the largest spans, and the Akashi bridge under construction in Japan will have a span of 2 km. However as the span increases, the weight of the main cables comes to dominate the design, and it is believed that a span of about 2.5 km is the largest that can practically be achieved with the use of steel. Aramid and carbon offer the possibility of much larger spans, with serious consideration being given to spans well in excess of 5 km [3], which would make possible, for instance, a crossing of the Straits of Messina.

Cable-stayed bridges are currently used for spans between about 200 and 800 m. They are stiffer than suspension bridges, and less susceptible to dynamic problems. The dead load of the deck can be kept quite small, so that the live load becomes dominant, which means that the limiting factor for most designs is the fatigue resistance of the cables. Steel cables are frequently restricted to stress ranges of about 200 MPa, and fibres offer the possibility of significantly better performance, although much testing is required to ensure that this capability is achievable in full size ropes.

In all these cases, the effects of length on both strength and fatigue will be important. Prestressing tendons are often several hundred metres long, especially if unbonded, and are the most highly stressed of all structural elements, regularly being tensioned to 70% of their ultimate strength. If some engineers' aspirations are achieved, cables in suspension and cable-stayed bridges may well have lengths of several kilometres.

1.3 General length effects

The basic principles of the interrelation between specimen or component lengths and mechanical failure, namely the extreme value statistics of the weak link effect and the nature of the load sharing, are the same for fibre ropes as for wire ropes. Indeed, much of the work on the subject, starting with the paper by Pierce published 66 years ago [4], and continuing through Daniels [5,6], Coleman [7], and Spencer-Smith [8] to Phoenix [9] and his colleagues, has been driven by textile research interests.

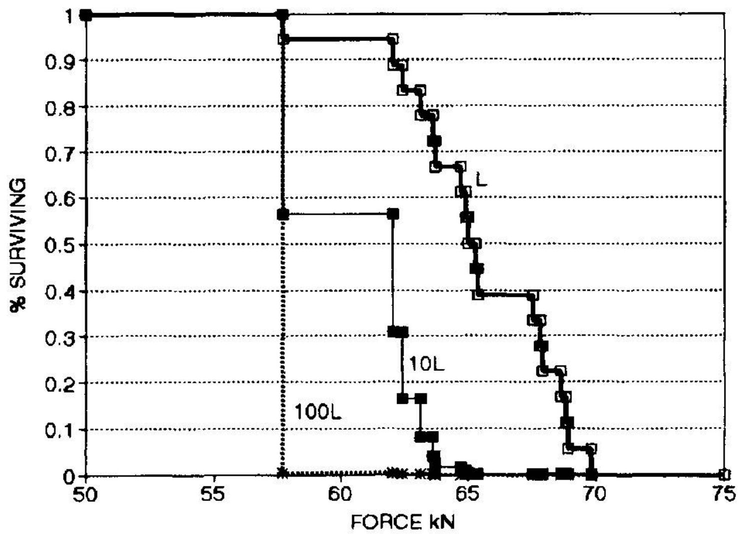

Fig. 2 Statistics of failure for aramid Parafil rope breaks [10].
Line L is for 18 test results at length L = 500 mm. Lines 10L and 100L are cumulative distributions for ropes of length 10L and 100L, made up randomly from the 18 test values.

It is worth dramatising the problem facing engineers by a simple example. Fig. 2 gives breaking loads in 18 tests on 500 mm lengths of 5 tonne (approximately 10 mm diameter) Parafil Type A (polyester core) ropes, carried out by Amaniampong [10]. If, unjustifiably, we make the assumption that longer lengths could be treated as a random sequence of the 18 test pieces, then the survival diagrams for different lengths would be as shown. This highlights a number of problems.

- It is rare to get as many as 18 tensile test results even on small ropes, and prohibitively expensive for fatigue tests on large ropes.
- The direct numerical procedure, as used above, which may give good predictions when the ratio of lengths is much less than the number of test results, is clearly useless for longer lengths when it predicts that almost all would fail at the same lowest value. In order to make predictions, it is necessary to know extreme values of the distribution. What are the probabilities of failure at loads, or lifetimes, lower than the lowest observed experimentally? Any appreciable extrapolation, based on fitting the central values of the distribution, may be seriously misleading, even if there is a single mode of failure responsible for the total distribution of breaks.
- It is also possible that there may be infrequent defects giving rise to other modes of failure, which make the real distribution multimodal and extrapolation invalid.
- Does the nature of the break change when the length is greater than the test length?
- To what extent does correlation between the properties of neighbouring elements, as considered by Spencer-Smith for textile yarns [8], invalidate any theory based on a random sequence of units?
- Can laboratory tests on small ropes be applied to the behaviour of large ropes in real structures?

The technology of fibre ropes in relation to these problems differs from that of wire ropes in the following ways.

- There is no base of engineering experience in use. Uncertainties in theory and experiment need to be covered by large safety factors, which may destroy the economic advantage. Or, as a distinguished old theoretician of the subject commented: "A few bridges will have to fall down before we solve the problems!".
- Whereas wire ropes are made up of a comparatively small number of wires, a large fibre rope will contain millions of fibres. This affects the real nature of failure, especially in fatigue, as well as the difficulty of hypothetical modelling.
- The lengths over which failure spreads may be much larger. In unstructured ropes, the filaments, yarns or sub-ropes may not take up a full share of load until several metres from a break.
- Although polymer science has made great advances in the 60 years since macromolecules have been recognised as constituents of materials, understanding of mechanical properties, especially fracture and fatigue, is less advanced than in metals, which have simpler structures and are not anisotropic or visco-elastic.

One way forward is the high-risk route of empirical solutions based on rough calculations and safety factors, progressively improved as an experiential database is built up. The only alternative appears to be a programme of well-designed experiments on fibres, yarns and cords, to determine relevant material properties, combined with theoretical modelling of fibre assemblies, validated by numerous tests on small ropes and a few tests on large ropes. But this is a formidable undertaking, which will partly be explored later in this paper.

2. FATIGUE MECHANISMS IN FIBRE ROPES

2.1 The identification of fatigue mechanisms

There have been a number of studies of what can broadly be described as fatigue in ropes in the last 15 or 20 years, but these have mostly been related to the wide range of marine uses. In addition, the advent of the scanning electron microscope and the development of new fatigue tests have led to recognition of various modes of fracture and fatigue in fibres in different circumstances [11].

The first requirements for a rope member in an engineering structure are strength and extensibility relative to the design load. These already involve the complications of length effects. Then there may be issues of chemical degradation, though this would be expected to be a uniform weakening over whole lengths and should be avoidable by a suitable choice of material. External abrasion, if it occurs, is likely to be localised and obvious, and can be mitigated by protection. This leaves the most important factor in determining long-term durability as fatigue failure within ropes. Parsey [12] has identified six modes as occurring in ropes. The problem might therefore seem to be to calculate the lifetimes under whichever of the six modes are likely to occur, taking into account the length effects, and see which is shortest. However, two reservations should be made about the implied simplicity of this approach. At least two modes are catch-all titles for a collection of effects, and many interact strongly with one another.

2.2 Creep rupture

Creep rupture is a significant effect in polymer ropes under high sustained loads, as demonstrated by Mandell [13]. His equation is a variant of that proposed for time-dependence of fibre strength by Meredith [14] many years ago:

$$S_u = S_g\,[1 - k\,\log(t_u/t_g)] \qquad (1)$$

where S is strength, t is time, subscripts u and g refer to unknown (use) time and given (test) time, and k is the strength-time coefficient.

Table 2 illustrates the extreme sensitivity to the value of k. For nylon, Meredith found k = 0.08; and Mandell found k = 0.05 for polyester. Current indications are that aramid has a value less than 0.05, and that polyethylene, including HMPE, is near 0.2, but more reliable experimental data are needed.

k	time to fail at per cent of 1 second break load 20%	50%	80%
0.05	300 million years	300 years	3 hours
0.1	3 years	1 day	2 minutes
0.2	3 hours	5 minutes	10 seconds

Table 2 Effect of strength-time coefficient on time to fail

The length effects in creep rupture are essentially the same as in slow tensile testing. The difference is that the sequential break of fibres, leading eventually to rope failure, occurs as time passes instead of as load increases.

2.3 Hysteresis heating; internal abrasion; tensile fatigue

Hysteresis heating during repeated loading is due both to energy losses within fibres and to friction between fibres. It can be controlled by increasing the efficiency of heat transfer from the rope. The direct effect is the reduction of fibre strength as temperature increases, and the length effects will be similar to those in tensile testing.

Mandell's paper [13] confirms other studies [15] that internal abrasion is a prime cause of failure in tension-tension cycling of structured ropes at low loads. It results from cyclically varying shear forces at contacts where there is relative motion of components. This will not occur in tension cycling of parallel-lay ropes. However, it may be a major factor if there is rope bending or lateral strumming.

The occurrence of the special forms of tensile fatigue [11], found in nylon and polyester fibres cycled from zero load to a fraction of the normal break load, seems to be an infrequent occurrence in ropes in practice, though they have occasionally been observed.

2.4 Bending, buckling and compression; structural fatigue

The most severe fatigue occurs in fibres when cyclic compressive or shear forces are present. Bending, buckling and compression cover a variety of forms of disturbance within rope structures, which may lead to such stresses. At the fibre level, repeated axial compression leads to breakdown at kinkbands; and cyclic shear stresses, resulting from variable curvature, lead to splitting of fibres.

Any oriented linear elements will buckle when subject to axial compression. For a free length of rope as a whole, this usually gives a mild curvature, which will have a negligible effect on the fibres, but sometimes it can lead to severe bending and twisting of the rope. When the axial compression is applied to elements confined by neighbouring elements, either as strands, yarns or fibres within a rope, or as fibrils or polymer molecules within a fibre, compression leads to a sharp kinking, which can be seriously damaging.

Axial compression within a rope will occur on the inside of bends and can also come from differential length changes on twisting. Some recent studies have indicated that this problem may arise in unexpected circumstances. For example, there is a well-documented study [16] of the failure of a Kevlar rope after deployment on buoys prior to mooring an oil-rig. Wave motion had caused a rise and fall, which generated torque waves and consequent compression and failure in the rope. A careful redesign, so as to avoid torsion and provide the right degree of restraint from the cover, solved the problem. In other situations relative movement of components can cause problems: this may occur at terminations or result from lack of control in manufacture causing length disparities in components.

Structural fatigue is another ill-defined fatigue mode, which can be regarded as a more severe form of buckling and compression. It involves such substantial disturbance of the rope structure that some components cease to carry load and others carry more and break. Hockling, which sometimes occurs on the sudden release from tension of three-strand ropes, is an extreme example of the effect.

