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Autor: Gabriel, Knut

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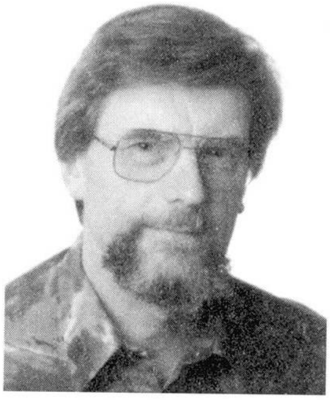
History of Tension Members and their Behaviour

Historique des membrures tendues et leur comportement

Die Geschichte der Zugglieder und deren Verhalten

Knut GABRIEL
Struct. Eng.
Univ. of Stuttgart
Stuttgart, Germany



Knut Gabriel, born 1938, studied structural engineering at the University of Karlsruhe. For 9 years he worked at the office of Leonhardt-Andrä and then transferred to the University where he is researching tendons and cable constructions and teaching in this field.

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.

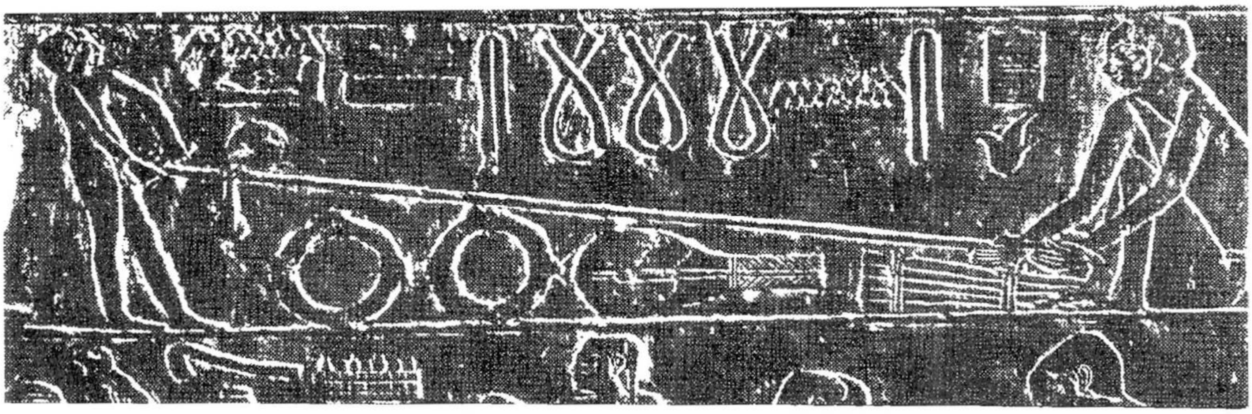


Fig. 1 Papyrus ropery shown on a Egyptian half-relief [1]

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.

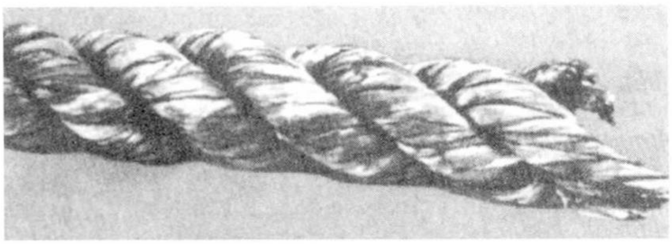


Fig. 2 Early Egyptian papyrus rope, 3 strands with 8-9 threads per strand (about 2900 B.C.), discovered in Sakkara [1]

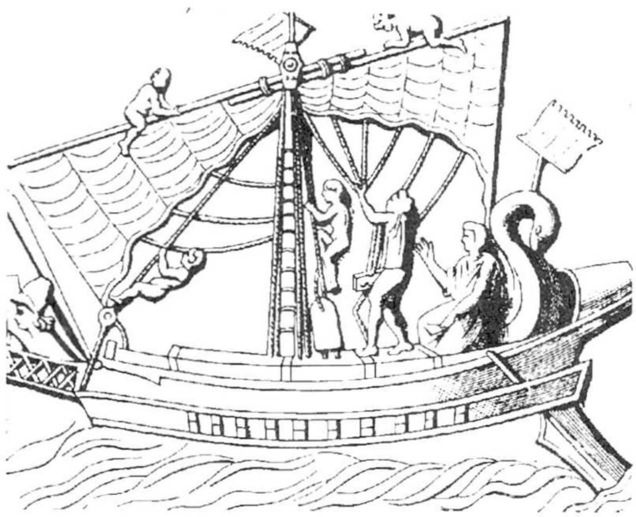


Fig. 3 Relief from Naevoleia Tyche's grave in Pompeji [3]

