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Failure Mechanisms in Fatigue

Mécanismes d'endommagement en fatigue

Schädigungsmechanismen bei Ermüdung

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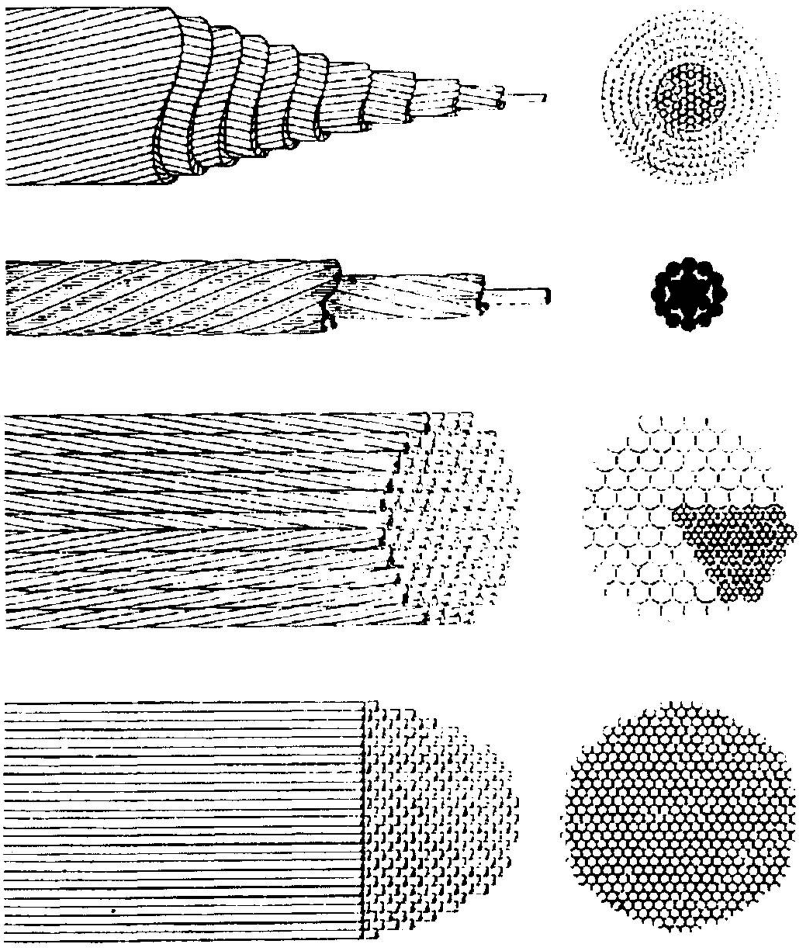
SUMMARY
The metallurgical and the structural engineering aspects of failure mechanisms and their effects are presented, which can lead to an early failure of tendons. The influence of the tendon-length was given only limited consideration. The deciding factors are disturbances ocurring at the clamps and the end anchorages as well as incomplete or damaged corrosion protection systems.

RÉSUMÉ
Les aspects métallurgiques et structuraux des mécanismes de ruine sont exposés, ainsi que leurs effets qui peuvent conduire à la rupture prématurée d'éléments tendus. L'influence de la longueur de l'élément tendu ne peut être prise en compte que de façon très limitée. Les éléments déterminants sont les désordres survenant au niveau de clavettes et des ancrages terminaux, ainsi que les systèmes de protection anti-corrosion incomplets ou endommagés.

ZUSAMMENFASUNG
Aus der Sicht der Metallurgen und des konstruktiven Bauingenieurs werden Schädigungsmechanismen und deren Auswirkungen geschildert, welche zu frühzeitigem Versagen von Zuggliedern führen können, wobei ein Einfluß der Zuggliedlänge nur sehr begrenzt berücksichtigt werden kann. Ausschlaggebend sind Störungen an Klemmpunkten und Endverankerungen sowie unvollständige oder zu Schaden gekommene Korrosions-schutzsysteme.

1. INTRODUCTION

High-strength materials, used today for bridging the ever increasing spans in the form of external pretensioning of concrete load bearing members or in the form of free tendons used for suspending or supporting bridge decks [1, 2], are thin fibres or metal wires which are combined into units of great load bearing capacity by means of sometimes complicated constructions. Since high tensile strengths can be produced economically only by small cross-sections (for example cold-drawing of steel, directed blending of plastics, quenching of glass), high-strength tendons with great loadbearing capacity have a large surface that has to be protected. n wires within one tendon have a n times larger surface than a cylindrical bar of the same total cross-section. Also, during bundling and stranding a lot of gaps and hollow spaces occur between the single elements (fig. 1) and the fibres and wires are less ductile and more sensitive to transversal stress due to their high-performance tensile strength. The surface quality and the impact of pollutants, which are intensified by the gaps and the unavoidable friction-motion are the main factors triggering fatigue fractures, which always start at the surface.



Cable Nets
Bridges
15 MN

Rope Ways
Hoisting Facilities
2 MN

Stays
Suspended Roofs
20 MN

Stays
Suspended Bridges
30 MN

Fig.1 Cross-sections of various cable-constructions and their fields of application
- Locked coil rope
- Round strand rope
- Parallel strand cable
- Parallel wire cable

Building construction does not allow large free tendon lengths and the intensified impact of pollutants in the area of the many anchorages, clamps and deviations [3] places high demands on the protection of these details (fig. 2).

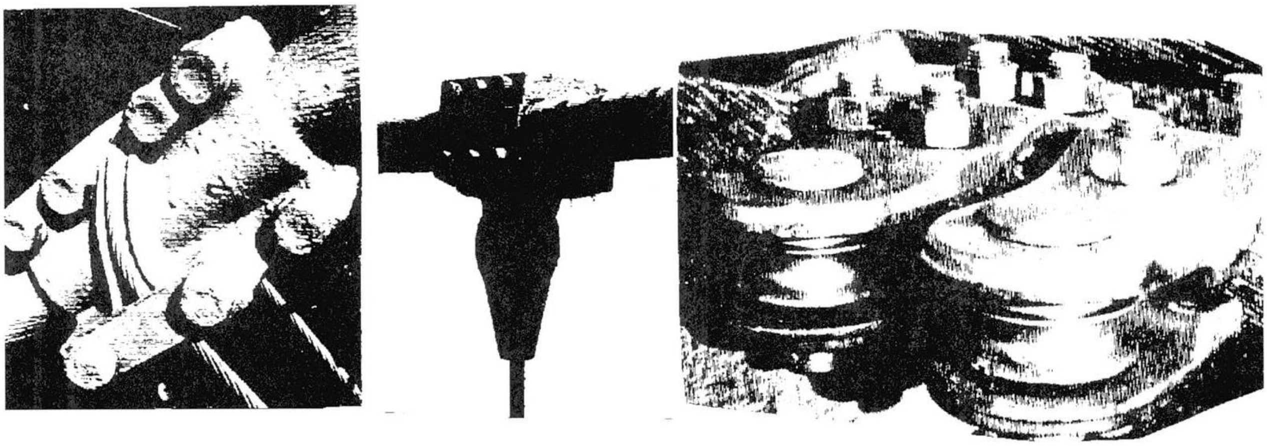


Fig.2 Clamped boundary-cables

Great cable lengths occur in case of suspension- and stay-cable-bridges as well as high, guyed masts. The selected load-bearing system also effects the security and the life expectancy, as does the form of the cross-section in the case of the large cables themselves. It is also relevant to security whether or not the selected construction of the cable should be redundant, sufficiently safe for inspection, and whether or not the parts should be replaceable, the wires and strands are bundled or should, as ropes, form a closed wire-system [4, 5].

The system can contain very long, free cables, which seem to be economical due to a small number of fittings (only 2 anchorages each), but they are subject to greater stresses due to wind- and traffic-induced deformations and vibrations. Therefore in the case of large bridge construction all variations ranging from the classical suspension-bridge-system to the simple stay-cable-bridge can be selected, according to the tasking and the marginal conditions [1] (fig. 3). This leads to a walk on the tightrope between the large, but easier deformable lengths and the increase in the number of fittings.

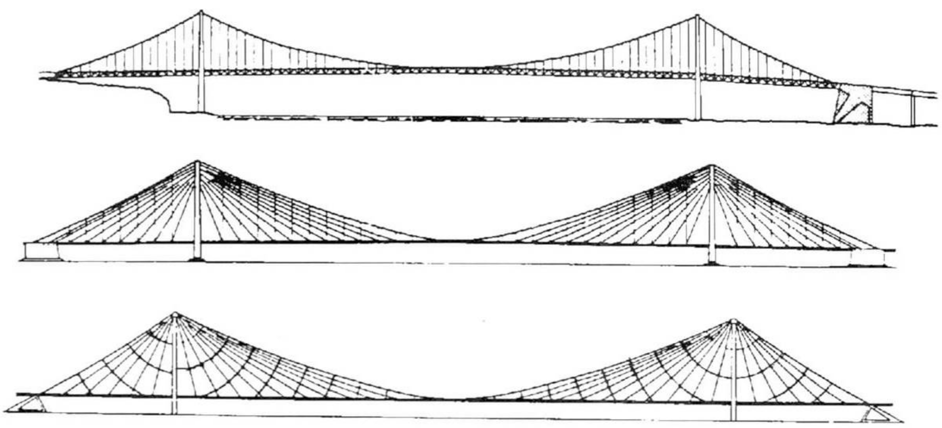


Fig.3 Loadbearing systems of large suspended bridges [1]

2. FATIGUE BEHAVIOUR OF WELL-PROTECTED SYSTEMS

2.1 Influence of material

According to mechanical and chemical influences, metal structural members as well as high-strength wires for ropes and bundles submitted to fatigue loading may undergo irreversible structural modifications. Based on the alternating loading, slip lines and slip bands may occur. Afterwards micro- and macro-cracks produced may extend and continue until fracture.