3 VARIOUS ASPECTS OF LENGTH EFFECTS IN FATIGUE

3.1 The total system

The long-term durability of a fibre rope used as a tension member depends on the interactive response of the total system as illustrated in Table 3. It would be an impossible task to develop a usable model applicable to any combination of environment, structure and rope. Some basic features can usefully be studied by academic exercises, but there is a danger that uncritical application of mathematical theory may lead to false predictions. Real engineering progress will only be made by working in detail on design studies, including experiment, theory and computation, for particular installations.

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structural integrity of system

EXTERNAL LOADING - traffic, wind, waves, structure etc
WHOLE STRUCTURE RESPONSE - system dynamics
FORCES ON ROPE + TERMINATION - rope properties
RESPONSE OF SUCCESSIVE ROPE ELEMENTS - system dynamics
FORCES ON LOCAL ROPE ELEMENTS - rope properties
FORCES ON FIBRES - rope micro-mechanics
DAMAGE TO FIBRE STRUCTURE - fibre properties

structural integrity of fibres

Table 3 Total system response

For similar reasons, our specific contribution to this workshop consists of a number of separate items, which bring out significant aspects of the problem. It is noted above that many of the fatigue mechanisms likely to operate in fibre ropes lead to a sequence of failure that is similar in principle to failure in a tensile test. Consequently a priority is to find ways of handling the unresolved problems of length effects on the breaking load of ropes. If we can understand this properly, the approach to length effects in fatigue should be much clearer.

3.2 Yarn tests

Even when carried out manually, and more so with automatic testers, it is practical to make very large numbers of yarn tensile tests, and thus satisfy the statistical needs of experimental input into models. The validity of predictions could be tested by extending such studies to small cords, which represented characteristic features of rope construction. Yarn testing is also of particular interest for the light it throws on the applicability of extreme value statistics and the problems of interpretation, where the practising engineer may fall into error, especially as the views of the experts do not always coincide.

Amaniampong [10] carried out a series of tests on Kevlar and polyester yarns at different test lengths. Both break force and break elongation were measured, and the corresponding values of break stress and strain determined. Amaniampong then used the Kolmogorov-Smirnov tests to indicate which gave the best fit among the often used normal and log-normal distributions and the theoretically preferable Weibull and Gumbel distributions. He found that all four forms were variously predicted, with no very clear pattern for different parameters, test lengths or fibre types. This indicates the difficulty of interpreting yarn test data properly. The use of K-S tests may also be criticised [17] on the grounds that they should not, in principle, be used to discriminate between various distributions but only to validate a previous choice, which ideally would be made on physical grounds. The normal distribution is defined for $-\infty \le x \le \infty$, and should not be used when, as with tensile strength values, x cannot take negative values. In addition, as pointed out by Peirce [4], weak link theory shows that, if the distribution were normal at one length, it would not be normal at any other; in contrast to this, the Weibull form remains valid at all lengths. On the other hand, it might be argued that, in the absence of a good physical model and provided the extrapolation is not too large, the best empirical fitting may be the most appropriate.

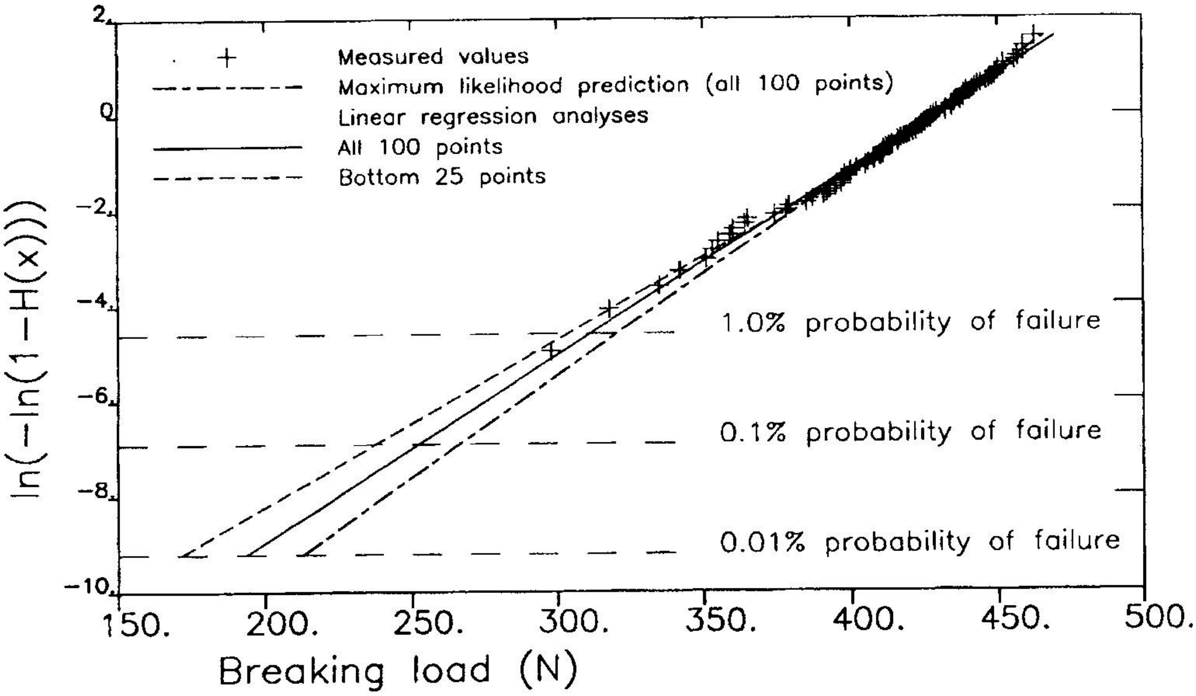

Fig. 3 Weibull plots of 100 yarn strength values measured by Amaniampong [10]

The problem becomes acute, and of practical importance, when the analysis is required to find extreme values, which lie beyond the range of observed values, as is often necessary for long ropes. As one example, Fig. 3 shows the results of 100 tests on Kevlar 49 yarns, each taken from a different spool. The cumulative distribution function H(x), when plotted in the form ln(-ln(1-H(x))) against the measured value, should give a straight line if the Weibull or Gumbel distributions apply. Various attempts, reflecting different theoretical approaches to statistics, have been made to fit straight lines through the data. A maximum likelihood prediction gives less weight to the outliers in the distribution, and fits the main sequence of tests well. However, the lower outliers may well be important, so a simpler linear regression analysis would be more appropriate, and predicts a lower strength at the bottom of the distribution. The process can be taken further, and, as suggested by Castillo and Sarabia [18], only the tail data used. Another line in Fig 3 is a linear regression for the bottom 25 points, which gives even more weight to the lower extreme values. The predicted failure strengths at the 1% probability level range from 304 to 321 Newtons, with greater variation at lower probabilities of failure. These variations are significant, since it has been found [19] that Parafil ropes have their maximum strength when about 1-2% of the weakest yarns have failed.

To complicate matters even further, the low outliers in some test sets plotted in the form of some distributions are stronger than the central values suggest, while in some other test sets, or for other forms of distribution in the same set, they are weaker. In some cases, the results for force and nominal stress show different behaviour, indicating that the cross-sectional area is not constant along the length. For some rope constructions, it is not stress but strain that must be considered, and again different distributions apply.

3.3 Fatigue and length effects in parallel-lay ropes

Several of the fatigue problems associated with structured ropes disappear when parallel-lay ropes are used, although other considerations arise. Of the six causes of fatigue identified above, most are eliminated or simplified in parallel-lay ropes when subject solely to tensile loads, though they will occur, and may become serious, if bending or twisting deformations are imposed. There is considerable evidence that "fatigue" in tension of many types of fibre is related to duration of loading, rather than number of cycles [13]. It is thus likely that long-term life in parallel-lay ropes is related to creep rupture, possibly enhanced by increased temperature due to hysteretic heating within fibres (but not to friction between fibres), although this simplification to a single factor needs thorough investigation and validation.

The length effects of particular interest in parallel-lay ropes, whether for failure in simple tensile loading or in long-term creep rupture, are associated with the degree of interaction between fibres. A broken filament can clearly carry no load at the break. But how far along the rope is it before that filament carries a full load? If there is no interaction, the whole length of the filament becomes inoperative, and the strength of the rope will be the sum of the weakest places in what may be several kilometres of each filament. In contrast to this, if there is strong interaction, the load-carrying capability builds up rapidly, weak places are supported by neighbouring fibres, and the strength is given by the weakest single cross-section.

In practice, the component yarns in Parafil ropes are twisted to a small extent, but sufficient to ensure that the individual filaments are mutually supported, and it is interaction between yarns that must be considered. In multi-rope constructions, the interaction is between sub-ropes. In the simplest idealised model of parallel components, there is no basis for any transverse forces. Consequently, if the classical law for frictional contact is assumed, there is no interaction. In actual parallel-lay ropes, interaction will occur due to causes such as pressure from the jacket, possibly transverse forces from some secondary structural features, and adhesive forces between fibres. This means that there will be a transfer of load to broken filaments over a length which can be regarded as a characteristic length for rope failure. The terms "effective length" and "recovery length" are used for similar concepts. In parallel-lay ropes, it has been estimated that the characteristic length may be as much as several metres. This has important consequences both as regards the relation between test results on short lengths of rope and the use of long lengths, and as regards the internal structural mechanics of ropes.

Amaniampong [10] has taken the bundle theory, as developed by Daniels [6], and extended it to allow for variable slack in the yarns and non-linearity of the stress-strain curve. He combined this with his own yarn test data, and the idea of a characteristic length, to produce predictions of the strength of ropes of different sizes and lengths. Ropes carry their maximum load when only a small proportion of the weakest yarns break, so that the variation in strength is caused by the variation in the number of yarns in the lower tail of the distribution. As ropes get larger, the shape of this tail gets closer to that of an infinite population, so that the chance of getting a random set of very low values, causing greater variation in rope strength, is reduced. In a long rope, which can be regarded as a series of characteristic length pieces whose strengths are independent, the weakest link principle is applied and the strength decreases as the rope gets longer. But, if the variability is low, as in large ropes, the length effect can be quite small. Amaniampong calculates that, over a length of 3 km, a 60 tonne Kevlar Parafil rope loses only about 2% of its characteristic strength (as measured at less than 6 m), whereas a 6 tonne rope would lose 5%. He also applied bundle theory to creep rupture behaviour of aramid parallel-lay ropes. Working only from data on filaments, he predicted that these ropes would fail after 100 years, when loaded to 60% of their short-term strength. This is in close agreement with predictions based on empirical data by Guimares [20].

3.4 Length effects in structured ropes

The increased interaction due to the generation of transverse forces in structured (twisted and braided) ropes means that the characteristic length will usually be less than the rope diameter, so that the weak link effect will be operative at any test length. If interaction is extremely strong, as in a homogeneous solid, then breaks will propagate continuously across the material. This situation would not occur in ropes, though there is the statistical problem of the tendency of some neighbouring components to break. Some structure optimises strength, but also results in deterioration due to obliquity as mentioned previously and can lead to the occurrence of fatigue due to internal abrasion, kinkbands and structural changes.