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"

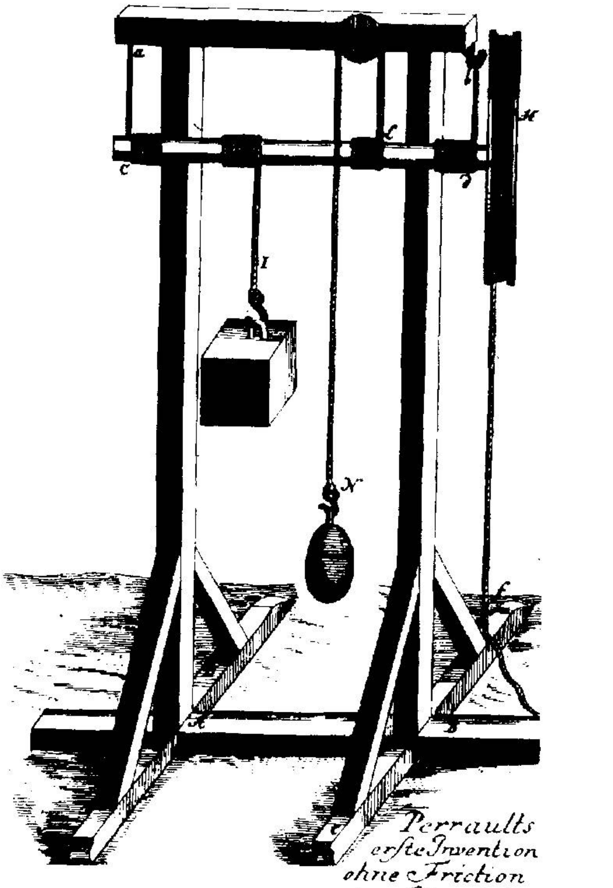
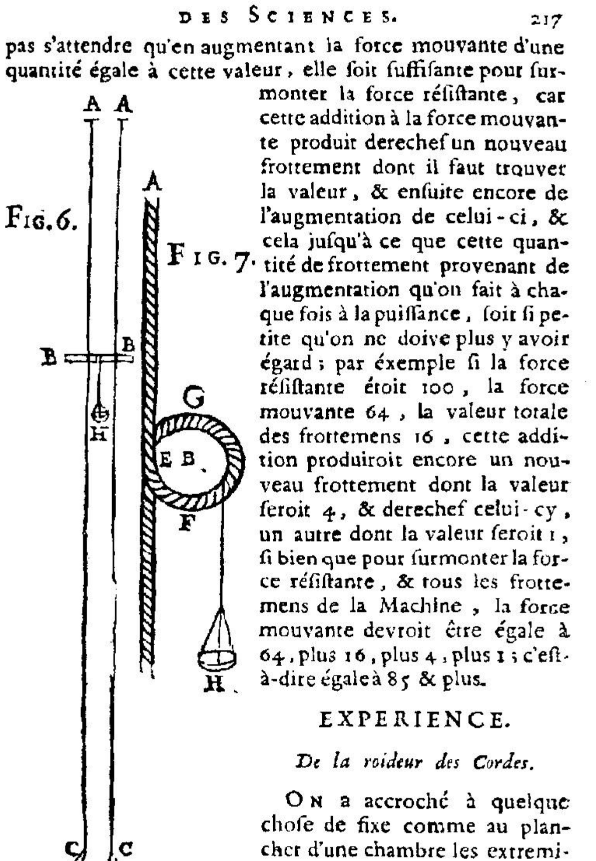


