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Herstellverfahren und Korrosionsschutz der Hauptkabel von Hängebrücken

Manufacture and Corrosion Protection of the Main Cables of Suspension Bridges

Fabrication et résistance à la corrosion des câbles principaux des ponts suspendus

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Wolfgang Borelly, geboren 1906. Unter seiner Verantwortung wurden mehrere Brücken über Weichsel- und Rheinstrom errichtet. Er war 17 Jahre hindurch Baudezernent (City-Engineer) der Stadt Mannheim. In den letzten Jahren hat er auf dem Gebiete "kabelüberspannter Brücken" internationale Forschung betrieben.

ZUSAMMENFASSUNG
Die Ausführungen begründen, weshalb bei den angestrebten grösseren Spannweiten der Hängebrücken die bekannten Herstell- und Montageverfahren für die Hauptkabel nicht mehr genügen und die dabei vorhandene starke Abhängigkeit von den Wetterverhältnissen solche Arbeiten unkalkulierbar macht. Es wird ein neuartiges Verfahren erläutert, mit dem die Schwierigkeiten überwunden werden und dabei gleichzeitig der Korrosionsschutzwert durch das automatisch vorgenommene Auffüllen aller Hohlräume zwischen den im Kabel völlig parallel angeordneten Drähten mit einem speziellen Kunststoff sehr wirksam gesteigert wird.

SUMMARY
This paper presents the reasons why the conventional method of manufacture and assembly of the main cables of suspension bridges no longer satisfies the requirements of the larger spans envisages and why the existing dependence on the climatic conditions makes such work an incalculable risk. The paper describes a new process which eliminates difficulties. At the same time the corrosion protection is improved substantially by the automatic filling of the voids between the wires with a special plastic material.

RESUME
L'exposé est consacré aux procédés de fabrication et de montage des câbles principaux utilisés dans la construction des ponts suspendus. Les raisons pour lesquelles les procédés classiques ne répondent plus aux exigences sont décrites; la très forte dépendance des conditions atmosphériques rend aussi de tels projets incalculables. Un nouveau procédé permettant de surmonter ces difficultés est décrit; la résistance du câble principal à la corrosion a été très fortement augmentée, grâce à un remplissage par une matière synthétique de tous les espaces situés entre les câbles de plus petit calibre, strictement parallèles, qui constituent le câble principal.

1. BASIS - PRESENT STATUS

As generally known, plans are being made in several parts of the world to satisfy local requirements by constructing bridges with considerably longer spans than hitherto. It is intended to connect continents, to bridge arms of the sea, to limit the number of foundations in deep waters and, in addition, to avoid the risk of ships colliding with bridge piers located in navigable waters.

During the last fifty years great advances in general bridge construction have been made all over the world. But there has been hardly any significant progress in the construction of suspension bridge cables and in providing adequately resistant corrosion protection.

The methods used so far do no longer satisfy the technical and economic requirements with the spans increasing even further.

1.1 Air Spinning Method

In the "air spinning method" [1, 2], developed by the ingenious John Roebling last century, the lengths of the assembled wires must be adapted to those of the benchmarked guidewire by "sag comparison" in order to obtain wires of equal length and thus a uniform load distribution. The effort required for such longitudinal adjustments of the wires almost constantly swinging to and fro due to wind-induced oscillations increases more than proportionally as the bridge span increases. The overrun of the calculated construction time by approximately 153 % for the manufacture of the main cables for the Humber bridge in England completed in 1981 and having a main span of 1410 m is mainly due to these unavoidable difficulties according to the writer's observations on the site.

1.2 Installation of Prefabricated Parallel Wire Strands (PWS)

Prior to assembly of prefabricated parallel-wire strands [3], they must be reeled on drums while the parallel-wire strand, provisionally confined by plastic tapes, is being alternately turned about its longitudinal axis. At this juncture, I can mention briefly only a few of the noticeable peculiarities of this method worth mentioning, which were discussed in detail in a publication [4] by Mr Blair Birdsall: as with method 1.1, the wires or strands must be squeezed into a round configuration by means of so-called "compactors" exercising large lateral pressures. Within the circumscribing circle of the cable, the wires lie by no means well arranged in parallel; not infrequently they overlap. With this method the amount of voids customarily checked as a quality criterion in the USA can hardly be reduced to less than 19 to 23 % of the cable cross-sectional area. This applies also to the quality that can be achieved with the air spinning method. Hence, the desirable minimum of voids of about 12 % with 5 mm wire thickness is exceeded by up to 75 %. As regards the further critical results of the investigation and the resultant conclusions, reference is made to Mr Birdsall's publication for brevity's sake.