Many studies of braided and twisted nylon ropes for marine uses have shown that internal abrasion is the prime cause of failure in tension-tension cycling at low loads. For example, a braided nylon rope cycled wet from a low load to 50% of its normal break load failed after 970 cycles [21], when internal abrasion had cut through the filaments and reduced them to short fibres. This, as well as other reasons, leads to the choice of other fibres and less structured rope constructions in structural engineering. However, an interesting point of general principle arises in connection with the modelling of loss of strength due to internal abrasion.

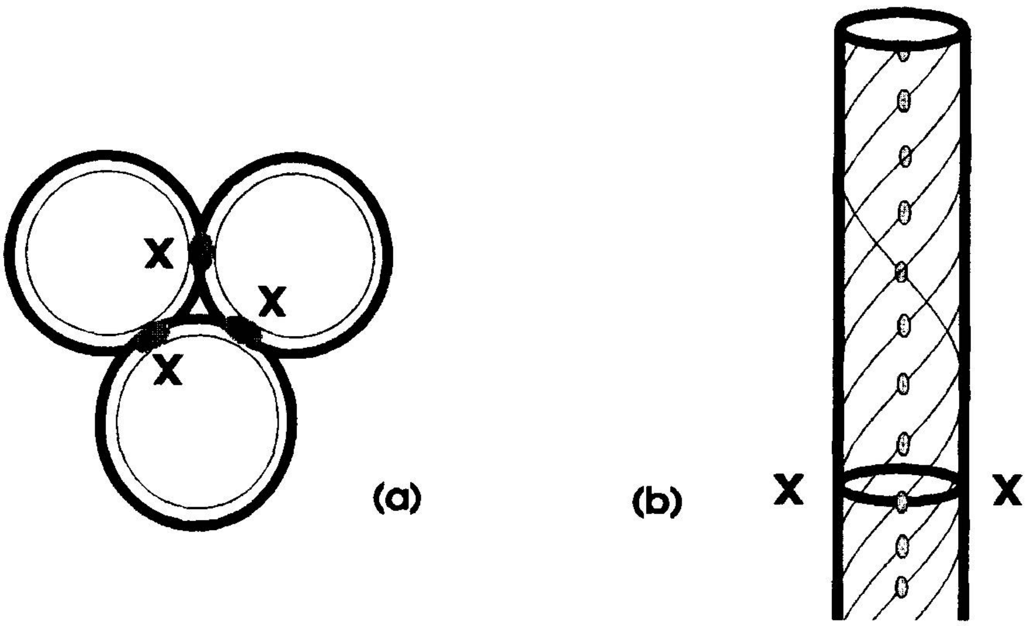

Fig. 4 Localised abrasion at contacts: (a) in cross-section; (b) along yarn

GEN-ROPE, which is a modelling program developed by TTI Ltd, incorporates the special feature that contact forces and displacements between components in twisted ropes during cyclic loading can be calculated. In principle, since these are the controlling factors, this should make it possible to predict the rate at which portions of fibres are worn away. In practice, adequate experimental data on rate of fibre wear is not available at present, and special experimentation would be needed in any particular design study. In addition, there is a length problem in relation to the effect of fibre wear on the rope mechanics, which is not completely addressed by any of the current models. Wear occurs at many different contacts, but let us concentrate attention on the most severe: inter-strand abrasion in a three-strand rope. In a given cross-section, the actual wear will be localised at the contact regions X in Fig. 4(a). After a given number of cycles the shaded portion of the strand will consist of fibre debris, which cannot carry load. If the rest of the cross-section is assumed to remain fully effective, the models would predict the revised rope load-elongation, and indicate failure when the residual strength had fallen to the level of the maximum applied load. However this ignores the fact that, due to the helical path of yarns in the strands, as shown in Fig. 4(b), neighbouring fibres will have been abraded at a cross-section that is a short distance along the strand. All outer fibres in the strand will be subject to abrasion within one turn of the helix.

The safest assumption would therefore be to assume that all fibres at the given depth from the strand surface in a complete ring cease to be load-bearing. However, this is too severe a requirement. In order to make a better prediction it will be necessary to modify GEN-ROPE by introducing the stress transfer and build-up of tension along the length of fibres away from the worn regions. Raoof [22] has examined the related questions of recovery length in wire ropes and strands.

3.5 Terminations and rope length

Various types of termination are used for fibre ropes: splices, potted ends, barrel-and-spike fittings etc. A practical problem, which worries design engineers, is that tensile and fatigue tests may result in failure at the termination. As with wire ropes, considerable attention is being paid to the design of terminations in order to minimise this problem. When there is failure at a termination, it seems that one is not gaining information on rope performance. In fact, the test result is a lower bound for strength or durability. A related and more difficult question is whether end effects change the static or fatigue performance in the rope away from the ends.

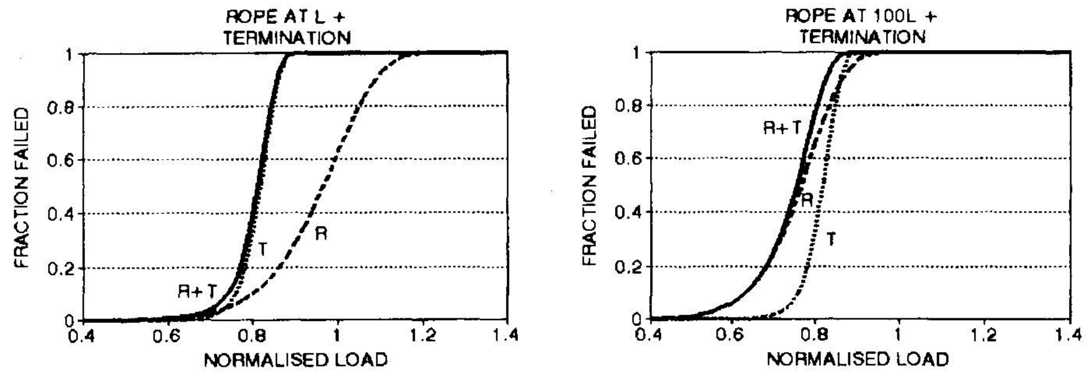

Fig. 5 Cumulative Weibull distributions, showing competitive failure of rope and terminations. For rope at length L, α = 1 and ρ = 10. For termination, α = 0.83 and ρ = 25. For rope at length 100L, calculation gives α = 0.79 and ρ remains equal to 10.

In actual use with long lengths, breakages away from the termination often become the norm. This is because the weak-link effect comes into play, as indicated by the exaggeratedly severe Weibull plots in Fig. 5. The probability distribution for the terminations is unaltered, but the distribution for the rope itself shifts to lower values at the long length. With the selected values, the failures for rope plus termination follow close to the termination line for the length L with just a few rope breaks, whereas at 100L the rope breaks are dominant.

4 CONCLUSION

Ropes made from the new high performance fibres offer ways of achieving very high strength and stiffness, at lower weights and even in smaller diameters than wire ropes. In addition, polyester fibre ropes give excellent properties at lower cost. However considerable theoretical and experimental work is needed in order to determine the optimum choices of fibre and rope constructions needed for particular applications. Six fatigue mechanisms have been identified, but testing is needed in order to generate an adequate data-base of material properties and actual rope performance.

The length effects are similar in principle to those occurring in wire ropes, resulting from weak link and bundle effects. Although statistical methods help in the use of limited data, there remains the problem of uncertainty as to what is the real distribution of weak places with probabilities much less than can be directly predicted from expèrimental data. However some recent work does indicate that the use of moderate safety factors will be sufficient to allow for these problems.

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Effects of Length on Fatigue of Steel Wires in Service

Effets de la longueur sur la fatigue des fils d'acier en service

Einfluß der Länge auf die Betriebsermüdung von Stahldrähten

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SUMMARY
Practical issues in relation to the fatigue of 5 mm wires, 7-wire prestressing strand, and hanger cables, are discussed. Examples are given of failures taken from bridges in service.

RÉSUMÉ
L'article traite de questions pratiques intéressant la fatigue des fils métalliques de 5 mm, des torons à précontrainte á 7 fils et des câbles de suspension. Il présente des exemples de défaillances constatées sur des ponts en service.

ZUSAMMENFASSUNG
Praktische Fragen in bezug auf die Ermüdung von 5 mm-Draht, 7-drähtigen Spannlitzen und Hängekabel werden diskutiert. Beispiele von Ausfällen an in Betrieb stehenden Brücken werden angeführt.

1. INTRODUCTION

Steel wires are used in bridge engineering for prestressed concrete beams and in cables for suspended and stayed structures. The wires are normally used as assemblages, for example as 7-wire prestressing strand, and as cables. There are a variety of types of prestressing strand but the most common form in current practice is 7-wire strand composed of a central 'king' wire having six wires helically wound around it with a lay length of between 12 and 18 times the nominal strand diameter. Suspension and stay cables are supplied in a number of configurations to suit the requirements and preferences of the designer. Typical types of cable configuration are: helically wound locked coil, multi strand, and parallel wire bundles. Sizes of the constituent wires are typically in the range 2 to 7mm diameter.

In the technical development of wire and strand the mechanical properties that have received most attention have been the breaking load, ductility and stress relaxation. Fatigue performance has received less attention and until recently has been treated as a secondary issue of little practical importance. In consequence fatigue testing has been carried out to variable standards and one of the few available recommendations to be published is by RILEM [1]. Here, it is recommended that for bars and wires the free length between grips should be at least 500mm. For strand it should be five times the lay length or 700mm. The cyclic testing frequency should be in the range 1.33 to 100 Hz but it is stated that 3.33 to 10 Hz is preferable. Control tests should involve at least six specimens. Failure of strand can be taken as fracture of one wire; no account should be taken of tests having fractures located within five strand diameters of the grips.

In practice many investigations have failed to meet the RILEM recommendations. Indeed they are quite difficult to meet because few commercially available fatigue testing machines have suitable load ranges in combination with headrooms that will accommodate a specimen 500mm long plus special grips, let along 700mm. The gripping of wires and strands presents special problems which investigators have tackled in different ways but it remains quite difficult to avoid fractures within five strand diameters of the grips.

Engineers' attitudes to fatigue of wires have changed in recent years. This is partly as a result of fatigue failures that have occurred in service; in Germany prestressing tendons were found to have failed in fatigue at mechanical connections in a curved concrete box girder bridge and similar cracks were found in numerous other bridges as described by Sieble [2]. The CEB Model Code [3] has introduced fatigue clauses giving design assessment procedures and recommended fatigue strengths for prestressing steel. The properties and performance of different types of prestressing steel have been summarised by Mallett [4].