Fig. 4 Perrault's first invention to hoist a load [7] without friction



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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:

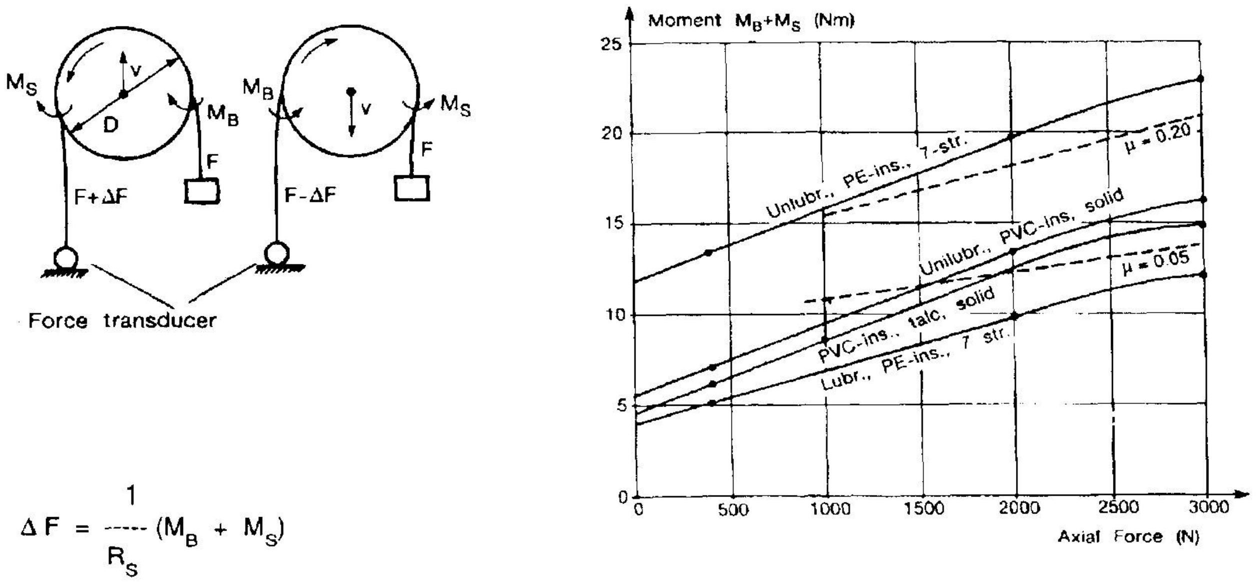
$$\Delta F = 0{,}3125 \cdot \frac{F_c \cdot d_c}{2R_s} \qquad \text{(Eq. 1)}$$

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.