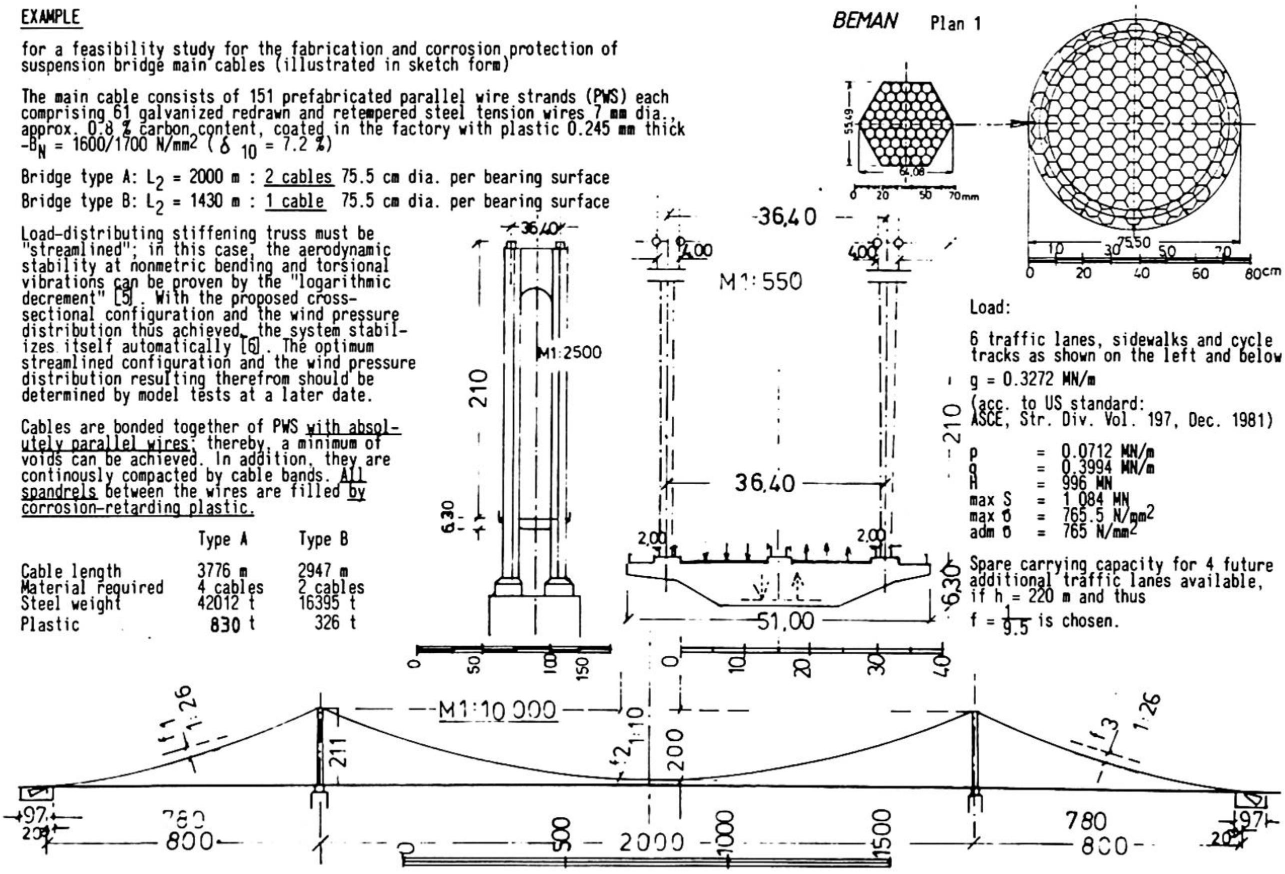
1.3 Corrosion Protection of Cables Today

All corrosion protection sheating, which can be applied only manually to the exterior surface of the finished cable on the site with considerable labor costs and losses in material, usually becomes leaky after some time. This is unavoidable where these sheaths join the cable bands. With this method it is therefore impossible without permanent, costly repairs to protect the interior of the cable for longer periods of time reliably against the ingress of moisture and condensate formation combined with the additional effects of any penetrating gases.

According to the late Professor Stüssi 5 , suspension bridges with main spans of 4450 m are technically feasible. At present, projects having spans of 3300 m are considered. The economic significance of a major increase in the service life of such bridges requiring investments in the amount of 1000 to 1500 million dollars certainly need not be debated. It would be of utmost importance for owners, state and local governments.

2. FEASIBILITY STUDY OF THE PROPOSED PROCESS

The proposed new process with which parallel location of the wires of 7 mm dia. with a markedly smaller amount of voids in the interior of the cable without wire squeezing due to compaction can be achieved, and a continuous internal corrosion protection promises a considerably longer service life, was investigated by a feasibility study to make a major step forward. In this study, certain data were calculated and certain conditions were verified by tests. The subsequent discussion is based on this example, Fig.1. In the case of longer spans, handling the proposed process will by no means become more difficult, whereas the conventional methods then will be far from being economical.



3. THE PROPOSED PROCESS

In view of the limited time available the author is, unfortunately, forced to present only a general survey of the quite complex procedures when describing the proposed process without giving detailed reasons. Therefore it is also impossible to discuss the results of all the previous considerations and the investigations necessary for solving some difficult individual problems that were carried out jointly with the research departments of some major German plastic manufacturers, BASF Ludwigshafen, Bayer AG Leverkusen and AEG-Elotherm Remscheid, and with the Geodetic Institute and the Research Institute for Building Materials of the University Karlsruhe.

3.1 Parallel Wire Strands Assembled Without Squeezing

The main cable is made up of prefabricated, hexagonal parallel-wire strands (PWS) of exact size, provided with conventional sockets in the shop, each strand comprising 61 galvanized and plastic-coated wires 7 mm dia. In the case of longer cables the number of wires must be reduced to 37 because of the high transportation weight. The strands are prepared in such a way that any displacement of the wires relative to each other is eliminated by bonding. Thus a firm, resilient wire strand is obtained without requiring wire pretreatment on the so-called "counterweight place" and without subsequent quality-reducing heavy squeezing of the round, often several times twisted wire strands into a cable by means of compactors.

3.2 Assembly and Longitudinal Adjustment

For this purpose, the wires of the individual PWS are heated by induction to 110°C in a continuous run at a uniform speed v = approx. 0.33 m/sec as unreeling and assembly are performed; then they are bonded together by means of separate "three-dimensional presses" and subsequently they are cooled down to nearly 41°C in a long cooling through - Fig. 2, p. 5. In this condition, the PWS is pulled across the sheaves of the catwalk from one anchorage to the other by means of the transporter rope used also in this process. Twisting of the PWS, in this case forming a solid hexagonal mass, is carefully avoided by special pulleys and controlled automatically when being put in place, see 3.3 and Fig.5, p.8.

3.3 Measures for Exact Temperature Adaptation of the Bonded PWS

Since for bonding the PWS a heat treatment is required and longitudinal adjustment of the individual PWS shall be effected by means of guidewires installed in each PWS instead of using the time-consuming "sag comparison", it is particularly important to adapt the temperatures during the various phases carefully. Benchmarks are provided on the guidewires already in the shop by means of "Invar" rollers and pulsed gas laser, a precision measurement procedure providing an accuracy of $L \times 5 \cdot 10^{-6}$. For this reason, each PWS is first mounted left and right of the tower cable saddle via separate rollerways and the auxiliary saddles equipped with pulleys - in the case studied - 4 each in 2 shifts per day. In the night after next, i.e. after a temperature adaptation period of 25 to 34 hours, the PWS are put in the proper place in the cable by special equipment, and after spraying the contact surfaces with sealing plastic they are bonded for their entire length with slight pressure by means of a specially developed "placement carriage" with jib, Fig. 5, p.8.