This paper deals mainly with fatigue of 5mm diameter steel wires in relation to some of the practical issues facing engineers responsible for designing and maintaining highway bridges. Data are drawn from several laboratory investigations in support of specific bridge investigations and are not from a single coherent programme.

2. PERFORMANCE OF SINGLE AND MULTI-WIRES

Length effects are of course the subject of this conference and it is generally understood that fatigue performance of wires reduces with increasing length; endurances for free lengths of 900mm are said to be some 20-50 per cent lower than for 250mm lengths depending on the value of mean stress. Investigators are aware that it is essential to test adequate free lengths, but as mentioned in Section 1, are often constrained by the dimensions of available testing machines. Leaving aside the dictates of scientific enquiry the practical reason for testing adequate lengths is to ensure that realistic lower-bound performances are obtained. In this context it should be noted that the performances usually quoted are for uniaxial tests carried out on free lengths of wire or strand in air. However, prestressing strand behaves differently when embedded in concrete and it is more relevant to test beams subjected to bending fatigue. In tests by Howells and Raithby [5], on prestressed lightweight aggregate beams of 15.4m length loaded under 4-point bending, the prestressing wires failed in fatigue after 0.289 million

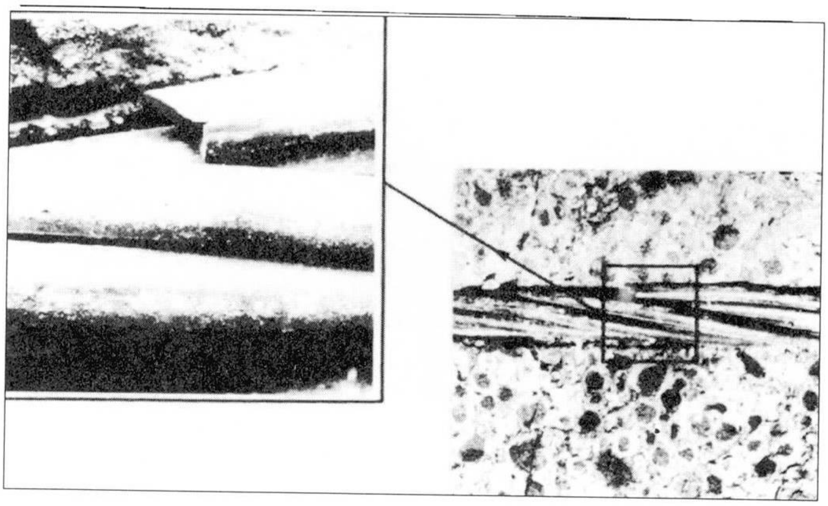

Fig 1 Fatigue fracture of prestressing strand in lightweight aggregate concrete beams.

cycles (see fig 1). Interestingly some of the wires failed at more than one place along their length. When the beam was demolished after the test, a number of pieces of wire, about 500mm long and having fatigue fractures at each end, were lifted out of the prestressing strand. This indicates that although the wires were broken in one place they were able to pick up load a short distance from the fracture face and incur a second fatigue failure. Thus it is evident that there is a different regime affecting the length effect for wires embedded in concrete.

In a series of investigations of highway bridges, axial fatigue tests were carried out in air on wires, strands and cables having free lengths of 160 to 2800mm. Failures were classified as when one wire in a strand had failed and when five wires in a cable had failed. Unfortunately the experimental conditions were dictated by the individual investigations so that there were too many variables to enable length effect to be commented on in any detail.

As part of an investigation of the collapse of Ynys y Gwas Bridge by Woodward [6], fatigue tests were conducted on samples of 5mm prestressing wires removed from the bridge. Many of the wires had fractured before the bridge collapsed and it was necessary to check whether fatigue had occurred. In the event the fracture surfaces were spoiled by corrosion and immersion in the river beneath the bridge and it was not possible to identify the mechanism of failure. Fatigue tests were conducted on wires selected as being (a) in pristine condition and (b) different degrees of corrosion. In these tests the free length between grips was 160mm ie 32 diameters. There was an emphasis on obtaining long endurances.

The fatigue data are shown in fig 2 where they are compared with data for 7-wire strand tested with a free length of 300mm. It is evident that the single wires exhibited slightly better performances at endurances beyond one million cycles but the difference was not as significant as had been anticipated, bearing in mind that the strand was tested in longer free lengths and furthermore there was the likelihood of fretting causing earlier initiation. The results are consistent with tests reported by Fisher and Viest [7] which indicated that wires can have higher fatigue strengths than strand.

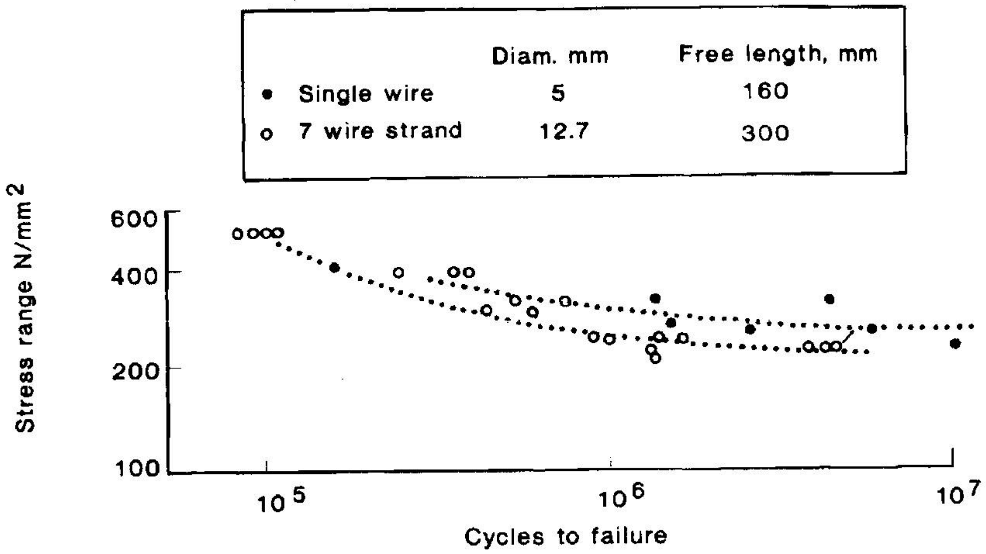

Fig.2 Endurances of single wires and strand

The data for the strand are compared with data from two other investigations involving tests on free lengths of 500 and 2800mm in fig 3. In this case there is

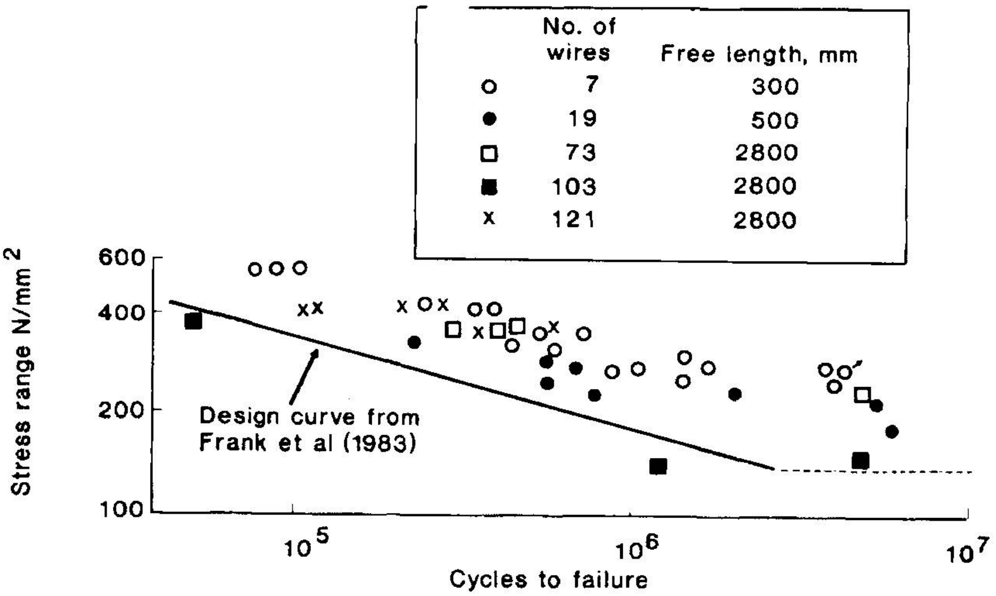

Fig.3 Endurances of strands and cables

a tendency for the tests on specimens having longer free lengths to exhibit lower performances. There was evidence of fretting in the 19-wire strand and the cables. The cables were tested with sockets fitted and failures were always in the vicinity of the socket. However, performance correlated surprisingly well with other work where failures occurred in the middle of the free length, Tilly [8], but the behaviour shown in fig 3 may be unrelated to the longer free length.

Comparatively little attention has been given to establishing performance curves for wires and strands. In one of the few comprehensive investigations Paulson, Frank and Breen [9] analysed available data for 7-wire strand and produced a recommended lower bound curve as shown in fig 3. It can be seen to correlate satisfactorily with the data in this paper.

3. CORROSION

The remnant fatigue strength of severely corroded wires and strands was investigated for samples removed from highway bridges after 16 to 21 years in service. The stress ranges were corrected to net values at the failed sections so that performances could be assessed on factors other than the loss of load bearing section.

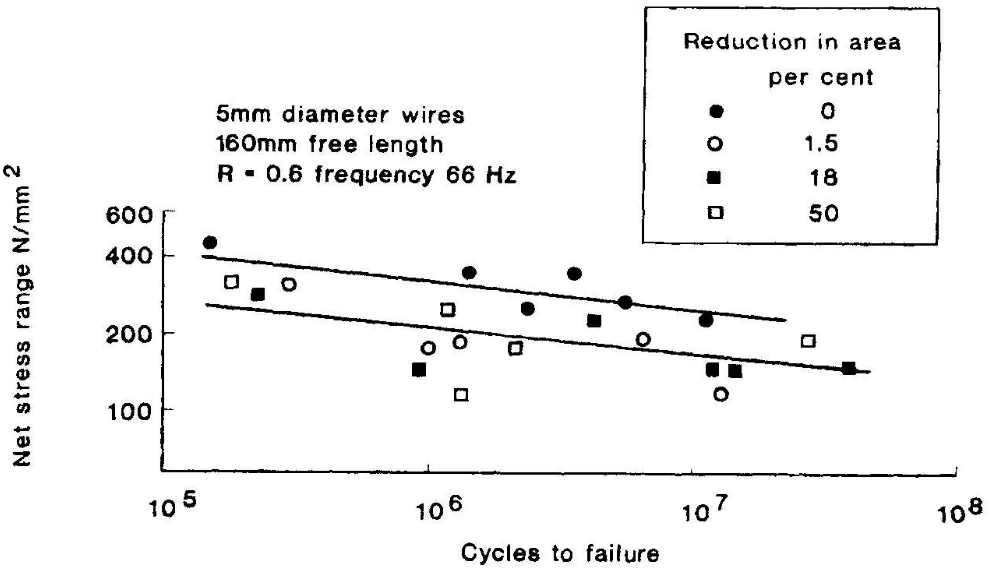

Fig.4 Endurances of corroded wires

For the single wires removed from Ynys y Gwas bridge there were losses in section of up to 50 per cent. The wires were classified into three levels of corrosion as shown in fig 4. It was evident that there is no apparent relationship between the extent of corrosion and reduction in fatigue strength. The overall reduction in lower bound net strength is about 50 per cent.