The properties of steel have an essential influence upon the fatigue behaviour [6-8]. For patented and cold-drawn wires out of unalloyed carbon steel, the fatigue strength increases by an increasing tensile strength until a cross-section reduction of about 80-86 % during drawing (fig. 4). For high-strength steel wires the surface quality has to be considered. Differences of surface roughness due to fabrication and surface imperfections (e.g. drawing marks) have a detrimental influence. Notch sensitivity rises by increasing strength. This is demonstrated in fig. 5 for the example of fatigue strength of smooth and ribbed prestressing steel wires of different strength.

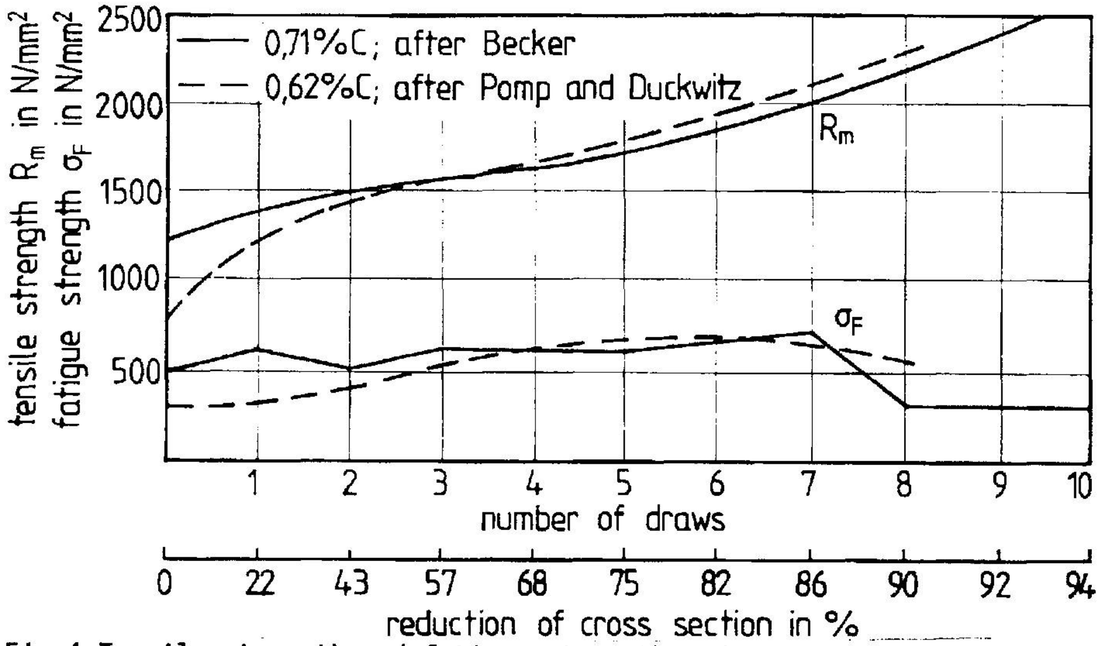


Fig.4 Tensile strength and fatigue strength under pulsating tensile stresses of cold drawn carbon steel wires [8]

For high-carbon steel wires with a degree of deformation > 65-75 % the fatigue strength is reduced by tempering [7]. Therefore, the non-heat-treated rope wires behave more favourably than the tempered prestressing steels. In [9] fatigue strength of 450 and 650 N/mm² were determined for non-tempered round wires with a strength of 1500 N/mm² and 1860 N/mm² respectively. Z-profile wires with a strength of 1470 N/mm² have a fatigue strength of 400 N/mm².

Strands and ropes have much lower fatigue strengths than single wires [7,9,11,12]. This is due to additional stress during roping, and friction between the wires (chapt. 3.4). Results of fatigue tests using unstranded galvanized wires, strands and ropes are shown in the Smith diagram in fig. 6 [11]. Worth noticing is the distance between the wire and the strand and also between the strand and the rope. The reduction of the fatigue strength of a wire increases with the wire strength during roping. Based on the results shown in [7], the following applies: If the strengths R_m are only 800-900 N/mm², the pulsating strength of the rope was only 0,25-0,35 R_m and for strength values of 1700-2000 N/mm², it is only 0,1-0,2 R_m.

Taking the dynamic behaviour into consideration, there is no advantage in using high-strength wires for the fabrication of ropes, as compared to low-strength wires.

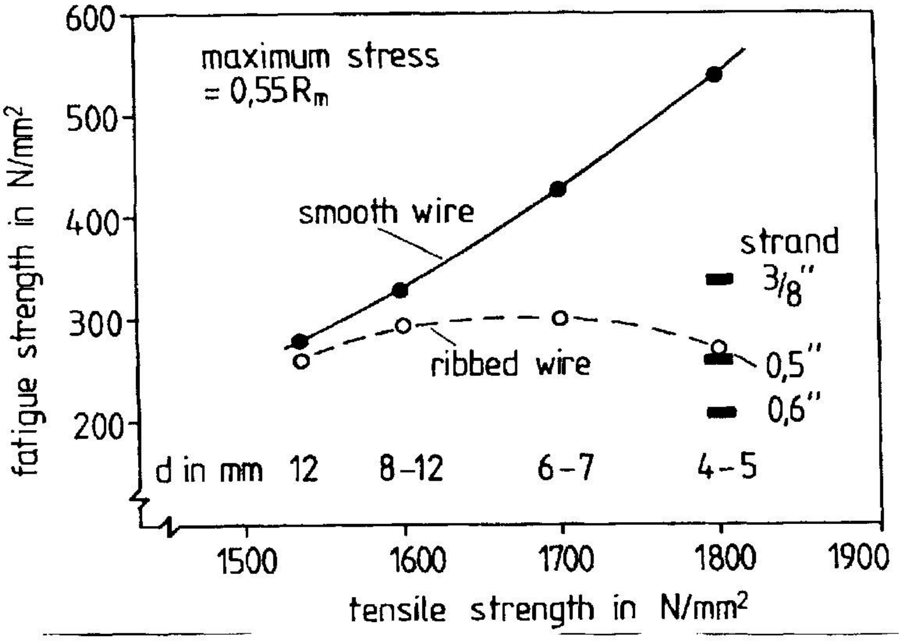


Fig.5 Fatigue strength of prestressing wires with smooth and ribbed surface and of strands (Nürnberger)

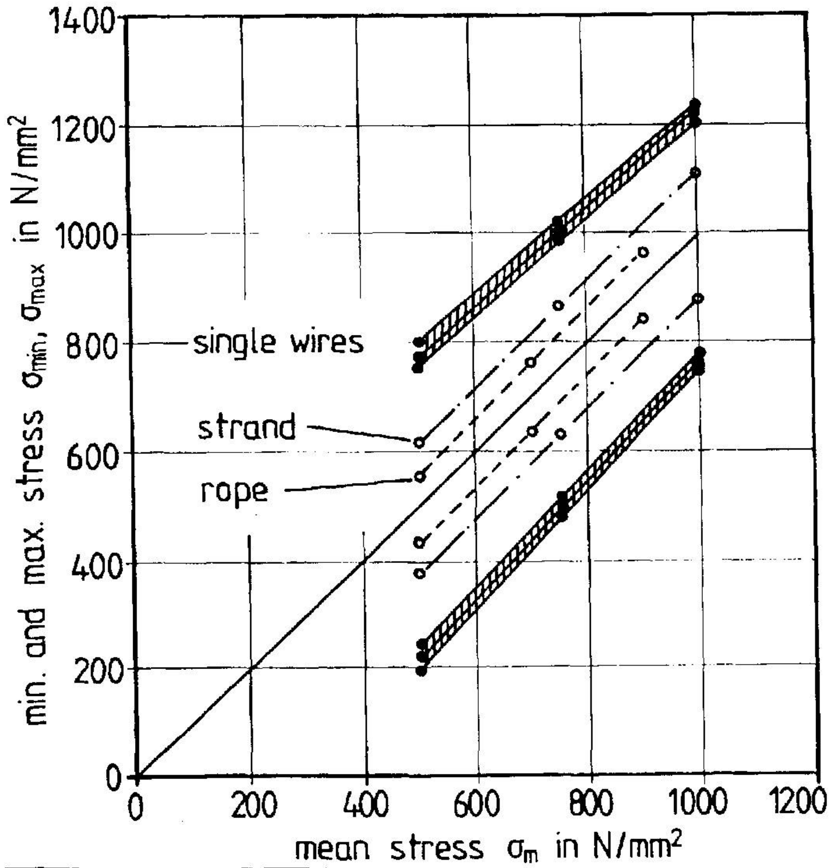


Fig.6 Fatigue resistance ability, Smith diagrams for ropes, strands (before roping) and wires (before stranding) (Becker) [11]

2.2 Influence of corrosion protection

Wires for ropes and bundles made of unalloyed steel could be protected against corrosion by metallic and/or organic coatings. The coating already improves the dynamic bearing capacity in the air.