3.4 Parallel Wire Position - Minimum of Voids

By means of this procedure, a cable cross section with absolutely parallel wires being in perfect six-point (60°) contact and placed closely side by side can be constructed as the section through the PWS shows. The voids amounting to approx. 12.5 % of the cross-sectional area, which closely approaches the theoretical minimum, are filled with the selected plastic without exception. The outer surface portions missing along the circumscribing circle must be supplemented by filling pieces of plastic tape in the area of the cable bands of light metal elements which are roughened on the inside in the steep section. When practical experience is available, attempts should be made to close such gaps at the cable perimeter by specially shaped PWS comprising only suitably shaped partial surfaces on which then soft steel wire is wrapped by the well-known wire-wrapping method. The protective value of the "inner corrosion protection ring", Section 6, p. 9, could thus be doubled.

LEGEND Nos 1 to 12

1 Drum for splayed PWS in flat position
2 Drum for separting film
3 Splaying device: Any longitudinal differences must be nearly equal
4 Splaying plate, nearly elliptical
5 Trumpet-shaped nozzle
6 Lifting device for initial arrangement
7 Caterpillar pull-off
8 Induction section
9 Three-dimensional press (schematic)
10 Intermittently operating device for applying the constricting bands
11 Cooling trough with countercurrent flow with specialy shaped rolls
12 Intermittently operating device for removal of constricting bands

PROCESS-DETAILS

I The PWS running through the devices and across the sheaves of the catwalks at a speed of 0.33m/sec are pressed together by means of "three-dimensional presses" (9) after inductive heating (8) to approximately 110°C. In this process the plastic flows into the voids between the parallel wires. Prior to entry in the cooling (11) trough with countercurrent fluid flow - an amount $Q=300m^3/h$ has to be drawn from nearby waters - the cohesion of the hexagonal PWS is secured until the hardening plastic guaranties dimensional stability at approx. 55°C, plan 2, p.5.

II For thos purpose, bands of polyamide or sheet steel of high tensile strength spaced approxymately 50cm and provided with an automatically closing "zipper" will be pulled intermittently around tightly by means of a device travelling forward at the rate of work progress and returning quickly through automatic release (10). After passage through the cooling trough, the bands will be cut open and discarded in a subsequent device. (12)

The located of all these devices is integrated appropriately in the anchorage.

III Some of them are suspended from the ceiling plate in such a manner that insertion of the PWS in the splay saddle and in the anchoring devices can be effected by means of pulley blocks and trolleys transverse to the cable direction without longitudinal displacement, moreover, bending in the vertical plane will remain small. Placement is effected after part of the dead-weight tension has been accommodated by a separating "frictional clamp" in the meantime. Prior to the transverse shift on the tower saddle, the respective PWS shall be placed in the final position of the cable saddle cross-section in the anchorage area.

Fig. 2 Preparation of the PWS on the site prior to assembly

BEMAN Plan 2

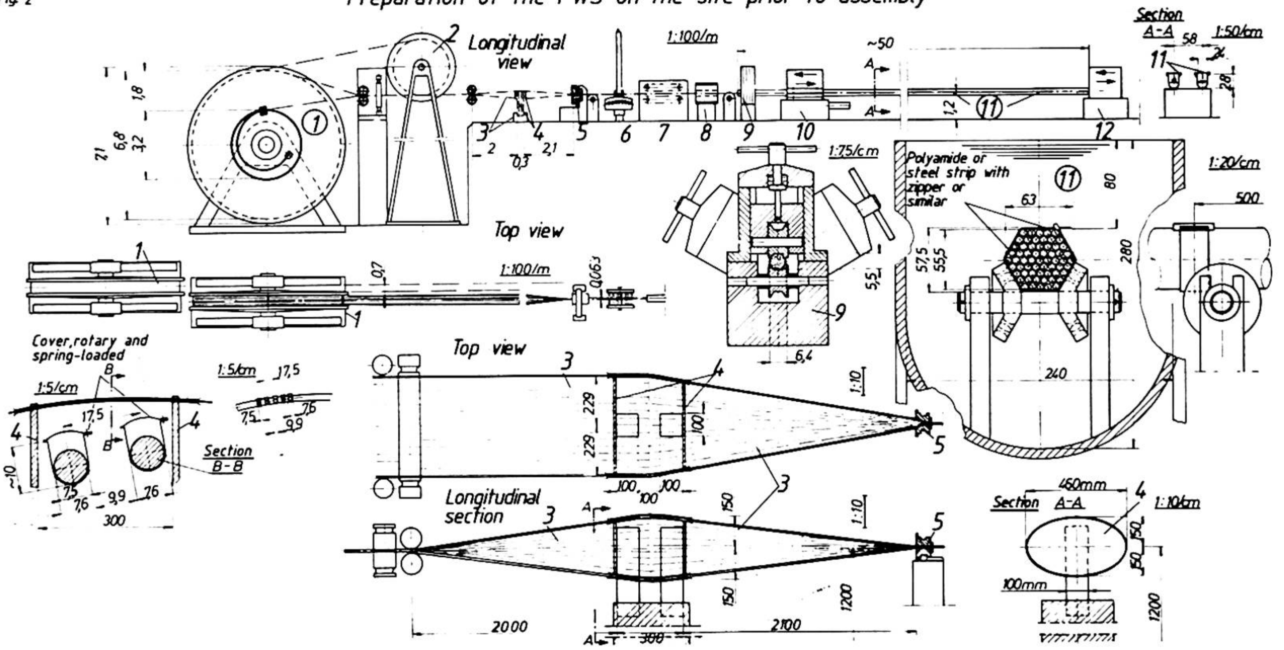
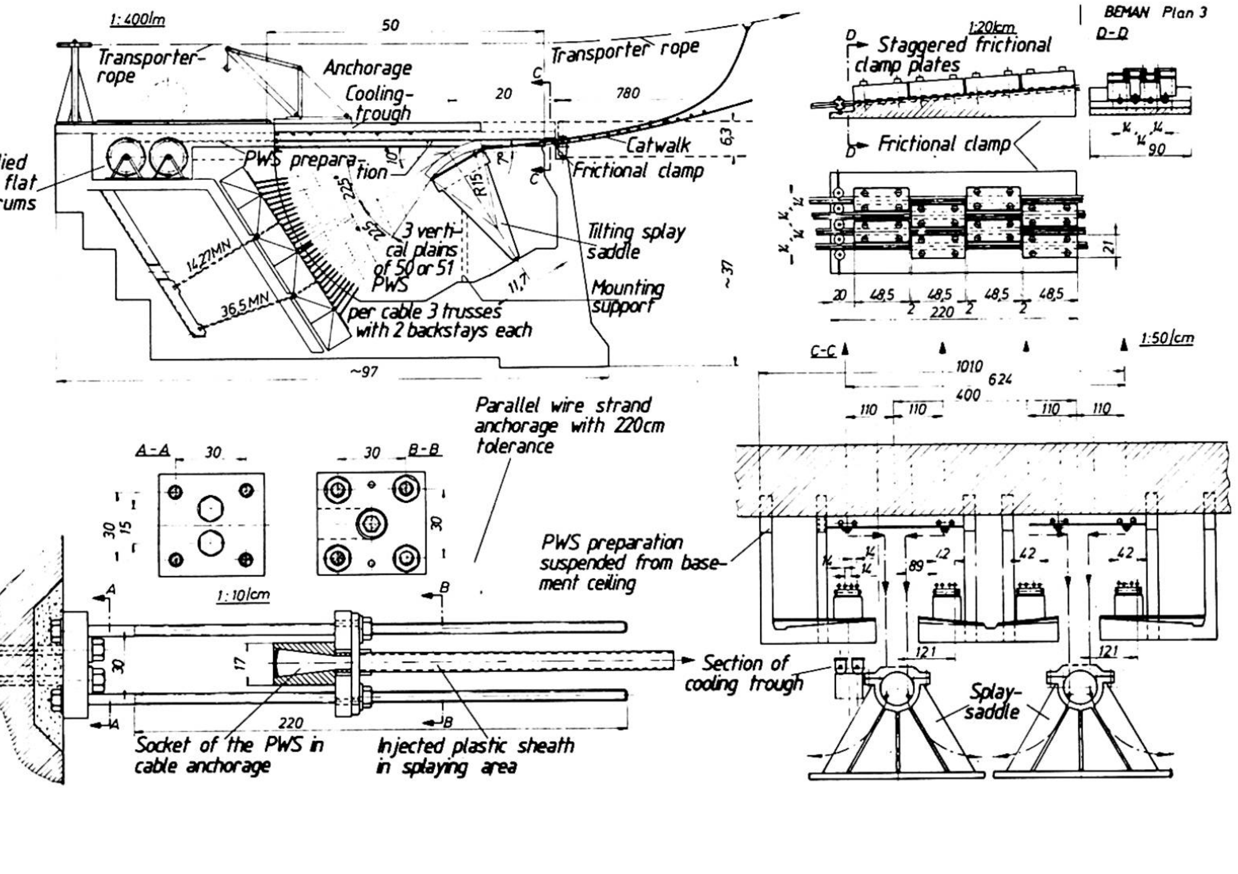