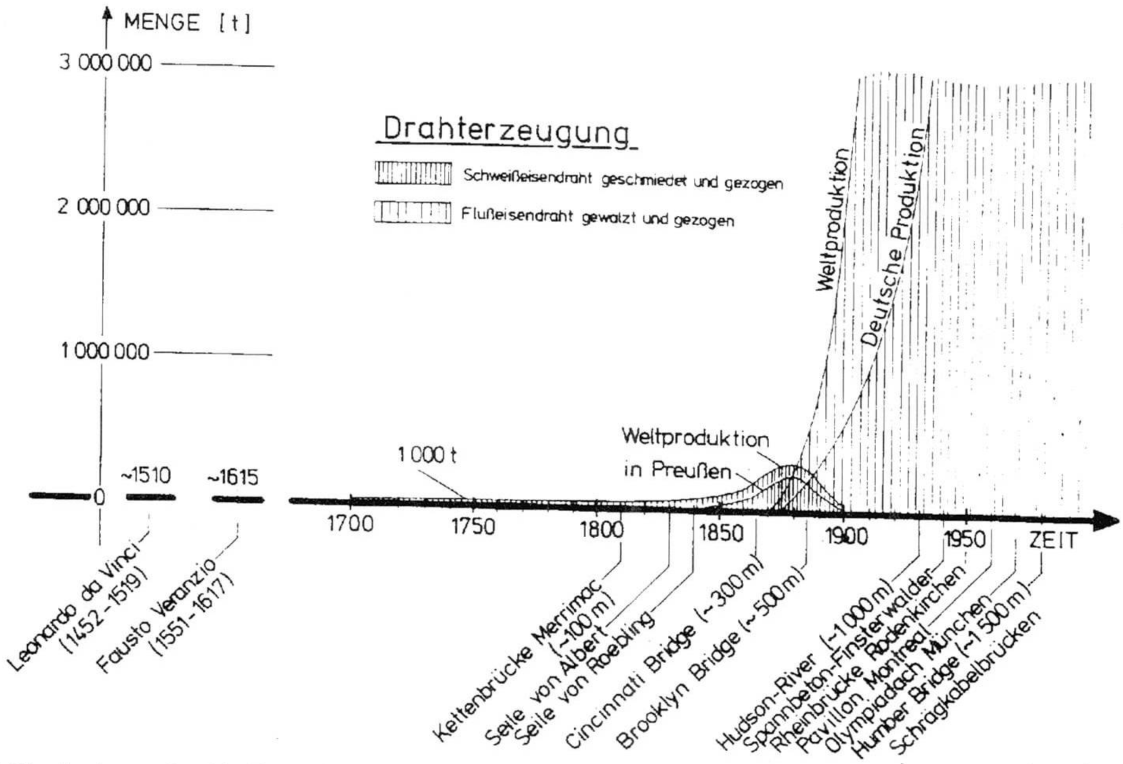


Fig. 7 Steel-wire-output in Prussia resp. Germany and world-wide (forged iron and ingot iron)

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.

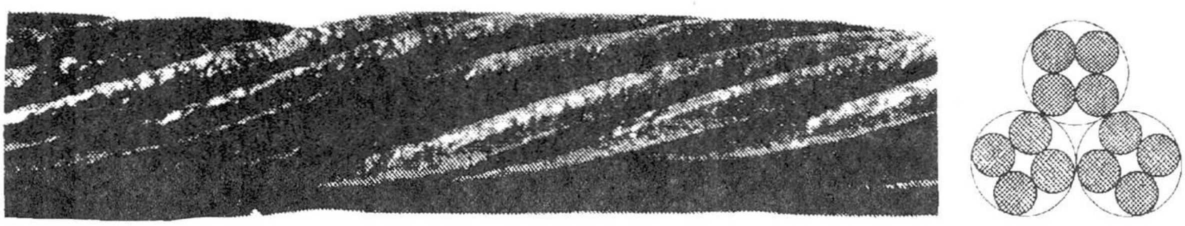


Fig. 8 Discovery of a cable which was probably manufactured according to Albert's instructions in the Harz Mountains (1834) [17]

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

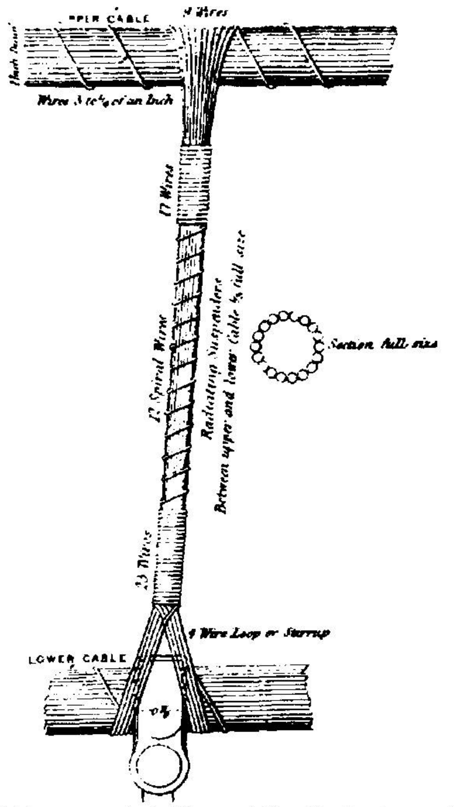


Fig. 10 Hanger-detailing of the first wire-cable-bridges by G.H. Dufour, Geneva (1822) [19]

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 available solid bars being bent and axially tensioned:

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

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

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

If $\sigma_N = 700$ 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

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

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.