The formation of a fatigue crack is influenced by physico-chemical interactions between the environment and the steel surface, activated by fatigue (chapt. 3.5). Not only liquids, but also gases and vapours may accelerate the deterioration process [13]. Dry air is already a surface-active medium and reduces the fatigue strength in comparison to the vaccuum. For high-strength steels the fatigue decreases by increasing the steam content in the air. Steel surfaces, activated by deformation, react with steam forming hydrogen which penetrates the steel and accelerates the formation of cracks as well as the crack propagation [14]. For the previously mentioned reasons, coatings impermeable to oxygen and steam (e.g. sufficiently thick reactive resins) improve the fatigue behaviour not only in corrosive environment (chapt. 3.5), but also in the air [13,15].

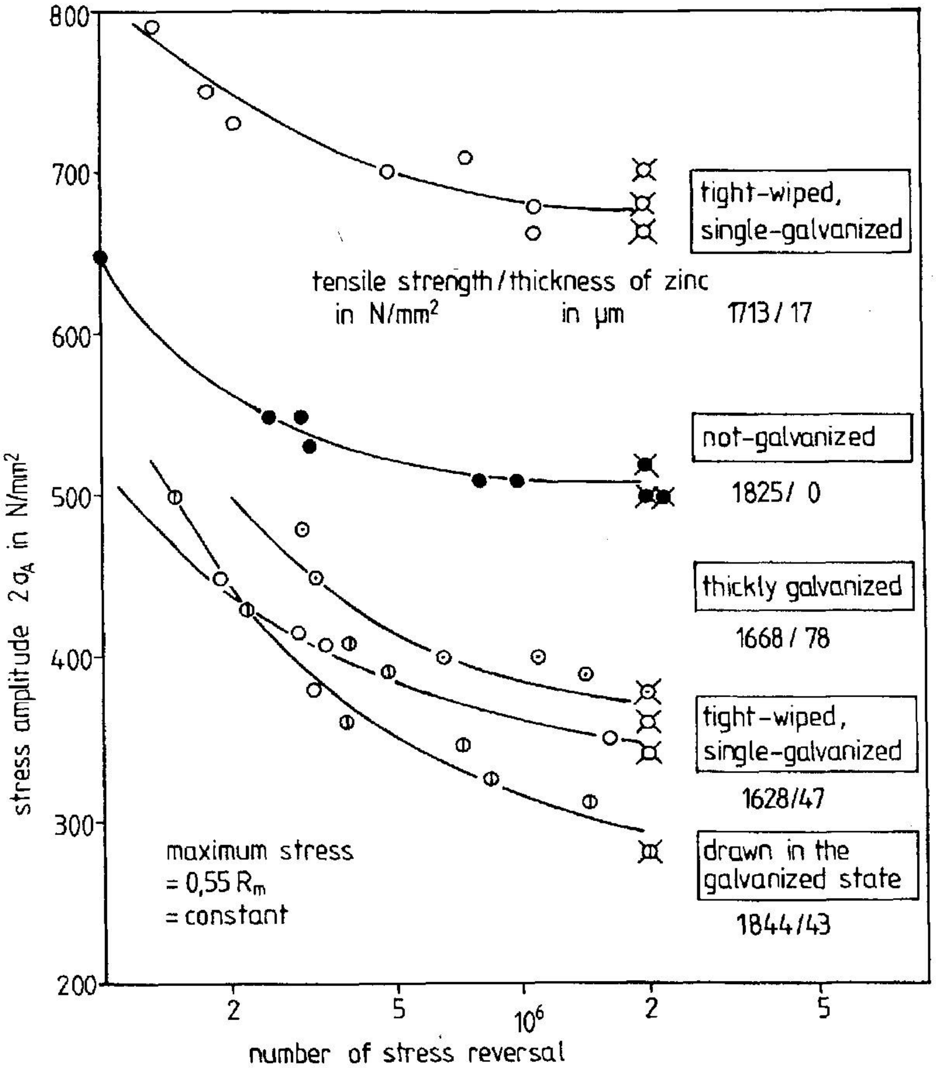


Fig.7 Results of fatigue tests of non-galvanized and galvanized cold-drawn and patented steel wires (tight-wiped of two fabrications) (Rehm, Nürnberger, Rieche) [17,18]

By galvanizing the wires, deterioration [7,16,17] as well as improvement [18] of the fatigue behaviour in the air may be established (fig. 7). An improvement of fatigue behaviour is due to:
- the sealing of the steel surface against the air,
- the thermal effect of the zinc bath which reduces the residual stresses.

An unfavourable effect is exerted by:
- the dipping of the steel surface, thus increasing the surface roughness as well as the amount of the absorbed hydrogen
- the notching effect of cracks in the iron-zinc-alloy layer (cracks result from handling and pulsation)

Electro-galvanizing may improve the fatigue strength (shielding effect), or the electrolytically released hydrogen may severely impair it [7,17].

3. INFLUENCE OF CHEMICAL ATTACK

3.1 Corrosion situation around tension members

Ropes and bundles (e.g. for the fastening of towers and bridges) are exposed to static/dynamic and corrosive influences. Corrosion promoting substances are water (high humidity, rain and condensation) and air (oxygen). Pollutants strengthen die attack. Extremely harmful sulphur dioxide is a result from burning fossile products. An industrial atmosphere contains up to 50 mg/m^3 of SO_2. After the oxidation and the reaction with water, sulphuric acid develops. The ph-content of atmospheric liquid substances, above all of dew and fog, may reach up to 3. Furthermore, the chlorides contained in de-icing salt-sprays are harmful. An oceanic athmosphere contains up to 0,1 mg/m^3. The corrosion of metals is generally enhanced by dust-deposits, which concentrate corrosive media and humidity.

3.2 Durability of organic and metallic coatings (galvanizing)

Organic coating

The coating has to separate the steel surface from the attacking media (passive corrosion protection). Plastics used as surface protection for metals show a certain permeability towards steam and oxygen. If the coatings are sufficiently thick, the resistance to diffusion is so high that corrosion underneath the coating may be neglected. As long as the protective system separates the steel wire from the surrounding area, no corrosion occurs.

According to [19], corrosive attacks are only possible if:
- the coating is not impermeable, e.g. pores exist,
- during construction the protective system is damaged, e.g. mechanically or by overexpansion,
- during operation mechanical effects (e.g. friction) or relative movements between the wires cause the coating to tear,
- under the influence of humidity and UV-light the coatings become brittle and tear under the mechanical loads or under the impact of temperature changes,
- permanent humidity causes the adhesive failure of mechanically sensitive coatings.

The following corrosive attacks may appear due to deteriorations of the coating (fig. 8) [20,21]:

Within the area of local defects oxygen-type corrosion may occur. If the coatings become (slightly) electrically conductive and are sufficiently permeable for oxygen (only in the case of thin coatings), corrosion will increase due to cell formation. The steel surface in the weak-point is the anode, and the coated steel surface is the cathode.

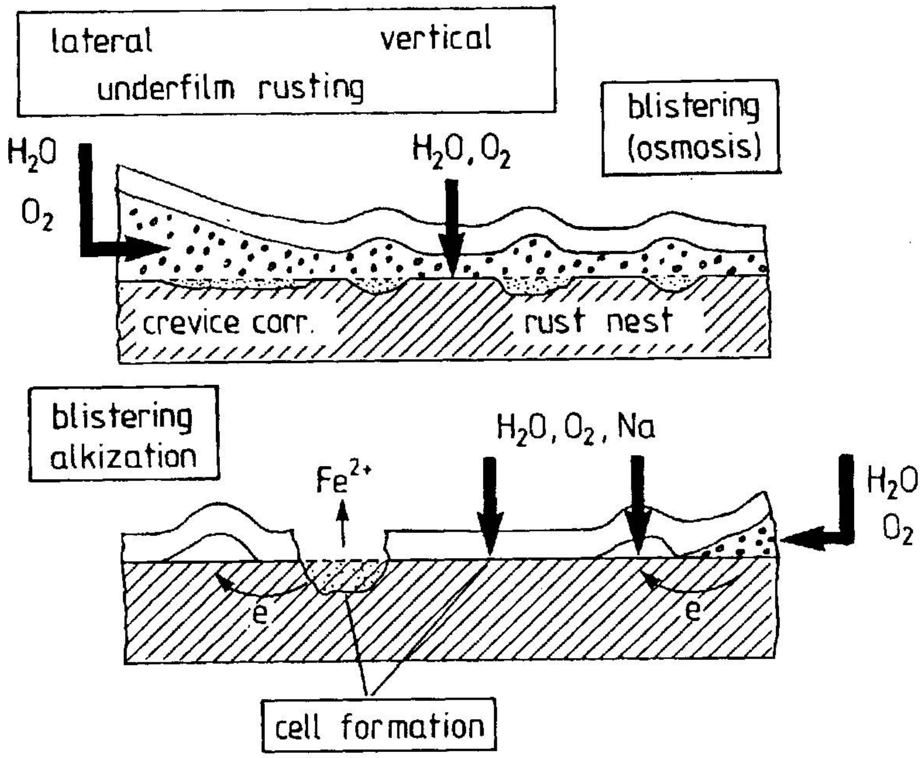


Fig.8 Possibilities of corrosion at coated surfaces

Near the defects in the coating or at the painting edges, an underfilm of rust occurs. Frequently it is supported by crevice-corrosion as a consequence of aeration cells. In the crevice, due to a hydrolysis and acidification of the liquid may occur, e.g.:

$$FeCl_2 + 2H_2O \rightarrow Fe(OH)_2 + 2\,HCl$$

In the case of underfilm rusting from the boundary, lack of adhesion due to insuffi- cient pre-treatment of the basis (rust spots) has an especially unfavourable effect. If the attacking medium contains salt, the corrosion may be uniform or pit-shaped. Exclusively in the case of thin-coated steel in frequent contact with water, blistering occurs. These may burst open and start the corrosion. Blisters are the result of the cathodic reaction near corroding areas underneath the coating:

$$1/2\ O_2 + H_2O + 2\ Na^+ + 2e^- \rightarrow 2\ NaOH$$

Galvanizing

Zinc coatings on steel protect against corrosion because protective carbon layers develop under atmospheric corrosion conditions. Under weathering corrosions rates of 1-10 μm annually are possible, depending on the aggressiveness of the atmosphere [22]. If the surface is poorly ventilated (e.g. water accumulations at low points, in crevices, frequent condensation), the formation of passive film is hindered and the corrosion rate increases extensively [19,23].

For duplex systems a combination of galvanization and organic coatings is applied. Only alkaline-resistant coatings (zinc corrosion products have an alkaline reaction) adhere to zinc-coated surfaces, and in the case of older zinc-coated surfaces, the adhesiveness is improved. Problems may occur if the coating is permeable for steam, but prevents CO_2-diffusion. Under these conditions a voluminous corrosion product $Zn(OH)_2$ develops instead of the protective zinc carbonate. Consequently, zinc is removed quickly and the coating peels off. The adhesiveness of the coating is desicively reduced, if it has been applied to surfaces, polluted by the atmosphere. Zinc salts have hygroscopic qualities and represent centers of disturbance for the coatings.

3.3 Fatigue behaviour of corroded wires

Corroded wires have a lower dynamic bearing capacity than new ones. The notching effect, i.e. the type and frequency of corrosive attacks, have an impact [12,19,24]. In the case of pit-shaped attacks, the reduction of the fatigue strength is greater than in the case of mainly uniform attacks (fig. 9). In the case of a drawn wire, 0,2mm deep corrosion pits or a more uniform corrosion with a depth of 1mm cause a low fatigue strength similar to that of a new wire exposed to additional fretting corrosion.

3.4 Fretting corrosion and fatigue

Tests in the air showed that single wires have a much more favourable fatigue behaviour than strands and ropes manufactured out of them (fig. 6).

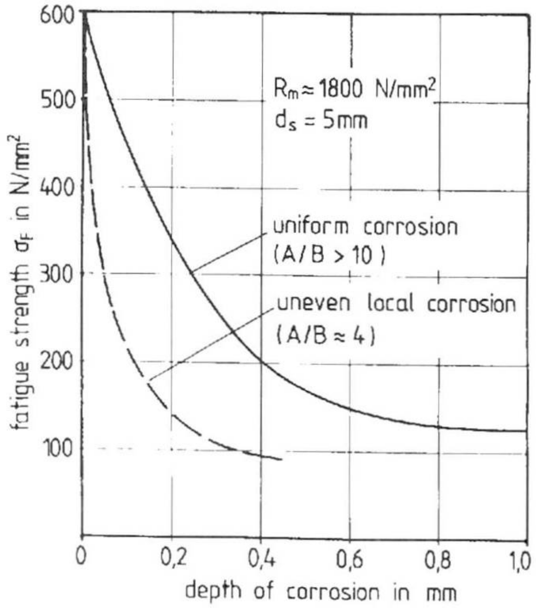
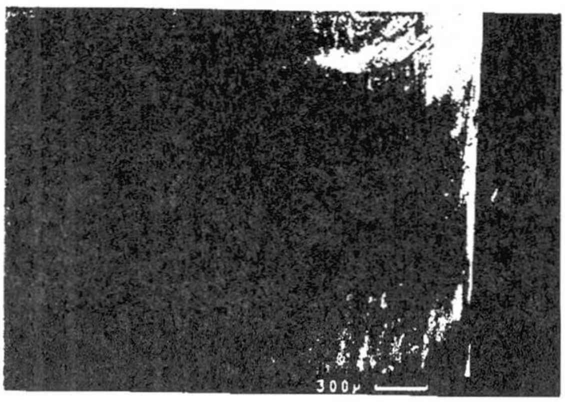


Fig.9 Fatigue strength under pulsating tensile stresses of corroded cold-drawn carbon steel wires (A=diameter of corrosion, B=depth of corrosion) (Neubert, Nürnberger) [24]



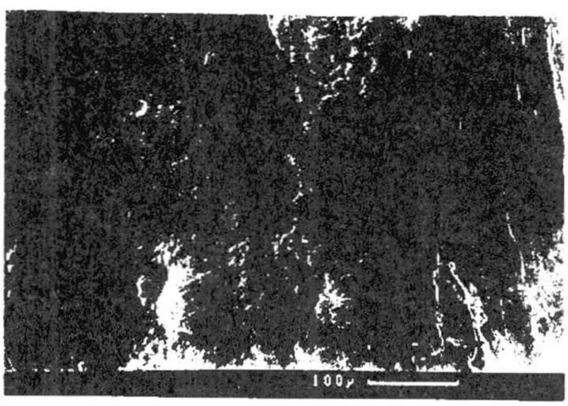
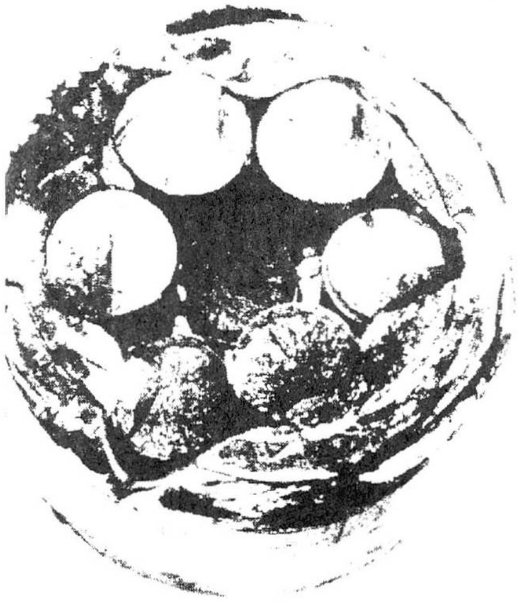


Fig.10 Fatigue cracks in the zone of fretting



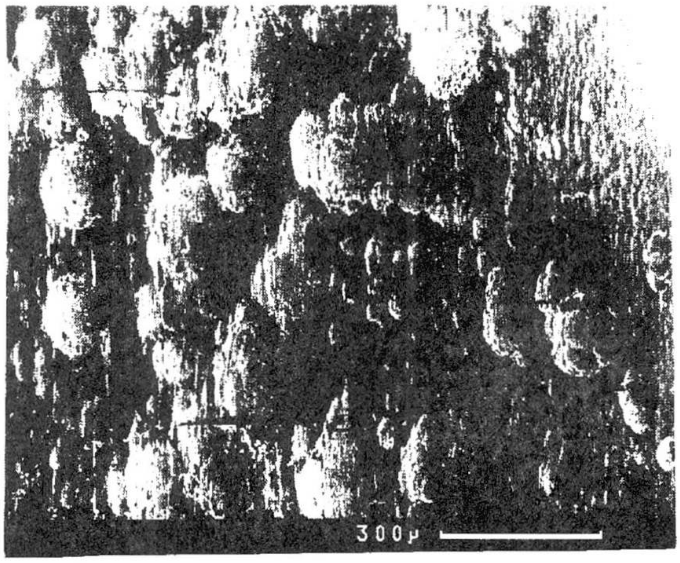


Fig.12 Pre-cracks at cold-drawn, unalloyed steel wire due to corrosion fatigue

Fig.11 Fatigue damage near fitting

In the rope, relative movements may occur between the wires. The result is a damage similar to the wear with a roughening of the wire surface. The surrounding air, i.e. the impact of an oxydizing medium, these friction surfaces are oxydized. Under fatigue loads, this fretting corrosion [25] causes additional tension stresses which constantly change their direction. Furthermore, the combination of mechanical and corrosive activity destroys the metal structure at the friction points, causing cracks which, in form of sharp notches, facilitate the development of permanent fractures [19,26] (fig. 10). Additional corrosive influences do not substantially increase the fretting corrosion compared to air.