Fig. 3

BEMAN Plan 3



4. ESTIMATED OUTPUT ACHIEVED WITH THE PROPOSED PROCESS

The equipment permits assembly of 4 PWS approx. 3800 m long in 2 dayshifts each and, when the personnel has become familiar with the job, to place 2 PWS each in the cable in one run during the night shift. Thus, considering on adequately estimated reduction of 25 % for repairs and contigencies at the start, the following output could be achieved:

Each day 0.75 x 4 x 3800 x 18.42 = 210 t of steel wire,
per working hours 1/24 = 8.7 t/h.

The average output achieved when fabricating the main cables of the Bosporus bridge amounted to 4.7 t/h of steel wire, which does not include the additional time required for squeezing the strands by means of the compactors [2].

In the case studied one facility will be used for fabricating 2 cables one after the other located side by side. Thus fabrication of all 4 cables with 2 facilities and 25 % reserve will take a period of

$$\frac{42012}{2 \times 24 \times 8.7} = 101 \text{ working days, i.e. approx. 4 months.}$$

In addition, the compacting otherwise necessary is eliminated.

5. FACILITIES FOR EXECUTION

5.1 Gentle Reeling and Unreeling by Splaying of the PWS

For the g e n t l e reeling and unreeling of the PWS comprising 60 plastic-coated wires with a benchmarked guidewire the special procedure described in [8] is used where the strands are splayed into layers 46 cm wide without twisting and squeezing, carefully avoiding relative longitudinal displacements. Then they are reeled and restored to the hexagonal configuration in a similar way on the site.

5.2 Preparation and Bonding of the PWS

The preparation of the PWS - heating up to 110° C, bonding and cooling down to approx. 41°C is shown in Fig. 2, p.5; the placement at the anchorage in the basement of the abutment is shown in Fig. 3, p. 5. Instead of bonding the last section ahead of the socket, the PWS shall be provided with a two-part shell and, in addition, filled with plastic by a process tested at the writer's location, for in this area damage is known to occur more frequently. Moreover, the basement must be permanently air-conditioned.

5.3 Plastic Deformation of the Plastic Material Decreases the Wire Stresses in the Curved Area

Bending of the bonded strands around the radius of the auxiliary saddle and later the tower saddle poses a serious problem which, however, has now almost been solved by tests.

The bending radius shall be increased at 10 m, if necessary, to 12.50 m, Fig. 4, p. 8, top section. The full normal tension resulting from the PWS deadweight can be brought into effect only by and by through gradually tensioning the PWS first resting on rollers. Prior to placing the PWS laterally into its final position, a period of 25 to 34 hours is allowed to elapse during which the plastic in the spandrels undergoes viscoelastic deformation due to the stresses it is subjected to during the bending process so that the layers of the PWS can be displaced a little in the longitudinal direction (relaxation). Therefore, the forced expansion paths caused by the bends extend over a greater length of the sections adjoining the saddle so that the stresses are substantially decreased gradually due to creepage of the plastic as was proven by long-term tests; see paragraph 7.6, p.11. If the stress relief so achieved is not fully satisfactory, partial inductive heating of the PWS resting on the rollerways of the auxiliary saddle is required during the adaptation process.