For the 7-wire strand there were fewer specimens and it was not possible to classify corrosion damage in the same way as for the single wires. The losses in section were 5 to 15 per cent but very badly corroded sections having more than one wire broken were excluded. It was found that the reduction in lower bound fatigue strength, shown in fig 5, is about 35 per cent. There were fewer tests and less experimental scatter than for the single wires and if more tests had been conducted the overall reduction might have been as much as for the single wires ie 50 per cent.

These results are compatible with the earlier investigations by Neubert and Nurnberger [10] who investigated the effects of depth of pit in smooth bars and reported reductions in fatigue strength of up to 60 per cent for pits 1.25mm deep. Erdmann, Kordina and Neisecke [11] tested prestressing steel removed from demolished structures. They found reductions in strength of up to 50 per cent caused by corrosion pits up to 0.25mm deep but were unable to establish a relationship between fatigue strength and depth of pit.

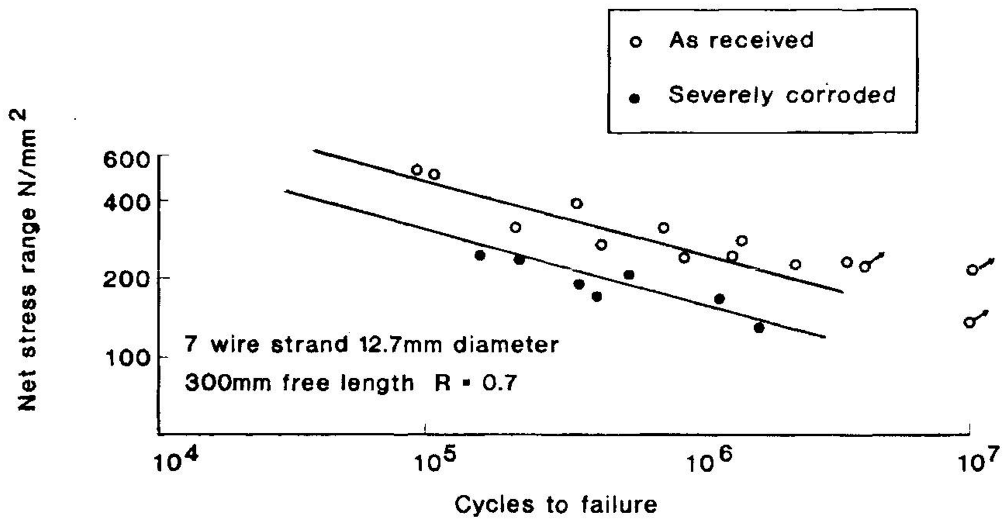

Fig.5 Endurances of corroded prestressing strand
(Strands removed from structures after 16-21yr)

The lack of correlation between fatigue performance and pit depth, and between loss in section and performance, may be explained by the order of magnitude difference between the number of cycles to crack initiation and the number in propagation. If a relatively small pit depth is sufficient to eliminate the initiation stage, so that most if not all of the endurance is in propagation, then a deeper crack will merely reduce the remnant life by a little more. In consequence the different performances for various pit depths are likely to be relatively small and most probably masked by experimental scatter.

Corrosion almost certainly influences length effect because the statistical distribution of corrosion pits is likely to be different from the distribution of flaws present in the surface of uncorroded wires. There is no information currently available on length effects under these circumstances.

4. FRACTURE TYPES

It has been estimated that a smooth defect free wire should have a fatigue endurance limit of about 360 N/mm². However, typical wires in service are not free of defects and the 'as received' 5mm wires tested by Woodward [6] exhibited a fatigue stress range of about 220 N/mm² at 10 million cycles. Typically, the fatigue cracking is initiated at a defect on the surface and propagates on a plane at 90° to the longitudinal axis of the wire, until the section is no longer able to support the maximum cyclic stress and final fracture takes place, see fig 6.

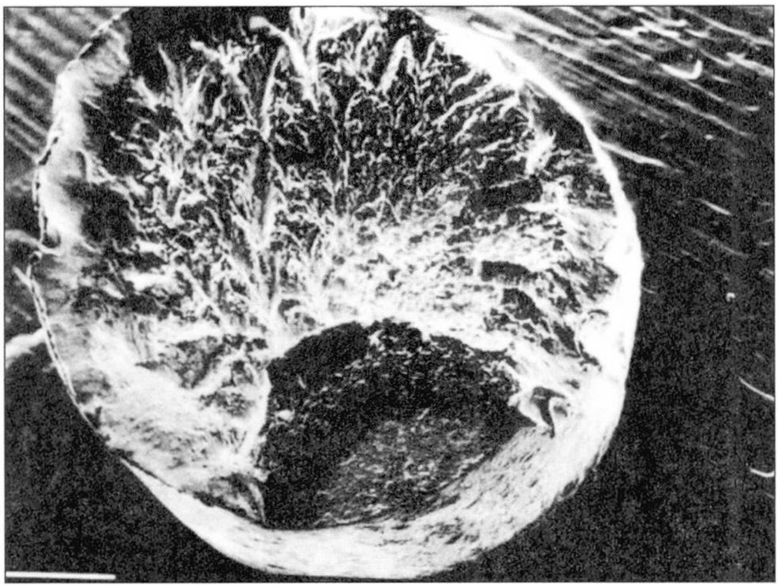

Fig 6 Fatigue fracture of 5mm wire.

The final fracture may be on a plane inclined to the longitudinal axis or may be brittle type; both types occurred in these investigations. Other types of fracture that can occur include cracks initiated at fretting sites, at corrosion pits, and corrosion fatigue.

4.1 Fretting

The nature of strands is such that when they are tested under tensile loads relative movements occur between the spirally wound outer wires and between the outer and inner wires. This causes fretting at the points of contact between the wires leading to earlier initiation of cracks and reduced fatigue lives as discussed for 7-wire strand by Cullimore [12]. In the present investigations fretting

Fig 7 Fretting fatigue in 19-wire strand.

induced failures were identified in tests on the 19-wire strand - see fig 7. It was most dramatically exhibited on the larger cables tested in a specially designed bending regime as shown in fig 8, Tilly [13].

For fretting fatigue the length effect is related to the lay length of the strand or rope.

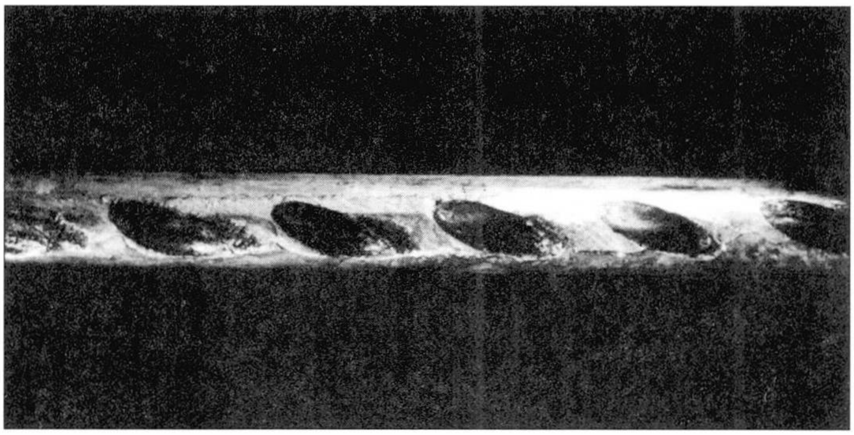

Fig 8 Fretting damage on 5mm wire from hanger cable.

4.2 Corrosion pits

As described in section 3 corrosion causes up to 50 per cent reduction in remnant fatigue strength due to the presence of pits causing local stress concentrations. Examples of fatigue initiated from corrosion pits are given in figs 9 and 10. Here the pit depths were about 0.8mm and 0.34mm respectively and are fairly typical of the more severely corroded wires. Final fracture of the 8mm diameter wire shown in fig 10 is brittle type.

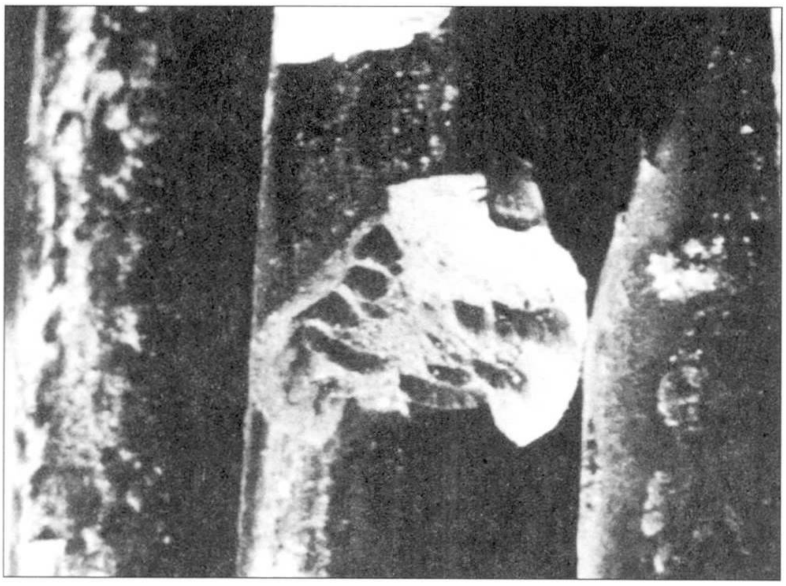

Fig 9 Initiation from corrosion pit in 19-wire strand.

The fatigue strength of corroded wires removed from a structure is a measure of performance which is useful for assessing remnant strength of structures but is not necessarily a correct simulation of the mechanics of corrosion and fatigue in practice. This is because corrosion and fatigue are interactive processes, as illustrated in the next section.

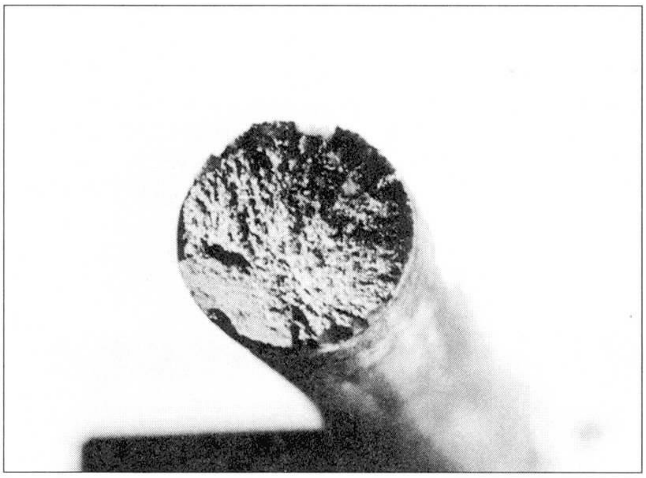

Fig 10 Initiation from corrosion pit in 8mm diameter wire.