Above all, due to the fretting corrosion 2 x 10^6 stress reversals were reached for the cable (for the maximum stress 42 % of the tensile strength), depending on the type of construction with the following stress amplitude:

open spiral cables: 180-200 N/mm^2
closed spiral calbes: 150-180 N/mm^2
parallel wire bundles: 200 N/mm^2

For single wires, a fatigue strength > 400 N/mm^2 is possible.

In addition, there are a number of structural influences such as clamps and anchorages which in the case of unaffected cables, can further reduce the above-mentioned fatigue cycles due to fretting corrosion. Cables anchored by cast zinc alloys, the entries of the wires into the casting are highly endangered due to the fretting corrosion and the development of fatigue cracks [27], since here the relative shifts and the compression between the wires reach their maximum. Fig. 11 shows the most frequent development of a permanent fracture in the cast of an experimental anchoring system. The fatigue strength of this type of wire are at 120-140 N/mm^2 in the sockets. Besides the reduction of the stress amplitude, there are structural possibilities to reduce the impact of the fretting corrosion [27,28]. The unfavourable mechanical stress may be decreased by reducing the relative shifts and the local compressions as well as the friction coefficient.

The simplest method would be to apply a durable lubrication layer between the contact surfaces. Soft-metal-coatings such as zinc and aluminium also have a favourable effect, contrary to hot-dip galvanizing, because the brittle iron-zinc alloy layer increases the wear. Also omitting the corrosive medium prevents fretting corrosion. Appropriate measures are the exclusion of the atmosphere (air) by durable coatings and the sealing of the load supporting details (e.g. with plastic) [29].

3.5 Corrosion fatigue

Besides the fretting corrosion occuring in the contact areas of the wires due to the air, corrosion fatigue cracking may develop in the case of single wires, cables or bundles under dynamic loads [7,19,26]. This means the favourite development and the spreading of cracks, caused by simultaneous corrosion [30]; Consequently this reduces the tolerable fatigue strength. No specific corrosive medium is necessary, however, the corrosion fatigue cracking depends on the type and the concentration of the corrosive medium. Fig. 13 shows the behaviour of cold-drawn wires in different media: Even water produces a reduction of the fatigue strength, though negligible from an engineering point of view. Acid water (acid rain, dew etc.) and solutions containing chloride (sea water, de-icing salt spray) produce a lower fatigue resistance than fretting corrosion in the air (100 N/mm^2 compared to 120-140 N/mm^2).

In the case of unalloyed steels, cracks preferably occur in corrosion pits., resulting in a pitted surface with numerous cracks (fig. 12). Therefore, corrosion fatigue in cables is promoted by structural conditions (e.g. formation of cracks with aeration cells) and by conditions caused by the surrounding media (e.g. chlorides), since local corrosion attacks are favoured.

Also a major factor is the frequency or duration: With decreasing frequency or increasing duration, the influence of the corrosion on the development and the spreading of cracks and thus the difference to the behaviour in air is more prominent (fig. 13).

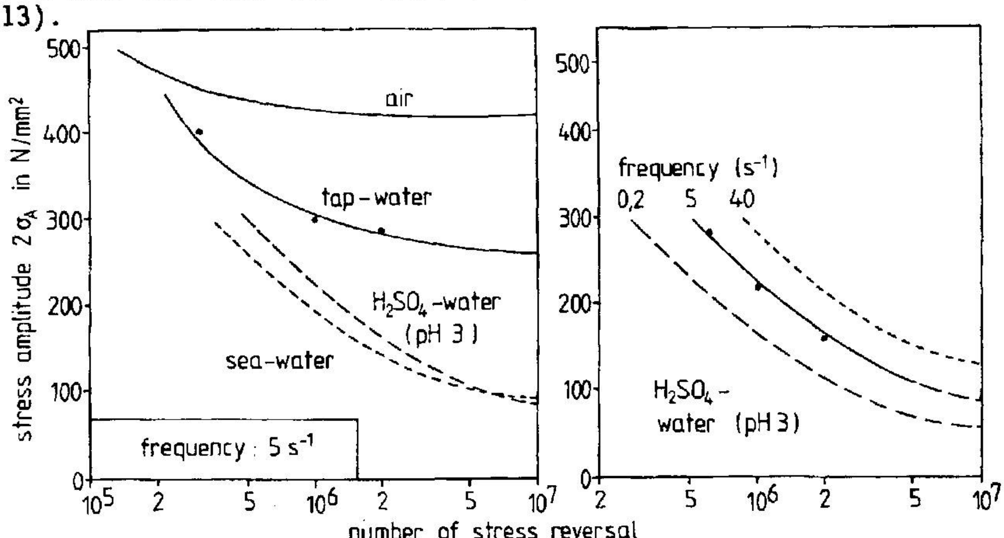


Fig.13 Fatigue behaviour under pulsating tensile stresses of cold-drawn, unalloyed steel wires ($R_m \approx 1750$ N/mm^2) in air and corrosion-promoting solutions (Nürnberger)

The corrosion fatigue behaviour of high-strength cable wires is improved by galvanization [31]. Fig. 14 illustrates, that in chloride containing solutions, as well as in sulphuric acid, the number of cycles to fracture is higher in the case of galvanized wires. The improvements due to galvanizations increase with decreasing frequency.

By manufacturing high-strength strands and cables out of austenitic, stainless steels, the general corrosion behaviour as well as the stress corrosion fatigue behaviour may be improved [32]. An additional protection by organic coatings is not necessary. Fig. 15 shows the results of fatigue tests under pulsating tensile stresses using strands out of high-strength, austenitic steel wires in chloride solution; results of tests with unalloyed steels are quoted for comparison. This shows that strands out of unalloyed steel behave much more unfavourable in chloride solution than in air. Here the influence of the frequency is much greater than in the case of unalloyed steels. At low frequencies the differences between the two materials are not prominent. The behaviour of high-alloyed steels depends upon its susceptibility towards pitting corrosion, since cracks start in corrosion areas. Stainless steels are susceptible towards fretting corrosion, which has an unfavourable effect on the fatigue behaviour with and without additional corrosion.

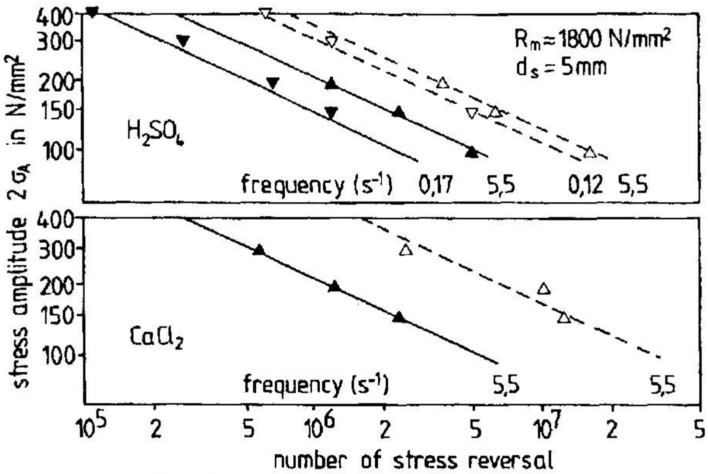


Fig.14 Fatigue tests under pulsating tensile stresses with galvanized and hot-galvanized drawn wires in diluted sulphuric acid (pH3) and 3% $CaCl_2$-solution (Wiume, Nürnberger) [31]

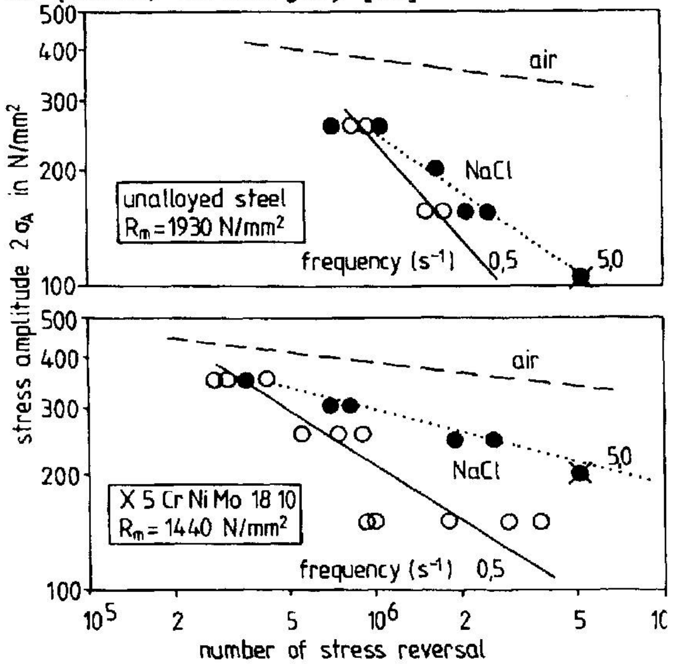


Fig.15 Corrosion fatigue behaviour of strands of high-strength wires of unalloyed and stainless steel in 3,5% NaCl-solution (Nürnberger, Wiume, Beul) [32]

4. WIRE MATERIAL AND WIRE PRODUCTION

Nowadays unalloyed carbon steel with 0.85 % C is a sufficiently examined and tested material available for large tendons. Its characteristics, relevant to its use, were examined mainly dependent on the ratio of Fe to C and the subsequent treatment (fig. 13). The alloys Mn and Si in essence improve the homogeneity of the material during pouring, hot-rolling, cold-drawing and the subsequent temperature treatment. Only recently the result were released [33], which prove a positive influence of a higher Si-percentage in the steel without this interfering with the galvanization process. This way the strength-reducing influence of heat-treatment on the cold-deformed steel-structure can even be reduced.