5.4 Devices on the Tower Top to Transfer the PWS from the Auxiliary Saddle into the Cable's Cross-Section and for Length Adjustment

After the PWS still resting on the rollers of the auxiliary saddle have been tensioned by special devices such that the tension due to its own weight is nearly full effective, lateral displacement in the vertical plane of the cable area takes place, first down at the anchorage and subsequently at the towers by means of an specially developed group of devices: 2 traverses located normal to each other - type "A" in cable direction and type "B" vertical to them -, 2 bridge cranes, each with trolleys. Prior to lifting, sideways displacement and laying into the cable saddle, a state of equilibrium of the forces effective on the left and right of the cable saddle must be achieved by appropriate pull from the anchorages. For any eventualities, there is still a working surface on the respective strand length of the large span that can be effected with little differential forces until length markings coincide in the cable saddle area.

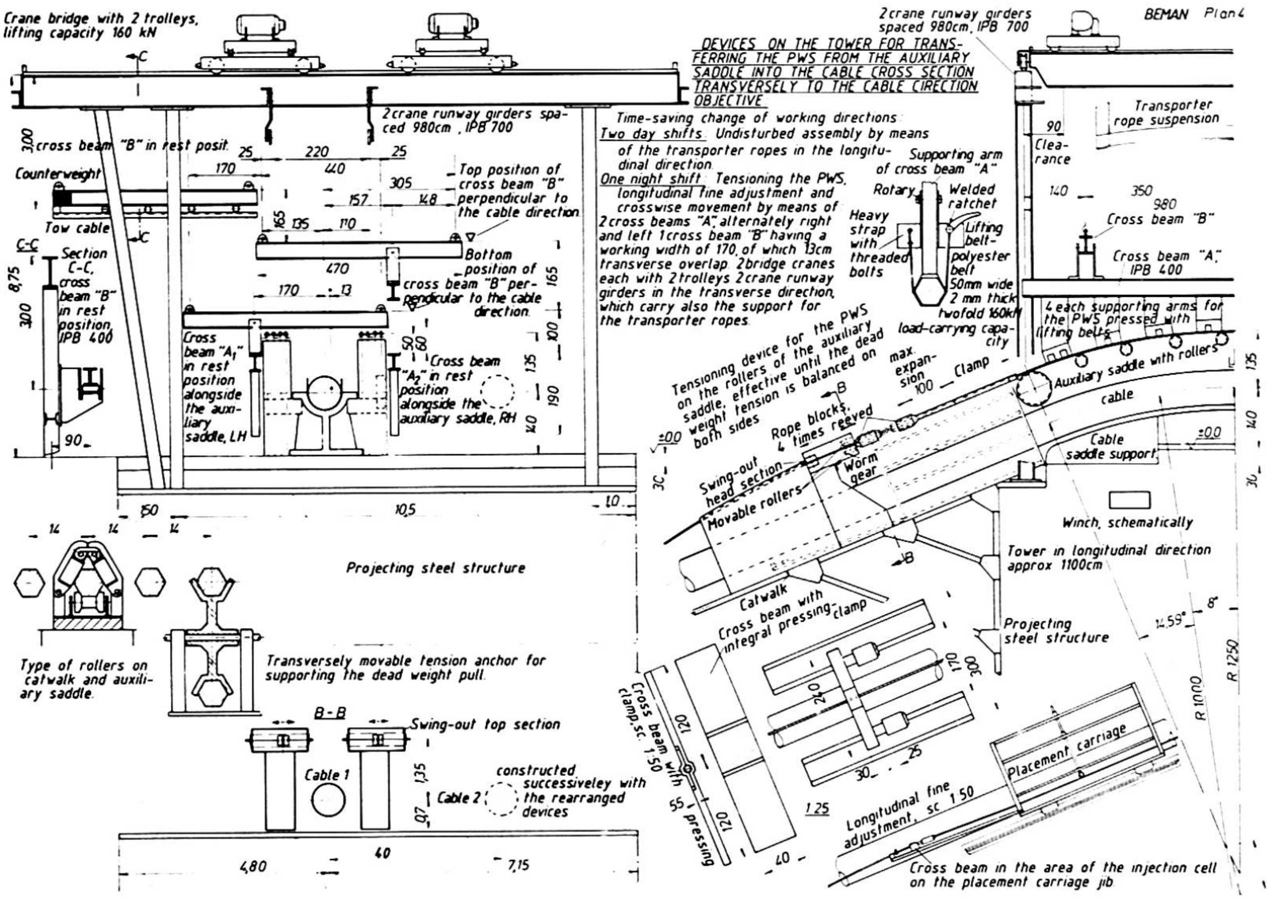
5.5 Devices for Inserting the PWS by means of "Placement-Carriages" in the Area of Free Cable Run and for Sealing the Cable-Joints