4.3 Corrosion Fatigue

An example of corrosion fatigue occurred in galvanised wires removed from the hanger cables of a suspension bridge after some 10 years in service. The cables are believed to have experienced higher load ranges than had been anticipated and wires were found to have fractured close to the sockets where there was a combination of high stress and corrosive conditions. The cables were subsequently replaced by larger diameters and an improved design of socket was used.

Fractures of the wires took place in two stages; initiation represented by a flat region at 90° to the axis of the wire, and the final shear failure represented by

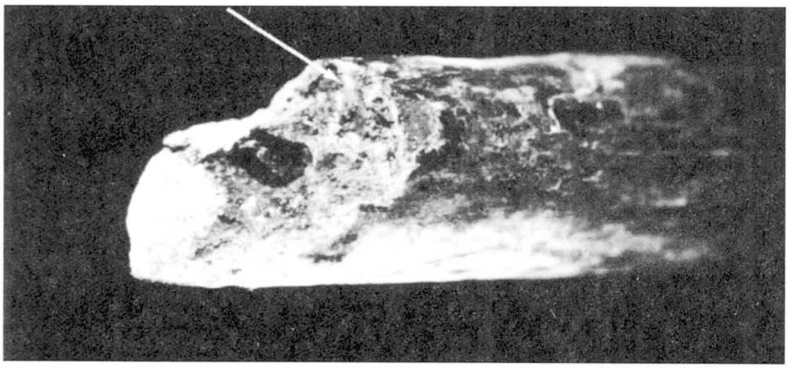

Fig 11 Corrosion fatigue failure of 3.4mm diameter wire after 10 years' service.

a fibrous region inclined to the axis, see fig 11. Numerous fatigue cracks developed in the soft zinc coating, some being deflected along the zinc-to-steel interface, and some propagated into the steel. A longitudinal section through a corrosion fatigue crack which did not lead to fracture is shown in fig 12 and it is evident that propagation was slow because there had been enough time for oxidation to occur. The longitudinal characteristics of the crack are typical of numerous others that were sectioned and are a reflection of the directional nature of the metallurgical properties of wire. It appears that there has been laminar splitting of the fibrous microstructure leading to lateral oxidation. In this example the crack appears to have initiated from the bottom of a corrosion pit which was about 0.2mm deep but there is no certainty because continued corrosion on the surface of the wire is likely to have changed the surface topography.

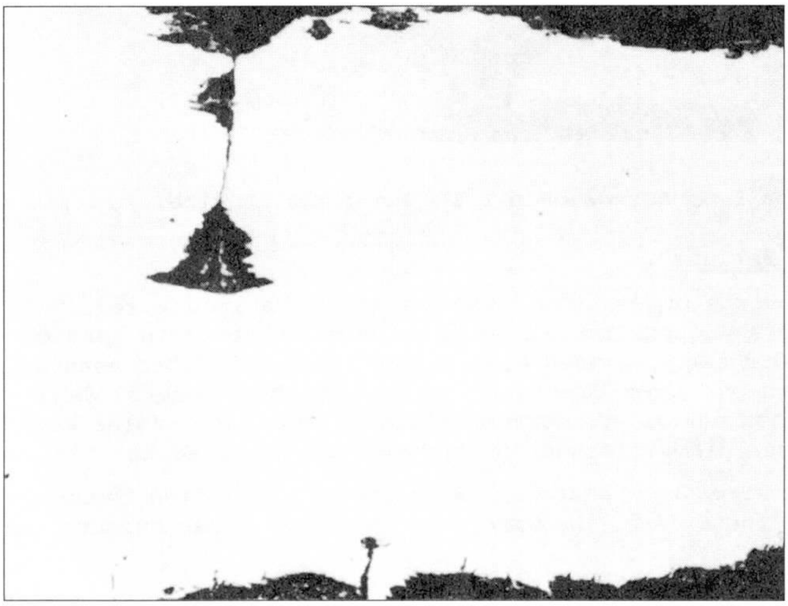

Fig 12 Corrosion fatigue crack adjacent to final fracture.

5. CONCLUDING REMARKS

A number of practical issues in relation to fatigue length effects have arisen through testing work in support of case studies of highway bridges.

It is important to test long sample lengths so that realistic lower bound fatigue strengths can be obtained. However it is not always possible to use suitable testing machines and there is a need to have more rigorously applied standards of testing.

In practice the length effects exhibited by single wires are likely to be modified in service conditions because wires are rarely used singly and are usually in 7-wire strand for pre-stressed concrete or as spirally wound cables for stays and suspenders. Parallel wire bundled cables are not considered in this paper. In strands and cables, initiation is dictated by the action of fretting and is therefore more dependent on lay length than on the statistical distribution of surface flaws. Corrosion can occur in service and influences the fatigue process through pits from which initiation can occur and by interacting with the crack propagation ie corrosion fatigue. Under corrosive conditions the length effect is likely to be dependent on the development and distribution of pits.

When prestressing strand is embedded in concrete the length effect is modified because of the transmission length between the concrete and steel. It is possible for wires to fracture but pick up load and fracture in a second position only 500mm or so from the first point. Work on reinforcement bars has shown that fatigue endurances in concrete are longer than in air and fracture locations are dictated by the disposition of cracking in the concrete rather than the presence of flaws on the surface of the steel. Although less comparative testing has been done on prestressing steel, it seems that the same situation applies and fractures coincide with cracks in the concrete.

ACKNOWLEDGEMENTS

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Fatigue Problems of Bridge Cables in Japan

Fatigue dans les câbles de ponts au Japon

Ermüdungsprobleme bei Brückenkabeln in Japan

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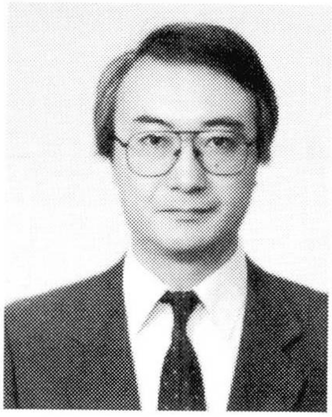

SUMMARY
Several long cable-stayed bridges and also the world´s longest suspension bridge have been built in recent years in Japan. This paper gives recent information on fatigue problems of bridge cables and indicates better solutions of cable system and the future developments from viewpoint of durabilty as well as fatigue strength and other mechanical properties.

RÉSUMÉ
Plusieurs ponts à aubans de grande portée ainsi que le pont suspendu le plus long du monde ont été tout récemment construits au Japon. Cette communication présente quelques informations récentes sur les problèmes relatifs à la fatigue des câbles de ponts et, par ailleurs, propose de meilleurs solutions pour les systèmes de câbles. Elle esquisse enfin leur développement futur, sous l'aspect de durabilité, de résistance à la fatigue et d'autres propriétés mécaniques.

ZUSAMMEMFASSUNG
In der letzten Zeit sind mehrere lange abgespannte Brücken sowie die weltlängste Hängebrücke in Japan gebaut worden. In der vorliegenden Arbeit werden gegenwärtige Auskunft über Ermüdungsprobleme an den Brückenkabeln erteilt, und bessere Lösungen für das Kabelsystem vorgeschlagen. Zuletzt wird die voraussichtliche Entwicklung hinsichtlich der Dauerhaftigkeit, der Ermüdungsbeanspruchung und anderen mechanischen Eigenschaften skizziert.

INTRODUCTION

Figure 1 shows how the cables of cable-stayed bridges in Japan have changed in recent years. As the size of cable-stayed bridge has become larger, cables have become longer and their diameter bigger even though multi-cable systems have been employed. The following points should thus be considered in the study based on these requirements.

(a) higher strength and modulus of elasticity

(b) higher fatigue strength both for tension and bending

(c) adequate corrosion protection

(d) easier installation and maintenance

The following describes the recent trends in the manufacture of bridge cables in consideration of the above points and additional matter which should be studied in the future.

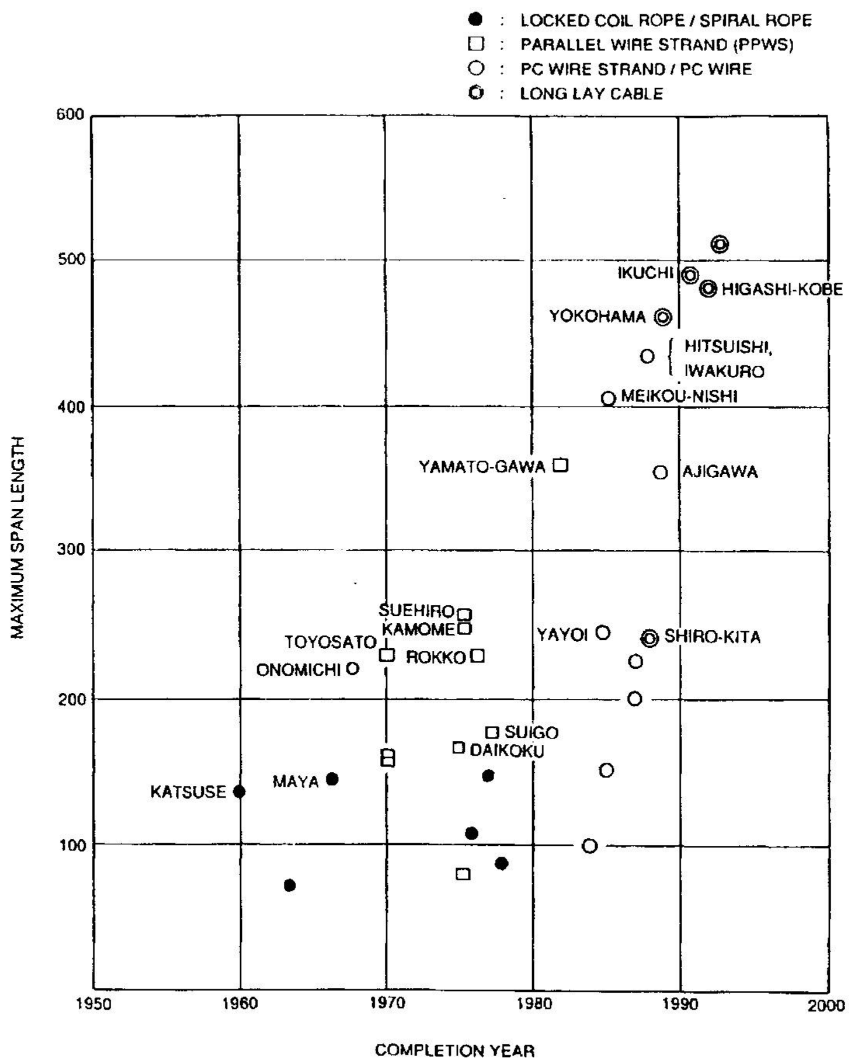

Fig.1 Historloal Change of Cable Type of Cable-Stayed Bridge in Japan

CABLE WIRE

1. Wire Rod

Cable wire is produced by two major processes : either by manufacturing wire rod or by wire producing processes like drawing and galvanizing.
The following factors influencing the fatigue strength arise mainly in wire rod stage.