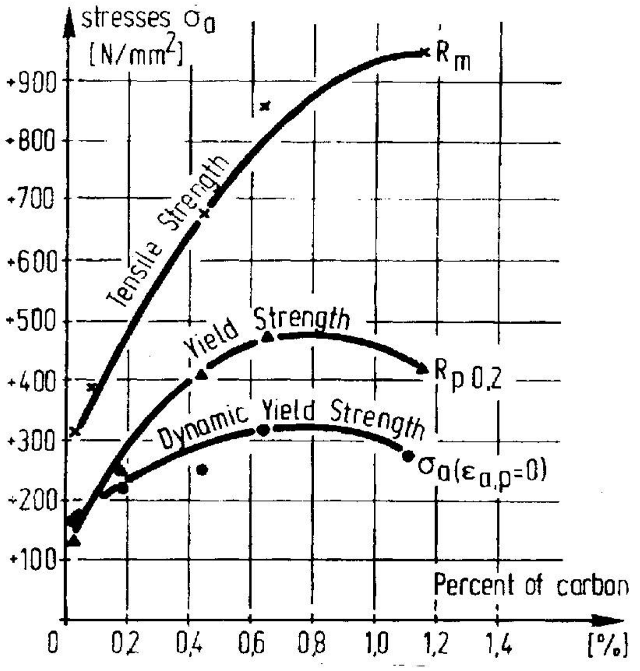


Fig.16 Different strengths depending on the carbon content of the iron (Fe) [34,35]

Whether or not the dynamic creep-limit [34], which can be regarded as the ultimate upper limit of a strictly elastic inflation stress [35] (fig. 16), is influenced by the higher Si-percentages could not yet be proven [36]. However, it also must be put in relation to the fatigue strength of even a long tendon. Therefore, literature lists only few test-series due to the great expenditure required for fatigue tests [37, 38, 39], and the evaluation of the results shown in fig. 17 are linked to certain production-charges and cannot claim to be generally valid, but they coincide very well with the figures in fig. 6.

5. TYPES OF CABLES

In a large tendon, wires can be placed parallel, semi-parallel and as wire-spirals of a rope (fig. 1). Elements produced in this way can be combined into larger dimensions by running parallel, being intertwined or stranded for a second time; this creates rope-bundles, strand-bundles or cable lay ropes. Depending on the wire-geometry, the size of the changes in the rope-force and an angle-deviation at the entry of the fittings, relativ movements will occur in a tendon (fig. 18), which nowadays can already be calculated [40] [41]. Spirally twisted wires move against each other, when looking at the neighboring wires of the same layer. The wires of neighboring layers for example in a spiral rope, rotate counter-clockwise around the point of contact. Here a relative movement occurs when the wires are pressed into each other due to the radial forces of the spiral geometry and an area of contact exists or shaping wires are pressed on top of each other on the surface (fully locked and half-locked coil rope).

	Prestressing Wire Ø 7mm (patented, cold drawn, stranded, heat treated)		Rope Wire Ø 7mm (patented, cold drawn, tested after stranding)		Prestressing Strand Ø 0,6' (patented, cold drawn, stranded, heat treated)	
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
Fatigue Strength (bare wire) $2\sigma_A$ [N/mm²] Specimen length ~ 500mm	420	40	360	45	250	30
Exponent of Inclination in the Wöhler-Diagram K	8,5	–	–	–	7,5	–
Tensile Strength (bare wire) R_m [N/mm²] Specimen length ~100mm	1770	36	1570	52	1670	42
Yield Strength $R_{p\,0,2}$ [N/mm²]	1560	39	1270	50	1470	52
Uniform Deformation A_{gl} [%]	36	6	20	4	40	7

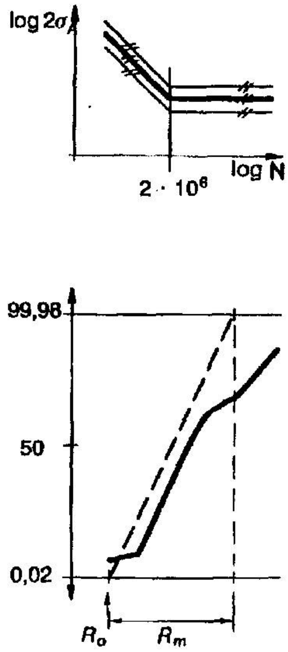
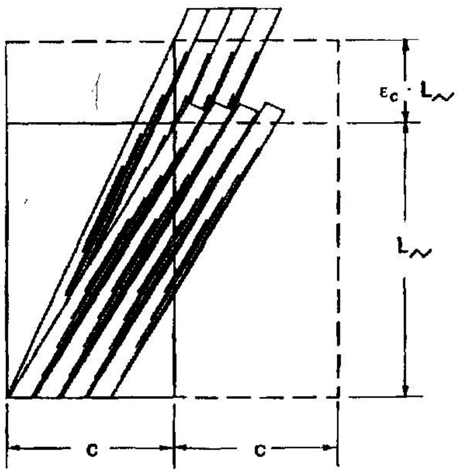
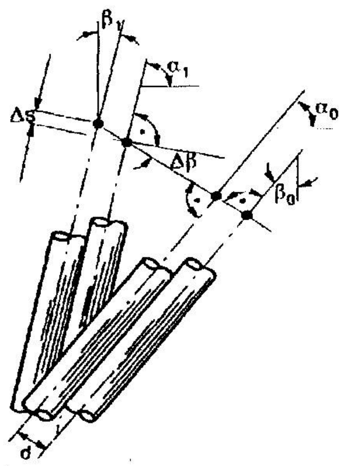


Fig.17 Statistic values of short specimen rupture tests (≈ 100mm) and fatigue tests (≈ 500mm) determined out of a special charge of these wires and strands



$$\text{ctg}\ \alpha_0 = \frac{\pi \cdot D_w}{L_{\sim}}$$

$$\text{ctg}\ \alpha_1 = \frac{\pi \cdot D_w(1 - \varepsilon_R)}{(1 + \varepsilon_c)\ L_{\sim}}$$



$L_{\sim}$ = Lay Length

D_w = Diameter of the Layer

ε_c = Cable Elongation

ε_R = Decreasing of Diameter

$$\Delta s = d \cdot \text{ctg}\Delta\alpha = d\ \frac{\text{ctg}\alpha_0\ \text{ctg}\alpha_1 + 1}{\text{ctg}\alpha_0 - \text{ctg}\alpha_1}$$

Fig.18 Relative movement Δs and rotation Δ β of wires in stranded cables [43]

The extent of the pressure, which determines the effects of the friction-corrosion just as the size of the friction-distance does [25], can also be established [42] [43]. It primarily depends on the size of the tendon force.

In tests and with the help of cross-checks, the friction coefficient was determined to be between 0.12 [44] and 0.15 [45], and a rope will act the same way as a total cross-section as long as this static friction is not overcome. In the case of movement, energy is lost for overcoming the friction.

Of course the friction coefficient also depends on the friction partners and the filling compound of the rope. If up to now only purely galavanized or galfan-galavanized wires are used (stainless steel wires are still rare), the friction coefficient will be extremely dependent on the quality of the lubricant, which has to resist high pressures and may not be rolled out. For example pure oils only lubricate a little because they are rolled out, oils with a high pigment-content (for example with zinc dust) increase the friction, which, in laboratory rope tests, can already be noticed from the temperature of the test element. Lubricants with aluminum pigments and poly-waxes showed favourable lubricating effects.