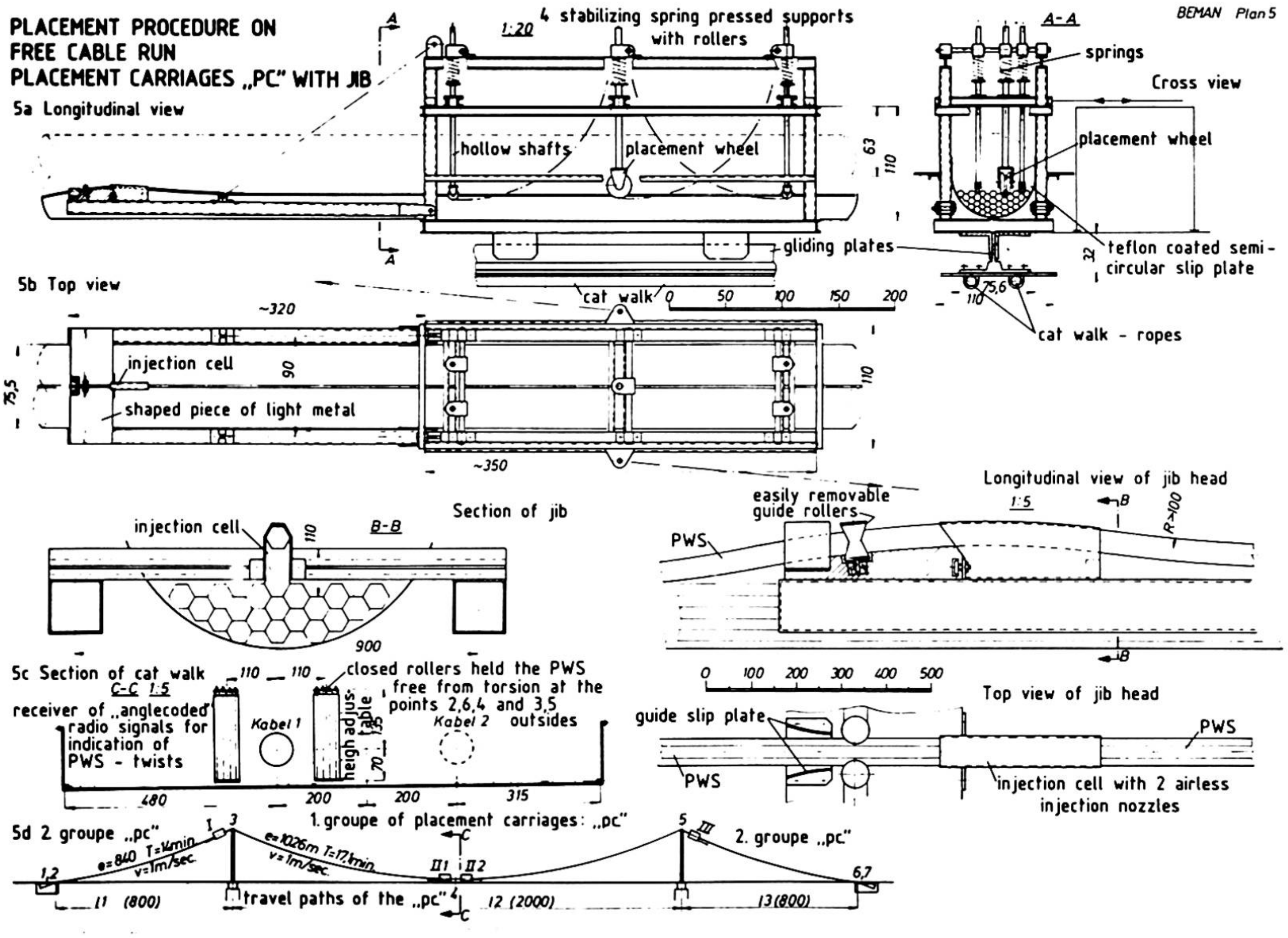
The PWS are put in place in the area between the tower and the splay saddles in the anchor chambres after lateral displacement by means of sliding forming devices which are 4 appropriately constructed "placement-carriages" (shortly named: "pc.") of light metal. They are moved in both directions by the transport-ropes as required. They surround the already assembled parts of cable-cross-section by a Teflon-coated halfround slip sheet, Fig.5, p.8. The top-part of the "pc." can be dismounted quickly to open the inner field of the "pc." and lead in the PWS. The PWS will be stabilized by gliding plates attached to the catwalk-ropes and by 4 tiltable spring-pressed hollow shafts with rollers at their ends. In the centre of the "pc." the PWS which shall be put in the cable-cross-section, will be led and pressed on by a placement-wheel which is attached to the end of a spring loaded tiltable support. The already erected cable parts are gripped by the jib. The PWS are lightly lifted by a laterally inserted "shaped piece" of light metal at the jib head causing only a slight vertical bend. Behind this is arranged a sheet metal encased "injection cell", Fig. 5b, p.8. Besides, this free space can be used for attaching the clamps on the PWS, Fig. 4, p.8. for the longitudinal fine adjustment during the erecting process. To avoid the turning and twisting of the PWS "closed rollers" are placed at the points: 2, 3, 4, 5, and 6, Fig.5d, p.8. Turnings, if any, shall be indicated by the receiver for anglecoded radio signals, Fig. 5c. The twists shall be corrected at the jibheads adequately. The slip plates and guide-rollers adapt the PWS in the right manner to the free run area.

Figure 5d shows the travel paths of the "pc.":
"Pc." II_1 and "pc." II_2 run simultaneously the way 4-3 and 4-5.
"Pc." I and "pc." III run subsequently the way 3-2 and 5-6.

At the same time happens the spraying of the grove with plastic material to seal the joints in the cable-cross-section. As the travel paths are finished the "shaped piece" at the jib head shall be taken out and the two groups of "pc." return after changing the transport-ropes.

Each placement carriage is equipped with light motor, compressor,fuel- and plastic-tanks, and radio transmitter.


BEMAN Plan 4
Crane bridge with 2 trolleys, lifting capacity 160 kN
2 crane runway girders spaced 980cm, IPB 700
DEVICES ON THE TOWER FOR TRANSFERRING THE PWS FROM THE AUXILIARY SADDLE INTO THE CABLE CROSS SECTION TRANSVERSELY TO THE CABLE CIRECTION
OBJECTIVE
Time-saving change of working directions
Two day shifts. Undisturbed assembly by means of the transporter ropes in the longitudinal direction
One night shift. Tensioning the PWS, longitudinal fine adjustment and crosswise movement by means of 2 cross beams "A" alternately right and left 1 cross beam "B" having a working width of 170, of which 13cm transverse overlap. 2 bridge cranes each with 2 trolleys 2 crane runway girders which carry also the support for the transporter ropes
cross beam "B" in rest posit.
Counterweight
Tow cable
Section C-C, cross beam "B" in rest position, IPB 400
Top position of cross beam "B" perpendicular to the cable direction
Bottom position of cross beam "B" perpendicular to the cable direction
Cross beam "A1" in rest position alongside the auxiliary saddle, LH
Cross beam "A2" in rest position alongside the auxiliary saddle, RH
Projecting steel structure
Type of rollers on catwalk and auxiliary saddle
Transversely movable tension anchor for supporting the dead weight pull
B-B
Swing-out top section
Cable 1
Cable 2
constructed successiveley with the rearranged devices
Transporter rope suspension
Clearance
Cross beam "B"
Cross beam "A", IPB 400
Supporting arm of cross beam "A"
Rotary
Welded ratchet
Heavy strap with threaded bolts
Lifting belt-polyester belt 50mm wide 2 mm thick twofold 160kN load-carrying capacity
4 each supporting arms for the PWS pressed with lifting belts
Auxiliary saddle with rollers
cable
Cable saddle support
Tensioning device for the PWS on the rollers of the auxiliary saddle, effective until the dead weight tension is balanced on both sides
max. expansion 100
Clamp
Rope blocks, 4 times reeved
Worm gear
Swing-out head section
Movable rollers
Winch, schematically
Tower in longitudinal direction approx 1100cm
Catwalk
Cross beam with integral pressing-clamp
Projecting steel structure
Cross beam with clamp, sc 1:50
pressing
Longitudinal fine adjustment, sc 1:50
Placement carriage
Cross beam in the area of the injection cell on the placement carriage jib