(a) de-carbonization layer on the surface
(b) surface flaw
(c) non-metalic inclusion
(d) inappropriate chemical composition

In a study of factors which may influence the initiation of fatigue fracture, T.Yokobori et al achieved some good experimental results, they showed that in the case of drawn wire made from patented material, non-metallic inclusions are much more likely to initiate fatigue cracks than sureface conditions and the initiation of these micro-cracks will occur only during 5 ~ 20% of the total life [1].

These factors are essential items in the quality control of wire rod. Table 1 shows the new specifications of wire rod for the Akashi Kaikyo Bridge (suspension bridge, mid span = 1,990m)[2]. Although it is basical considering

Table 1 Specification on Wire Rod for Cable Wire in HBS (G 3507)

		REQUIREMENT
SIZE	DIAMETER	LESS THAN ±0.40 mm
	ROUNDNESS	LESS THAN ±0.40 mm
NON-METALLIC INCLUSION	RATIO	LESS THAN 0.07 %
DE-CARBONIZATION LAYER	DEPTH OF LAYER	LESS THAN 0.07 mm
SURFACE FLAW	DEPTH OF FLAW	LESS THAN 0.07 mm

whether the probability of failure is proportional to the degree of the factors mentioned above, it would be better to have the more stringent quality control requirements. However, it would also be important to improve both the manufacturing method and the QA programme to ensure the degree of manufacturing error (even 3 σ) would satisfy the requirements, and also to recognize that any such consideration should be based upon the kind of material, manufacturing method and specifications/standards used.

2. Galvanized Wire

The drawing and galvanizing processes also affect the fatigue strength. The important factors in this are assumed to be as follows.

(a) reduction ratio in the drawing process
(b) heat applied in the galvanizing process
(c) thickness of the Fe-Zn alloy layer

These factors basically relate to the processes used by individual wire makers and their degree of expertise. However, it has been reported in the recent studies [3][4] that :

(a) When the reduction ratio in the drawing process goes up, the fatigue strength first goes down but goes up later on. However, there comes a peak soon. So, it could be said that it would be better to raise the fatigue strength not through the drawing process but through chemical means and the heating process.

(b) For high carbon steel, when temperature of 450°C is maintained for a certain period of time. Though the tensile strength drops, the fatigue strength does not go down much. However, of 480°C, the fatigue strength drops significantly. So, care must be taken in choosing the temperature and the time it is maintained for, which should both be strictly controlled.

(c) As the Fe-Zn alloy layer gets thicker, the fatigue strength goes down. However, if the Fe-Zn layer becomes too thin, the amount of heat required would be less so that pre-heating would necessary before galvanizing.

The above could be said to apply to the high carbon steel wire with a ultimate strength of 160 kgf/mm^2 used in most of the suspension bridges and the cable-stayed bridges in Japan. Recently, a stronger wire (σ_{ut}=180 kgf/mm^2) has been developed and has been used for the main cables of the Akashi Kaikyo Bridge. The features of this steel wire are as follows :

(a) Higher strength achieved using silicon.

(b) The effect of heat on the tensile strength is less than for conventional wire.

(c) The fatigue strength of this wire is equal to or more than that of conventional wire.

As mentioned above, steel wire can be strengthened mainly by drawing alone but there would be restrictions on ductility and fatigue strength. So, it would be better to strengthen it by chemical means and the heating process. It is known that, in addition to carbon, slicon manganese and chromium are good for strengthening wire in the heating process and that silicon raises the strength of patented materials without changing the lamellar spacing. The tensile strength increases by approximately 15 kgf/mm^2 when the silicon is increased to 1%. Also, silicon can control the cementaite, so for 1% silicon, the tensile strength would decrease not much during bluing, although in the case of high carbon steel, it will decrease by about 10 kgf/mm^2. Figure 2 shows the tensile strength for different temperatures for high carbon steel and steel with silicon [5].

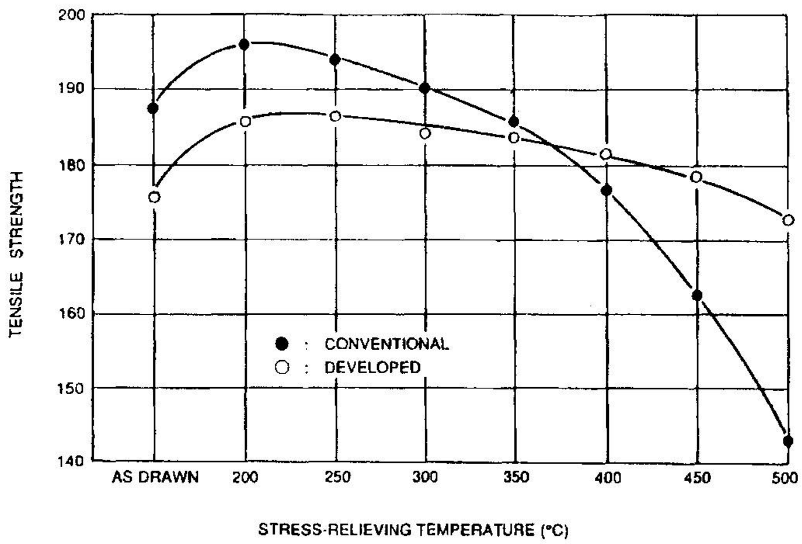

Fig. 2 Tensile Strength of Steel Wire at Stress-Relieving after Drawing Process

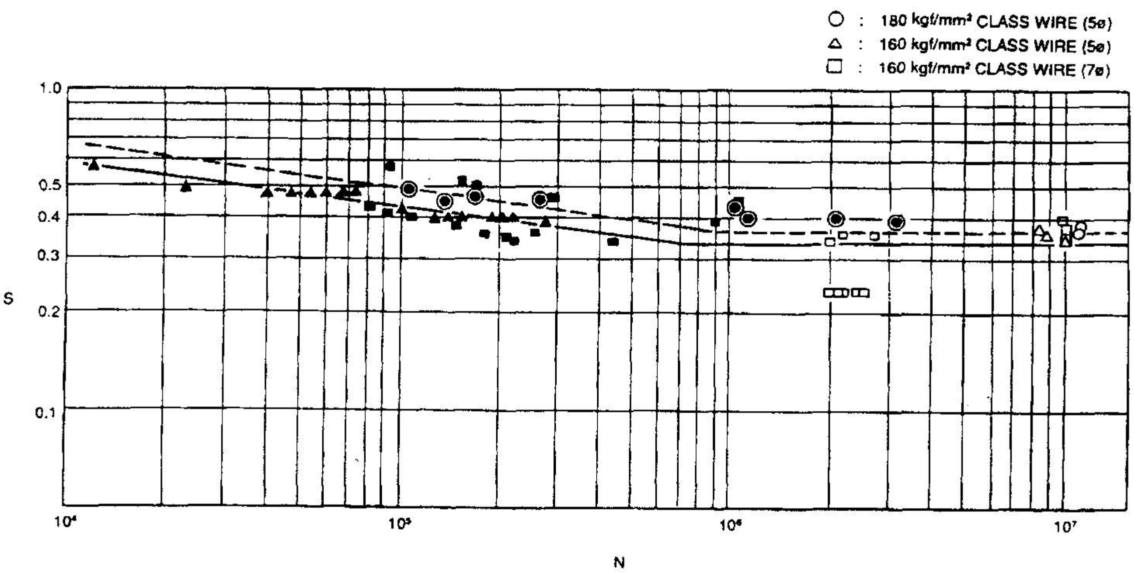

Fig. 3 S-N Curve of Galvanized Steel Wire

In newly developed wire, the strenghth has been improved and also reduction in strength due to the heat applied has been kept to a minimum. Therefore, it has good ductility which increases the fatigue strength (see Fig. 3), shows good results in the delayed fracture test and other mechanical properties are also good. Figure 3 gives a non-dimensional expression ; $S=(S_r f_u/[1-(f_m/f_u)^2])$ which f_u is the ultimate strength S_r is the stress range tested and f_m is the mean stress [6].

CABLE WITH ANCHORAGE

The factors influencing the fatigue fracture of cables are the fretting corrosion and the length deviation in a cable as an assembly of wires, the stress concentration, the fretting corrosion and the heat applied when the cable anchors were installed.

Figure 4 shows the difference between the fatigue test results for wires and cables with anchors. The cables have an impoved zinc socket at both ends which is asuumed to give a better fatigue strength than the conventional type. This difference in fatigue strengths is assumed to arise problems that still exist with anchors such as stress concentration at the fixing front, fretting corrosion in between wires and length variation in wires as well as defects in them.

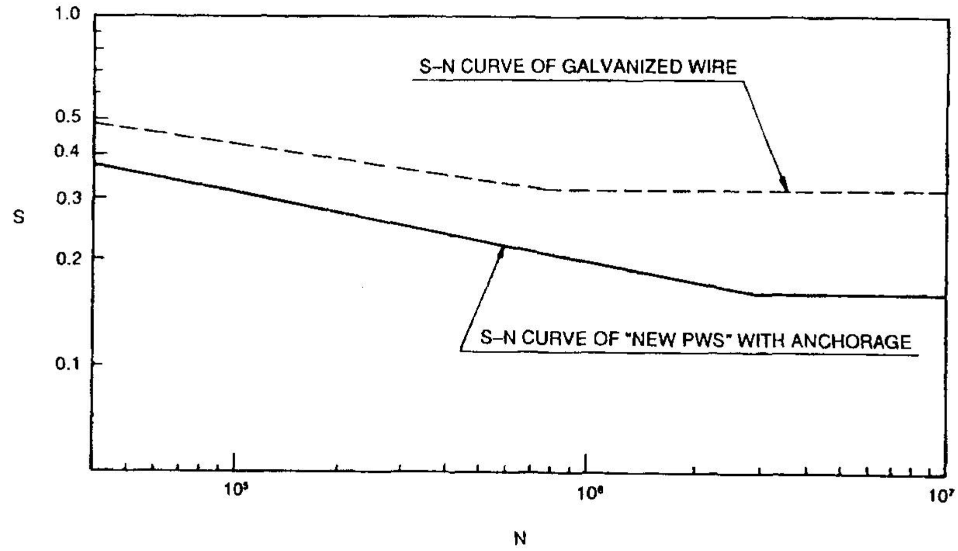

Fig. 4 Comparison on Fatigue Strength between Cable Wire and Cable with Anchor

Regarding the fatigue strength of the cable itself, several models assuming that it is an assembly of wire units have been proposed and discussed. These discussions have mainly concerned themselves with the variation in the amount of defects in wires. However, as mentioned above, the probability of defects basically depends upon the type of wire and cable, so it is important to specify the object of the study. The cable wire used for the Honshu Shikoku Bridge have given good results until now in that the variation in tensile strength (3σ) has been 5~7 kgf/mm^2. In this case, if the variation in fatigue strength could be somehow made proportional to that in the ultimate strength, the variation in fatigue strength in this type of wire would be relatively small.