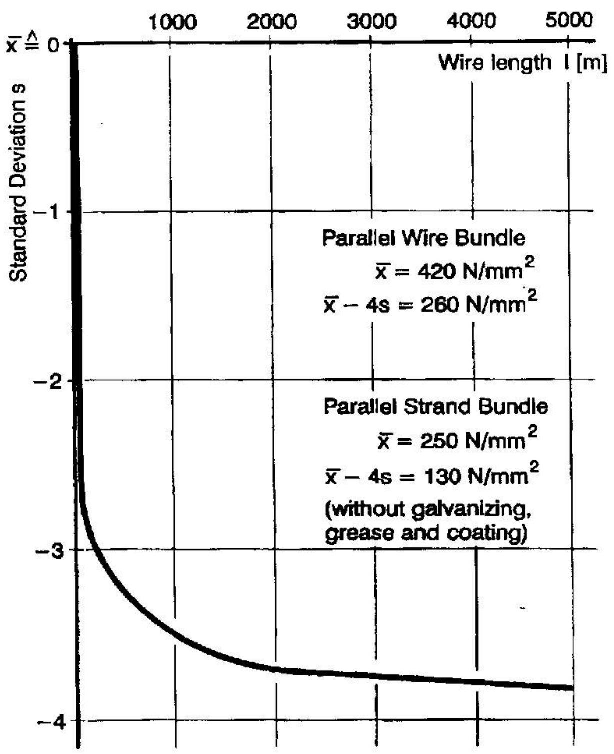


Fig.19 The reduction of the fatigue strength of a wire bundle out of over 100 elements, depending on the length

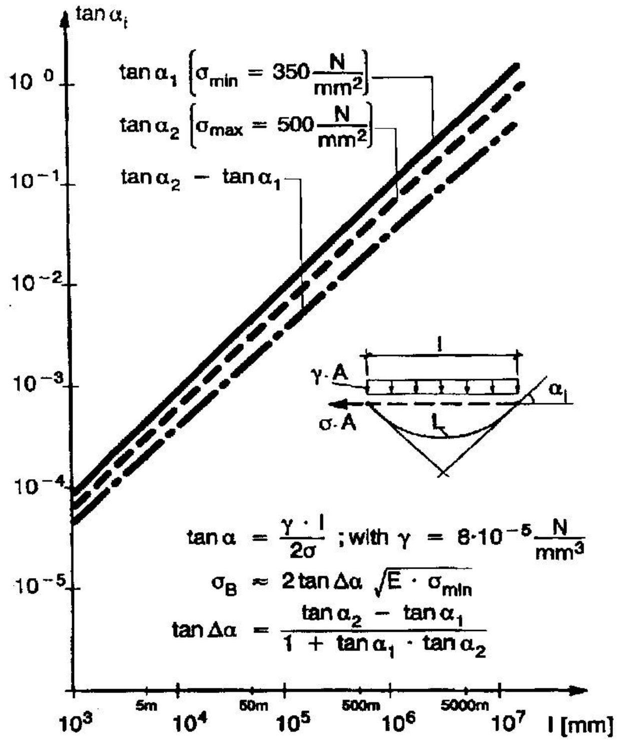


Fig.20 The increase of the entry angle at the end of a cable, sagging under dead load, depending on the length if the cable-tensio increases from 350 N/mm² to 500 N/mm²

The length-effect is extremely affected by the bonding between the single wires. In case of ropes it is a result of the friction between the wires [46], in case of wire- or strand-bundles it may result out of the induced concrete injection. This bonding only allows the broken wire to be effective as tension increase of the remaining cross-section over a short distance. It only has to be taken into consideration whether or not the broken ends damage the neighboring wires ahead of time.

Fig. 19 shows the decrease in strength for a bundle [35]. This clearly shows that the fatigue of an indefinitely long bundle or even a rope moves towards a limit, which has to be considered to be the mean of coincidental variables of the fatigue strength of the entire tendon without the scattering [39] and which has to correspond to a scale which might co-relate to the creep-limit [35]. It is necessary to determine the amount of stress, up to which no tearing occurs at dents or notches [47], consequently up to which the material stabilizes itself and is deformed only elastically. This should lead to the determination of the fatigue stress which can be endured by an indefinitely long bundle.

6. THE STRUCTURAL TENSION ELEMENT

The freely spanned tendons do not experience substantial relativ movements between the wires or serious bending stresses along their entire free length, neither due to a change in the sag, nor due to stimulated vibrations. A crucial factor are the changes in the entry-angles at the end anchorages, which lead to bending stresses in the tendon in the same way as the large deformations without expansion of a boundary cable with boundary clamps, or of a transversally pressed suspension cable equipped with hanger clamps found in suspension bridges can cause such additional stresses[48]. As an example in the case of a lateral spanned cable fig. 20 shows the change in the angle being dependent on the length, due to an increase in the load from 350 to 500 N/mm^2 longitudinal stress of the tendon.

Due to the weight limitation during assembly, the possibility of sufficient corrosion protection and the demand for replaceability of the tension elements, very large tendon units are introduced, which are more and more dessected, in order to make them accessible and to be able to inspect them. The access to the elements up to the point of anchorage is a far greater gain than the advantages resulting out of the redundancy of the dessected cable (fig. 21). The effect single flaws occurring during the production of the corrosion protection have on the security of the entire cable are kept down [49].

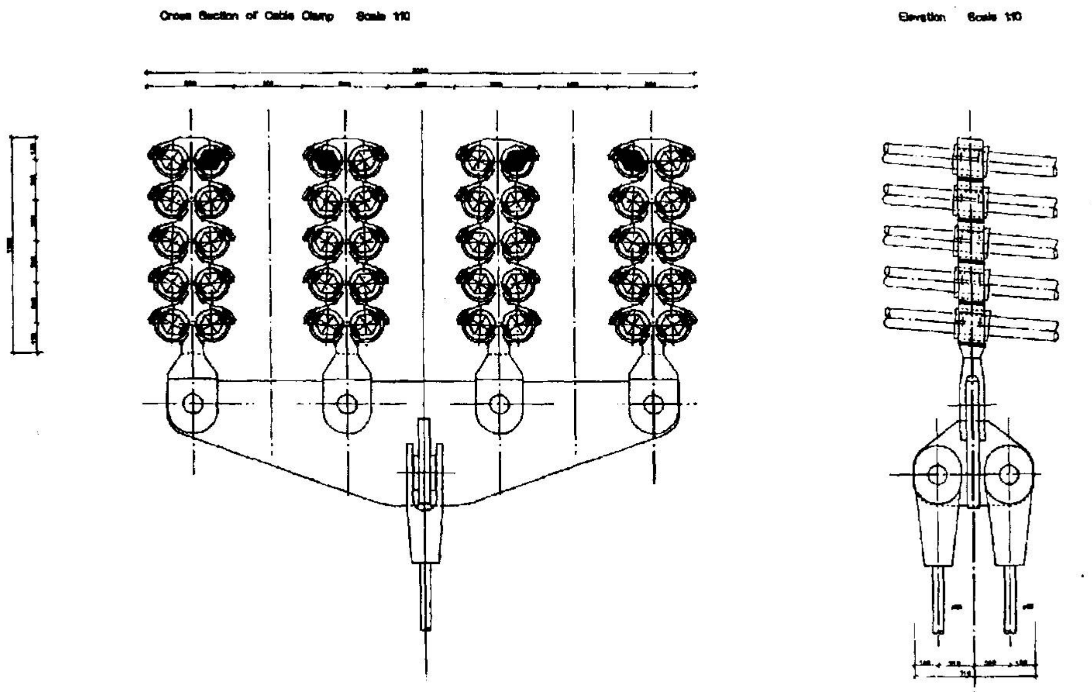


Fig.21 A dessected supporting cable of a suspension bridge, designed by Schlaich Bergermann and Partners

7. STRUCTURAL DETAILING

7.1 Clamping

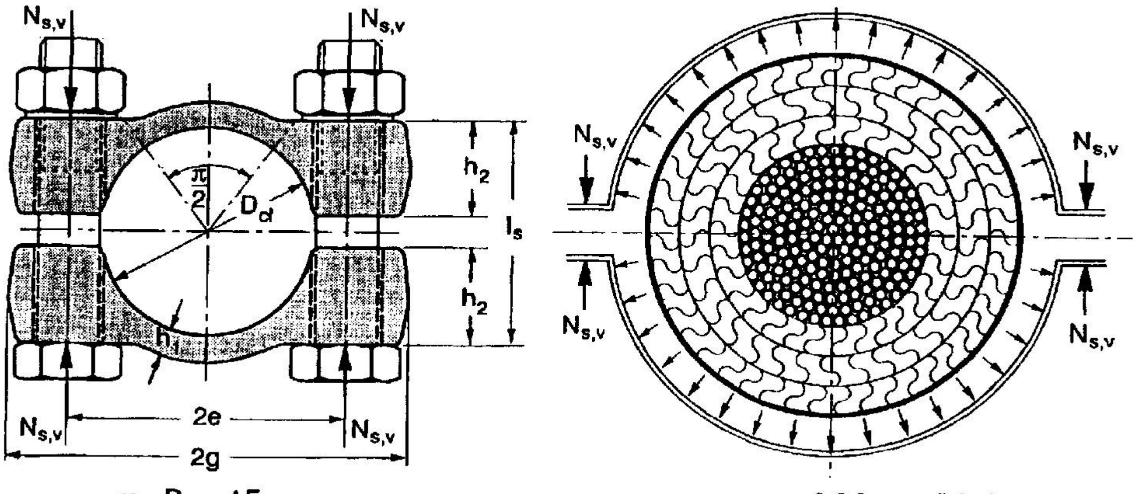
Loads are induced into a continuous cable via clamps by friction, which is activated between the cable and the clamps, which are usually pressed-on by high-strength screws [50]. The tension element becomes more resistant in the clamp-area, if the clamp absorbs part of the tensile stress [51]. The leap in resistance is sudden, and it depends on the cross-section-ratio between the clamp and the tendon, on the adhesive pressure and on the friction coefficient, whether the movement between the clamp and the tendon comes to a halt. In this case it has to be considered that the tendon - especially the ropes -, withdraw from the clamp-pressure with increasing axial force, and that a friction movement is hardly hindered [52] (fig. 22). A serious change in the medium tension of the dynamic inflation stress would have a very unfavourable effect.