PLACEMENT PROCEDURE ON FREE CABLE RUN
PLACEMENT CARRIAGES „PC" WITH JIB
BEMAN Plan 5
5a Longitudinal view
1:20
4 stabilizing spring pressed supports with rollers
hollow shafts
placement wheel
gliding plates
A-A
springs
Cross view
placement wheel
teflon coated semi-circular slip plate
cat walk - ropes
5b Top view
cat walk
injection cell
shaped piece of light metal
Section of jib
injection cell
B-B
Longitudinal view of jib head
1:5
easily removable guide rollers
PWS
5c Section of cat walk
C-C 1:5
receiver of „anglecoded" radio signals for indication of PWS - twists
closed rollers held the PWS free from torsion at the points 2,6,4 and 3,5 outsides
Kabel 1
Kabel 2
height adjustable
Top view of jib head
guide slip plate
PWS
injection cell with 2 airless injection nozzles
5d 2 groupe „pc"
1. groupe of placement carriages: „pc"
2. groupe „pc"
travel paths of the „pc"
l1 (800)
l2 (2000)
l3 (800)

6. CORROSION PREVENTION

Even multi-layer plastic sheaths of suspension bridge cables cannot provide long-term protection if the cables are exposed to UV radiation and oxygen in case of sunshine and if, in addition, cracks are generated in the embrittling material at the joints of the cable bands by frequent movements. Therefore, many experts rely only on galvanizing the wires and content themselves with the so-called "wire-wrapping". The cables of the Brooklyn bridge, N.Y., exhibit only minor defects even on the exposed run after 100 years. However, the anchoring sections in the abutment are in a poor condition, which would have required a protection of higher quality. If, however, the service life of so extremely expensive bridges as are being considered here is just about 100 years in an ambient atmosphere of medium aggressivity, the economic usefulness is inadequate, for replacing the main cables of suspension bridges of the sizes in question is hardly possible. Investments of approx. 1500 million dollars possibly required for large-span bridges then would hardly be justified economically. Therefore, in the general interest all specialists in this field are called upon to develop a permanent protection, a highly important creative challenge !

It is well-known that the embrittling plastic sheath at the cable band joints becomes leaky after only a few years so that moist air penetrates into the cable where it precipitates into condensed water. Later on, rainwater and aggressive media such as H_2SO_3 and chlorides penetrate into the interior to an increasing extent. Since little fresh air can enter, hardly any CO_2 particles are added. Moreover, the interior of the cable, in most cases consisting of up to 23 % of voids, does not dry up. Then the "heavy condensate attacks" begin resulting in the formation of zinc hydroxide which, in turn, cannot react further to form protective basic carbonates. It is an important fact that the aggression can cause destruction by corrosion inside the cable in all places at the same time, i.e. on 9211 wires corresponding to a surface area of 20256 cm^2 per unit length, provided a sufficient amount of aggressive media could penetrate. In the interior, only the zinc skin of about 300 gr/m^2, i.e. about 44 µm thickness of zinc coating, can provide protection (which is inadequate in the case of heavy aggression !).

The protection system shown in Fig.6, p.10, acts in an entirely different way.

Only when a protective ring - in this case assumed to consist of about 5 layers of galvanized wires - having a circumference of about 199.1 cm and being 3.125 cm thick, consisting of 10 layers of plastic spandrels and 9 narrows of a few µm between wires located closely side by side has been destroyed by the aggressive media, a core having a diameter of still 60.24 cm will be attacked, which would have a tension of 1.25 x all. σ with fully loaded bridge after complete failure of the outer ring. The service life of such a protective ring not exposed to UV radiation will exceed 100 years by far. Since, however, polymeric-organic plastics are subject to ageing under climatic influences, plastic experts refuse to give a quantitative resistance forecast for such a long period, pointing out that sufficiently long observations of the specific material properties are not available. To form an opinion it is important to know that in the arrangement proposed the ratio of possible areas of attack is 20256 : 199.1 = ca. 100 : 1. Moreover, the climatic conditions in the interior of the complete filled cable vary little from those in buried pipelines which are proven to be fully functional after 50 years. Furthermore, it should be noted that the plastic considered called "Levasint", an ethylene vinyl alcohol copolymer, was applied to traffic posts, street lamp poles and bridge railings which are exposed fully to UV radiation in various climates and also to the particularly aggressive climate prevailing in Saudi-Arabia.

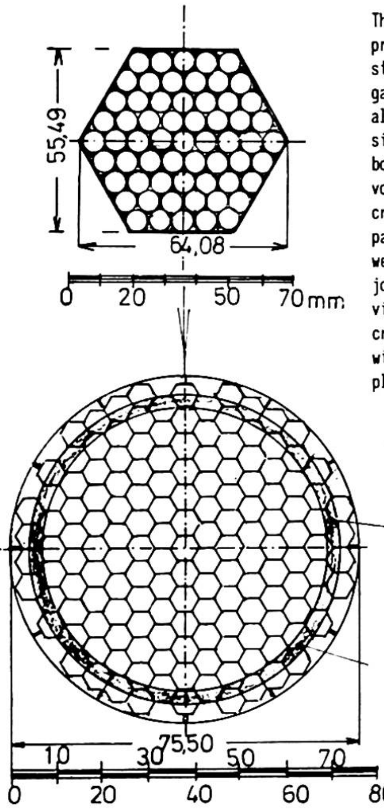
These plastic coatings of 320 μm thickness exhibit no deterioration after 10 years. In the case under consideration, t e n separately acting layers having a resistance 115 times greater (10 x 3665 : 320 μm) would have to be pierced one after the other under conditions of considerably lesser aggressivity of the corrosive forces !