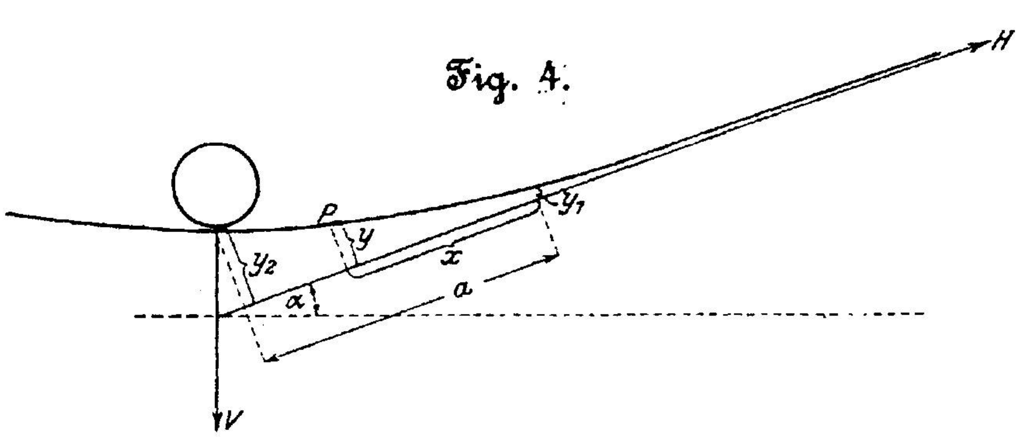
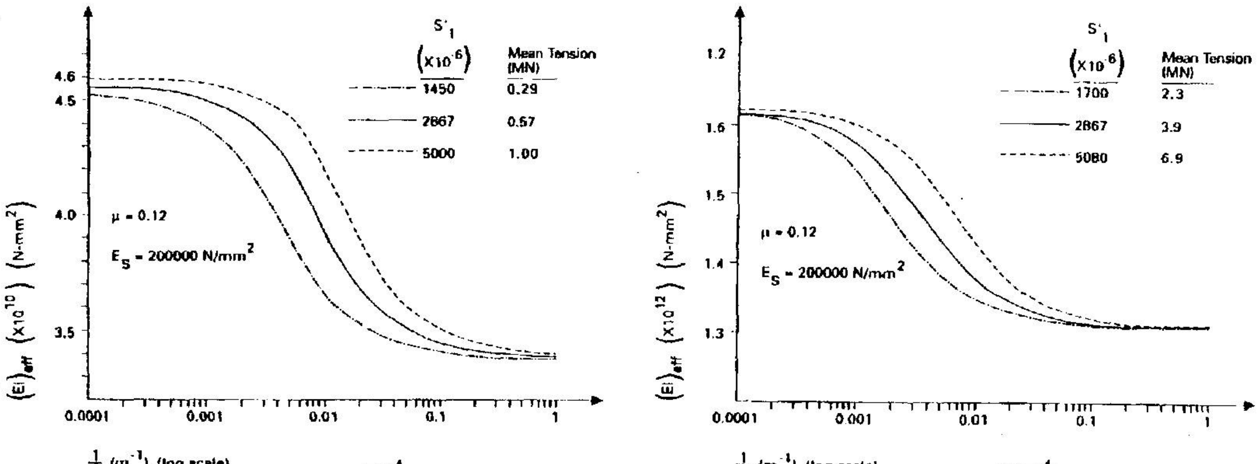


Fig. 11 A wheel riding on a standing cable (cable crane or cable railway) [33]

But at the same time the ratio of 2P/F can be treated equivalent to tg Δ φ according to the relevant vectored component placement whereas Δ φ 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

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

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 ($0.85^2 = 0.722$).



$$E_s \cdot J_{solid} = 200\,000 \cdot \pi \cdot \frac{52^4}{64} \cdot 0{,}75 \cdot 0{,}94^3 \qquad E_s \cdot J_{solid} = 200\,000 \cdot \pi \cdot \frac{127^4}{64} \cdot 0{,}75 \cdot 0{,}95^3$$

$$= 4{,}47 \cdot 10^{10}\,N \cdot mm^2 \qquad = 1{,}62 \cdot 10^{12}\,N \cdot mm^2$$

$$E_s\,J_{min} = 0{,}75\,E_s\,J_{solid} \qquad E_s\,J_{min} = 0{,}81\,E_s\,J_{solid}$$