Besides the wire, the fatigue strength of a cable depends much upon its structure. Table 2 shows the fatigue strengths of several types of cables. It shows that twisted wire rope suffers more from fretting problems than parallel wire cables. Figure 5 shows a failure distribution for wires subjected to the bending fatigue test. It can be seen that the parallel wire cable or similar cable, such as the long lay cable (e.g. NEW-PWS), would be better than wire rope.

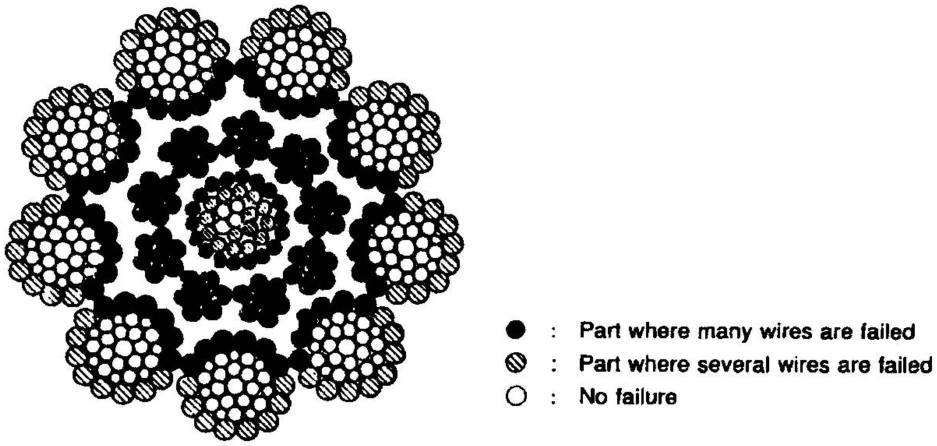

Fig. 5 Distribution of Failed Wire at Bending Fatigue Test of "Center Fit Rope Core" (CFRC)

Table 2 General comparison on Fatigue Strength between Types of Cable [7], [8]

		Fatigue Strength	
		Tension Fatigue ($\Delta\sigma$)	Bending Fatigue (Test Result)
WIRE ROPE	LCP	appr. 15(kgf/mm^2)	3~7% failure until 3×10^6 cicles at $\theta=\pm0.57°$
	SPR	ditto	———
	IWRC	13~14 (kgf/mm^2)	———
	CFRC	ditto	cable failure until 0.8×10^6 cicles at $\theta=\pm0.57°$
PPWS		15~20 (kgf/mm^2)	0.8~3% failure until 4×10^6 cicles at $\theta=\pm0.57°$
NEW-PWS		appr. 25(kgf/mm^2)	no failure until 3×10^6 cicles at $\theta=\pm0.6°$

The typical way installing cable anchors is by spreading out the wires inside a socket and pouring zinc or zinc alloy into it. However, even molten zinc is not capable of penetrating the small spaces between wires and eventually it would become concentrated in certain areas, especially at the outlet of the socket as shown in Figure 6-a. This would cause unequal tension in the wires, concentrating it in certain parts, and might increase the fretting there.

Figure 6-b shows an improved zinc socket which solves these problems. This socket is as resistant to fatigue as the well-known HiAm Anchor. Important features for anchors are a simple structure and ease of installation.

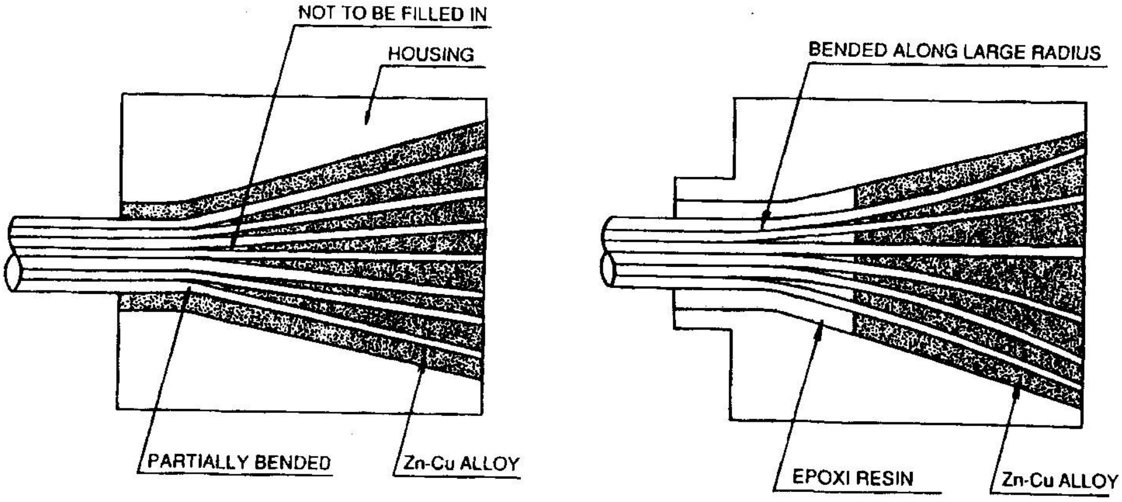

Fig. 6-a
Conventional Zinc Socket

Fig. 6-b
Improved Zinc Socket

OTHER TOPICS

In the case of bridge cables, corrosion protection and easy maintenance may be equally or more important than fatigue because probably we have never heard of bridge cables suffering from serious damage caused by pure fatigue. We can easily give several examples of corrosion problems in the history of cable suspended bridges.

Figure 7 shows the results of fatigue tests on corroded wires which were subjected to a Salt Spray Test (SST) for 50 days, 100 days and 150 days [9]. The results clearly show that the corroded wires have much less fatigue strength than sound wires. A rough wire surface may cause stress concentration lowering the fatigue strength as the amount of drop in fatigue strength becomes less as the wires become more corroded.

Besides the evaluation of corroded wires, it can be said that wire should thus be protected against corrosion, first of all, by galvanizing not by such a way as cement grouting. And methods should be developed for inspecting whether corrosion protectian is adequat or not. The magnetic, ultrasonic and other methods have been reported but being insufficient, still require further study. For this reference, it has been reported in the U.S. that a new method has been adopted to search for corrosion, even right inside of cable [10].

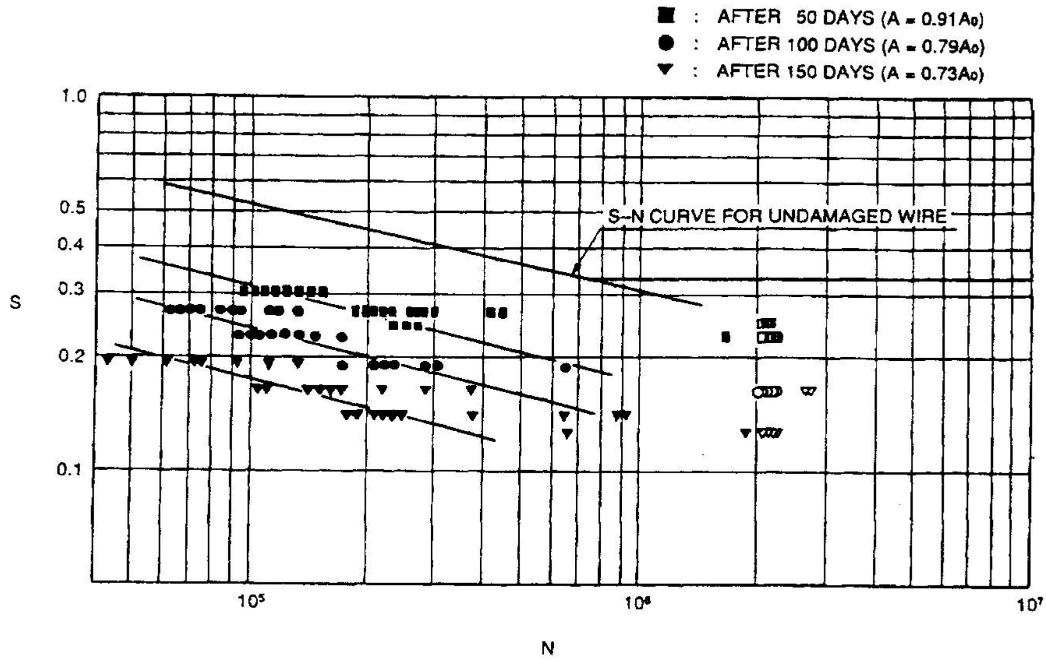

Fig. 7 S-N Curve of Galvanized Steel Wire after Salt Sprayed Test (Test Condition : 0.5 cm^3/min., Salt Water (pH 6.5-7.2)) (Courtesy of Kobe Steel)

CONCLUSION

Recently, much longer suspension bridges have been planned and built, such as the Akashi Kaikyo Bridge in Japan and the Great Belt Bridge in Denmark and the large cable-stayed bridges have been steped forward building. Because of this, an accurate understanging of the fatigue and bending fatigue properties of cables and problems associated with them as well as their tensile strength is extremely important. We should therefore consider the following to ensure the durability and quality of design, construction and maintenance of cables.

1. The higher strength wires so far developed and used for the main cables of the Akashi Kaikyo Bridge have high fatigue strengh and other good mechanical properties. However, concerning cable structure, it should be remembered that the parallel wire system has better fatigue performance and mechanical properties than conventional twisted wire ropes.

2. From the viewpoint of the whole cable system, it should be noticed that that cable anchors tend to be the weak point rather than the cable wires

themselves. Therefore, reliable anchors should be used to improve the design. It is also important that cable anchors should be designed for easy fabrication, and installation in accordance with manufacturing standards, as well as for mass production.

3. Concerning the long term use of cables as in cable-stayed bridges, both better corrosion protection and the easier maintenance are very important points. However, these two points are in conflict with each other and there is also the problem that the inside of the cable is hard to inspect. Polyethylene coverings have been used recently for many cable-stayed bridges which employ long lay cables with zinc coated wires but may still require improvement to make inspection and maintenance easier.

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