In order for the energy resulting due to friction not to cause friction corrosion, the area of the relative movement has to be carefully protected against entering air and dampness [26]. Friction corrosion can still lead to the failure of a wire, even after very high number of load changes.

7.2 Anchoring

Three anchoring systems are mainly used for deducing loads from high-strength wires of tendons with large loadbearing capacity (fig. 23):
- the wedge anchorage in the case of tensioning strands,
- the compressed, small heads of thick wires and strands, which are supported by a perforated sheet
- the metal-bonding of wire- and strand-bundles as well as cables.

The wedges, the compressed, small button heads and the bonding-cone have to be formed in such a way that the load is deduced over the shortest possible length, without noticably reducing the resistance against static stress [25]. The fact remains, that the anchorage is the weak-point of the entire tendon under inflating load, if additional measures are not taken to reduce the local stresses.



$$\Delta N_{s,v} = \frac{\pi \cdot D_{cl} \cdot \Delta F_c}{E_{c,p} \cdot A_c} \cdot \mu_c \frac{1}{\frac{\pi \cdot D_{cl}}{2 \cdot b_{cl} \cdot h_1 \cdot E_{cl}} + \frac{2l_s}{E_s A_s}}$$

μ_c = 0,3 for parallel wire
μ_c = 1,5 for not prestretched spiral ropes
μ_c = 0,8 for prestretched spiral ropes
$.._c$ = related to cables
$.._{cl}$ = related to clamps
$.._s$ = related to screws

Fig.22 The release of prestretched screws $\Delta N_{s,v}$ of a cable clamp, depending on the increase of the cable force ΔF_c

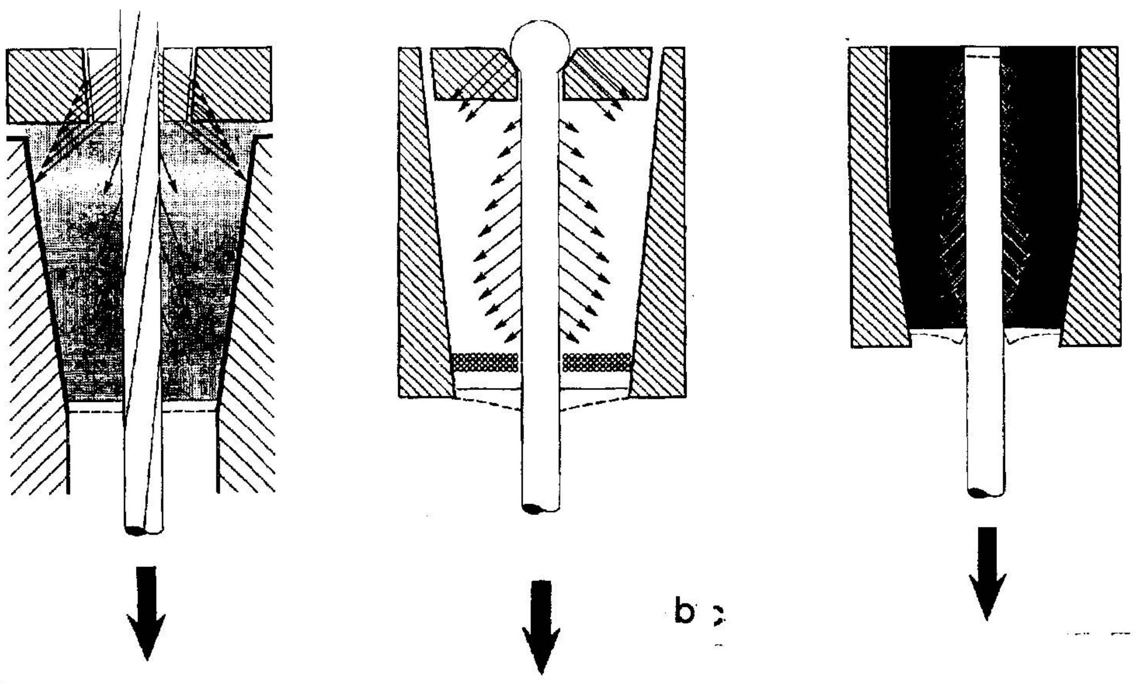


Fig.23 Anchoring mechanisms of
a) a wedge anchorage of strands with a cement grouted trumpet to lower the life load amplitudes in the anchoring zone
b) a steel bullet-resin compound for wire and strand bundles being additionally fixed in a perforated sheet by button heads
c) a metal cast cone for wire and strand bundles as well as ropes being fixed by friction caused by transverse, radial pressure

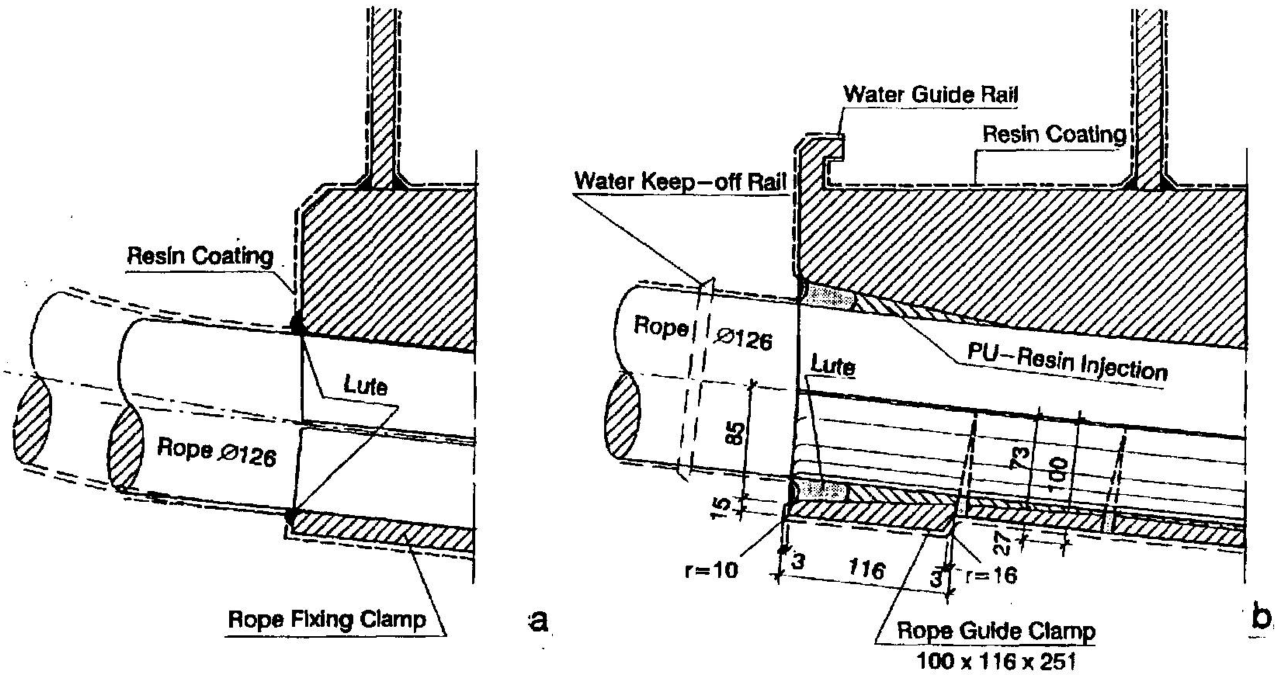


Fig.24 Constructive and coating measures to obtain good corrosion protection for ropes in the fitting areas
a) without a trumpet zone
b) with trumpet zone to avoid great bending stresses

One of the most common measures is injecting two-component plastics into the anchorage area. This is to prevent air and dampness from entering. Since the quality of such an injection cannot be checked, there is also the possibility to only have the static anchorage absorb a basic load (usually the dead load) and to intercept load fluctuations by using interim transmission constructions. Fig. 23 a) shows how the load change can be absorbed in the case of a trumpet injected with cement [53], and b) how the interim ball-plastic-mixture usually transferes the entire static load on to the socket and how the Epoxy-bonding receives the additional stresses [54], and how nowadays it is attempted in the case of the metal-bondings to extremely compress the entry into the cone in a transversal direction. However, a large gap between the tendon and the socket lets the area of entry vibrate with the expansion of the wires at the exit-area of the cone, respectively allows it to approach a final state in the course of several load changes, which eliminates further relative movements between wire and cone [55]. Laboratory-tests are proving that the anchorages are not the weak-point of a high-strength tendon. It is not known what they can really sustain and what stresses they are subjected to.

8. CORROSION PROTECTION

Close attention has to be paid to corrosion protection (fig. 24), since in the case of a damage assessment, the influence of corrosion always comes into play, i.e.: the corrosion protection was faulty or showed isolated damages which were not discovered in time [56] [57]. The controversy today is, if the protection is so complete that it lasts for a long time, but is hard to inspect, or if it is kept to a minimum and that the regular inspections are part of the protection.

A combination of individually protected single strands [58] or ropes out of galfan-coated wires [59], filled only with poly-waxes, are now regarded to be a practical alternative to the coating-systems of cables which are very expensive and have to be renewed.

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