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:

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

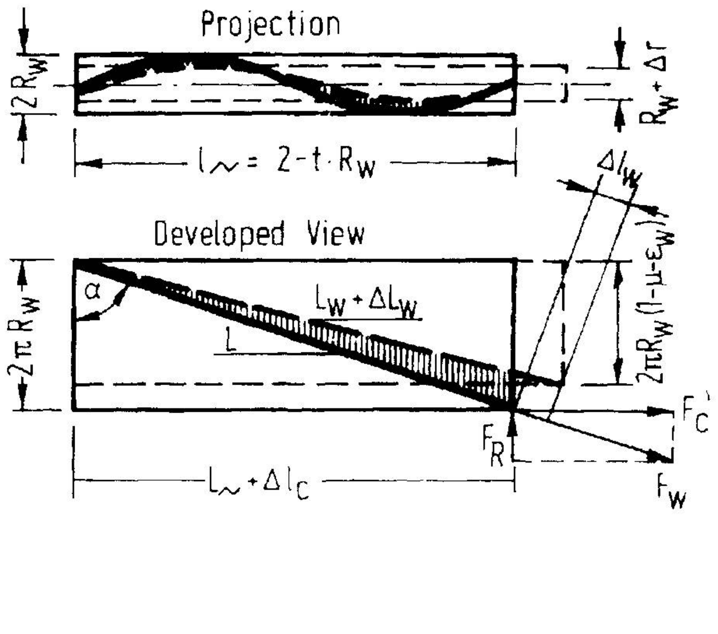


Fig. 13 A wire-layer in a straight spiral cable showing the elongation and the transversal contraction
a) view of the wire-layer
b) the wire-layer spred out in the plane

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:

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

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.