These considerations permit the conclusion that with such a protective system serious attack on the core will begin only when the service life of the conventionally treated bridge cables would have elapsed for a long time.

NOVEL CORROSION PROTECTION SYSTEM FOR SUSPENSION BRIDGE CABLES

Principle:

BEMAN Plan 6



The cable consists of 151 prefabricated parallel-wire strands each comprising 61 galvanized, absolutely parallel wires placed closely side by side, dia. 7 mm, bonded by filling the voids, max. 12,95 % of the cross-sectional area, with particularly resistant, well-adhering plastic. The joints between the individual PWS within the cable cross-section are closed with sealing plastic during placement.

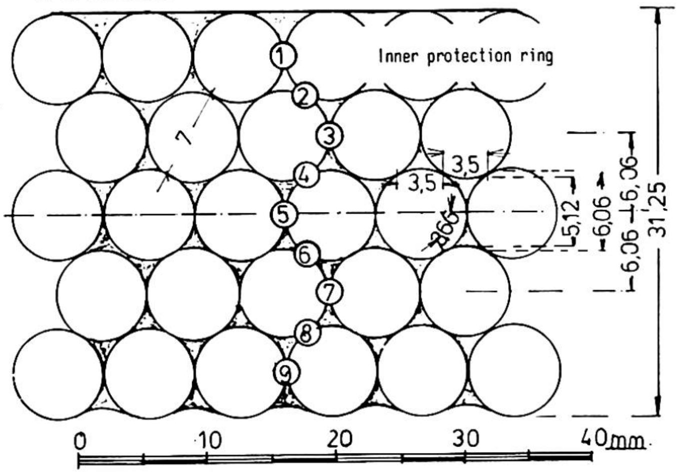
This results in the illustrated protection system:

Inner protection ring:
Thickness = 31,25 mm
assumed: 7403 inner wires = approx. 80 % of cable cross-section, then:
Maximum load approx. 0.56 · β_N possible, adm. σ thus exceeded by approx. 24 %

As effective interior cable protection ring 5 wire layers 31.25 mm thick are assumed. Up to the interior of the cable there are (2.n-1) narrows and (n) rows of plastic-filled spandrels, e.g. for the 5 closed exterior cable layers 9 narrows and 10 plastic spandrels in front each 2,2 mm² in area and 3.665 mm bottom length.

Owing to the special arrangement, corrosive attack occurs by layers and spaced in time.

According to the experience gained so far, each barrier is resistant for at least longer than 10 years, but probably much longer because of the limited access of the aggressive media due to the existing narrows and the elimination of the effects of UV radiation.



Consequently, with the favourable results to be expected one should make up one's mind to take into consideration a longer service life when performing a cost-effectiveness analysis. Thus, the additional cost of plastic needed in such structures becomes less important, especially since on the other hand there are considerable savings in manufacturing the cables.

The advantage to be able to use a very expensive bridge for some decades longer is of such economic importance that it should be worthwhile to apply the proposed methods to the construction of large bridges and thus to act in the spirit of the great example "John Roebling".

7. TEST RESULTS

7.1

A few years ago, the reeling and unreeling process described in [8] was tested with simplified devices by a West German wire manufacturer; the results were positive.

7.2

Inductive heating with 2 to 4 kHz waves and with a specified speed of 0.33m/sec was found to be fully effective in spring 1984.

7.3

Bonding affectiveness of the wires within the PWS - cable saddle area - was found to be 58.1 kN for a length of 1 m.

7.4

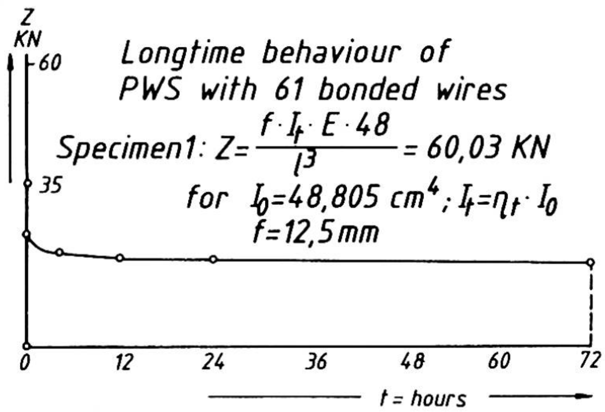
In a long-term test the adhesive capacity of the plastic material was tested on several 7-wire PWS 30 cm long, where a mean displacement of 2.56 mm (in reality only 2.49 mm were existing per wire layer) at v = 0.1 mm per second was specified. After a period of 40 h, the decrease in the adhesive stresses was determined to be only 18 %. A subsequent uninterrupted tensile test resulted in another increase by 81 % until ultimate failure. Tests to verify whether this adhesive capacity decreases with time shall be performed in about 3 months.

7.5

When bent on the curved cable saddle, the plastic-bonded PWS behaves like a viscoelastic material. The relaxation behaviour of the PWS and the reduction in the moment of inertia due to creepage of the plastic caused by the shear stresses occurring during bending on the cable saddle having a radius of 10 m was investigated in a long duration test with three 61-wire specimens 1.20 m long. Due to this effect the moment of Inertia

$$I_t = \frac{l^3 \cdot Z}{f \cdot E \cdot 48}$$

and, hence, the bending stresses in the curved area are substantially reduced as is evident from the graph and the table.



Specimen No.	Deflection	Z_0	Z_{12}	Z_{24}	Z_{36}	$Z_{72\,h}$	$I_{72\,h}$	η_t for I_0= 48,805
	mm	KN	KN	KN	KN	KN	cm⁴	cm⁴
1	12,5	35	19,25	18,00	17,95	17,40	14,15	0,29
2	12,5	29,9	20,17	19,76	19,50	19,40	15,77	0,32
3	6,5	23,7	15,52	15,24	14,90	14,49	22,65	0,46

The results of a long-term fatigue test and the development of a creep rate equation to answer the question which r e d u c t i o n i n t e n s i o n can be expected in the curved area with the time "t". According to [10] the quantities in the equation

$$Z_t = Z_0 \left\{ 1 - \frac{E/E_k}{1 + E/E_k} \cdot \left(1 - e^{-\frac{t}{T}(1 + E/E_k)}\right) \right\}$$

shall be determined by long-term fatigue tests.

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