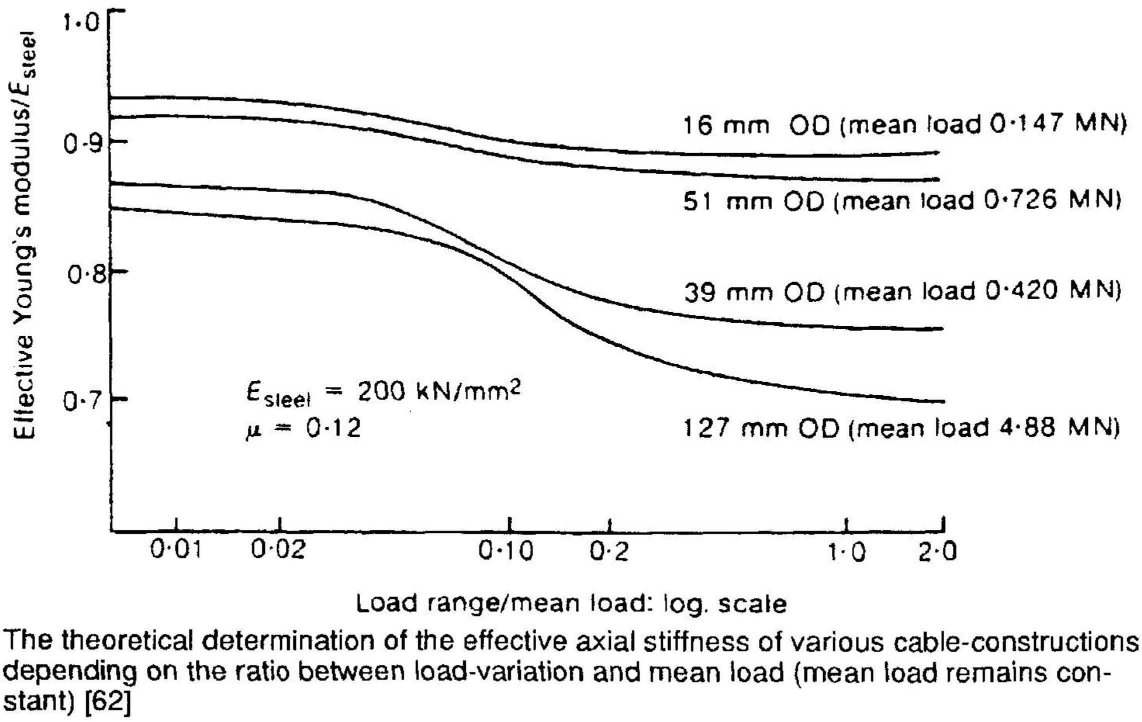


Fig. 14 The theoretical determination of the effective axial stiffness of various cable-constructions depending on the ratio between load-variation and mean load (mean load remains constant) [62]

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).

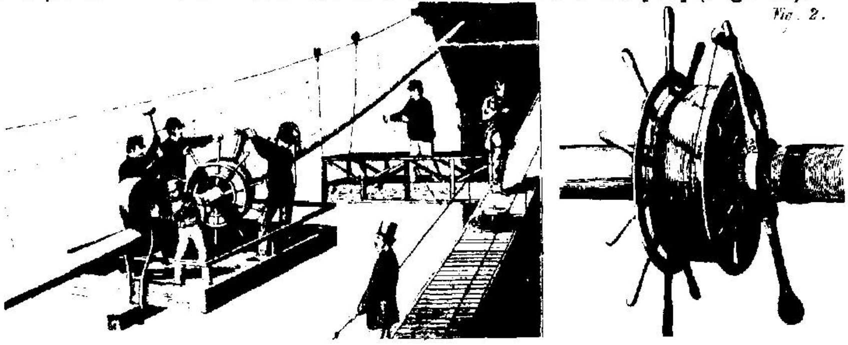


Fig. 15 The apparatus invented by John A. Roebling for wrapping soft galvanized wire around the cables

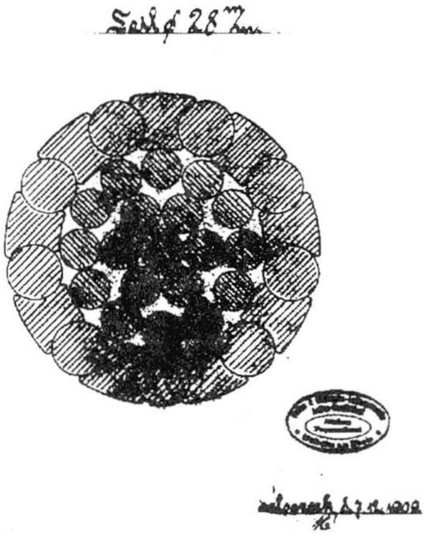


Fig. 17 Semi-closed spiral rope

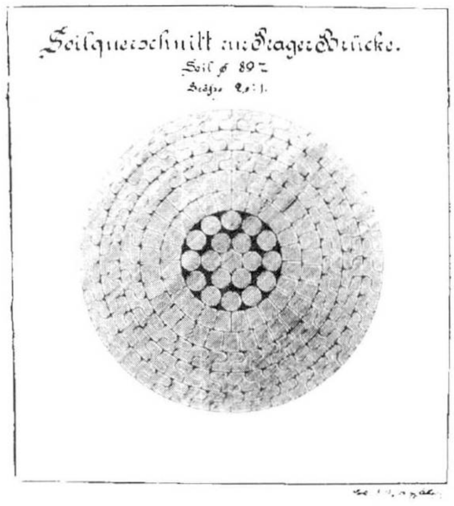


Fig. 16 Locked coil rope with a star-shaped core-wire, round-wire-core, trapezoid- and z-shaped sectional wires

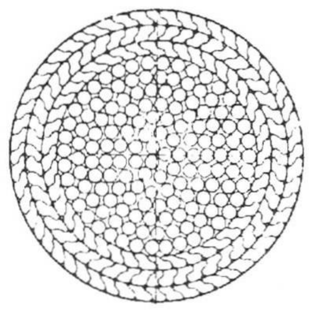
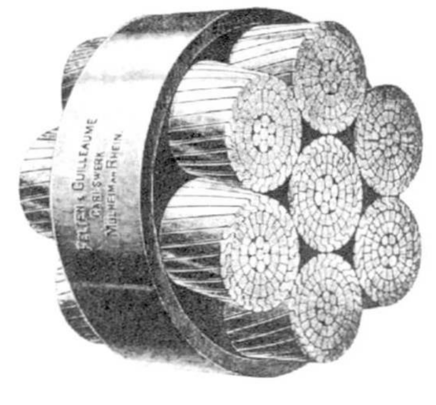


Fig. 18 Locked coil rope consisting only of round and z-shaped wires. The core is a triple-strand



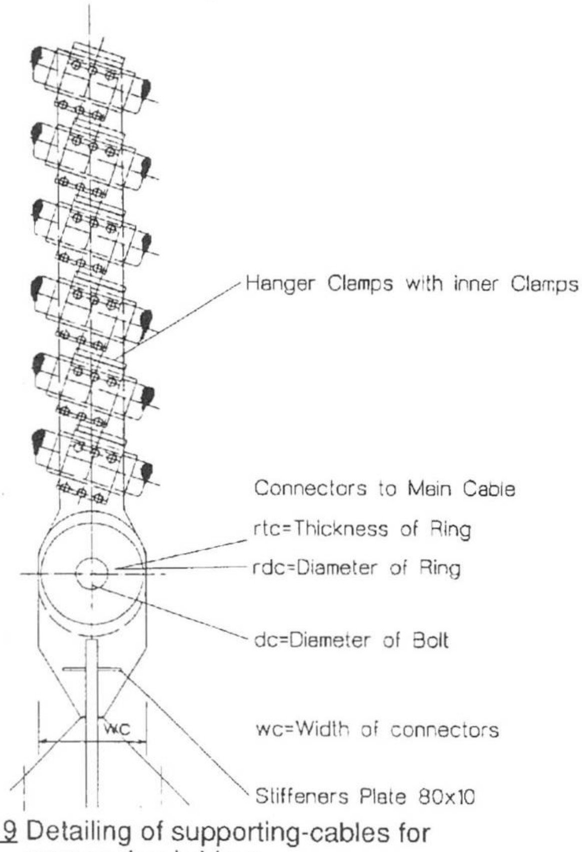


Fig. 19 Detailing of supporting-cables for suspension-bridges
a) as round cable made out of seven open spiral ropes [40]
b) as disolved cable consisting of smaller elements

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.

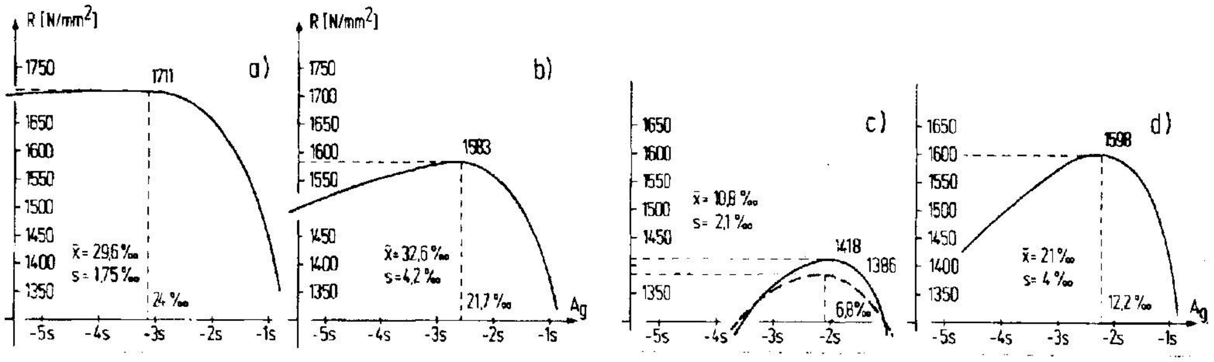


Fig. 20: The strength related to the initial cross-section and plotted as a function of the normal distribution of the uniform elongation before reduction of the tension-member-long individual elements [57]

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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