SIEMENS

380 kV Overhead Transmission Line over the Bosphorus

Contents

Introduction

The largest power station in the Turkish supplying system, Keban, Elbistan and Karakaya, are situated in the Asian part of the country. In order to cover the increasing demand for electrical energy in the industrial and population centres around Istanbul and in the European part of Turkey the public power utility Türkiye Elektrik Kurumu (TEK) built a 380 kV double-circuit overhead transmission line across the Bosphorus. TEK awarded the order for the design, supply and erection of the transmission line to a consortium consisting of Siemens AG and the Turkish company Mitas at the beginning of 1982. The new crossing is situated about 20 km north of the existing 145 kV crossing in operation since 1960.

Although this is unusual for such overhead transmission lines single conductors with a diameter of 60 mm have been used. For the purpose of suspending and terminating these conductors adapted insulator sets as well as suitable fittings had to be developed and to be tested thoroughly. Because of the approximately 1800 m long span over the waterway and the steep terrain, the most difficult task in erection of this crossing was the stringing of the conductors with a cross-section of more than 2000 mm^2. It was necessary to specially develop a conductor stringing method suitable for the unusual requirements concerned as well as the necessary stringing equipment.

The authors describe the crossing, the basic assumptions for the mechanical loads and the design of towers and foundations. They report on the selection and rating of the conductors, the insulator sets and fittings as well as on the problems concerning vibration damping. They go in details concerning the method and equipment used for stringing and deal with experience gained.

Johann Fenz

General description, loading assumptions, towers and foundations

Description of the crossing

The new 380 kV overhead line crossing ordered by Türkiye Elektrik Kurumu (TEK), the utility responsible for the power supply to the whole of Turkey, is situated 20 km to the north of Istanbul. The crossing has been designed for two circuits with a transmission capacity of 1400 MW each (**Fig. 1**). At the crossing site the Bosphorus is about 1200 m wide and has steep banks about 120 m high. The straits connect the Black Sea and the Sea of Marmara and are a busy international waterway. The shipping authorities specified a clear height over the Bosphorus of 70 m including the electrical safety clearance. This guarantees that even the largest oceangoing ships can pass without any restrictions [1]. The crossing section has a total length of 3100 m and consists of two suspension towers and four tension towers, each circuit being provided with its own tension towers. The span between the suspension towers is 1757 m, while the tension towers are situated at a distance of about 670 m from the suspension towers (**Fig. 2**). The towers carry the six conductors for the two transmission circuits and two earth wires.

The crossing is notable in three respects:

- It connects the high voltage grids of two continents over a shipping route.
- The conductors reach almost 60 mm in diameter and are among the thickest ever to be utilized in an overhead line.
- The span amounts to 1757 m.

On the European side the power is transported by two 380 kV circuits to the Alibeyköy substation for the supply of greater Istanbul and to the Ikitelli installation further to the west. On the Anatolian bank, one circuit runs into Ümraniye substation. The other is to be installed on a future line to Osmanca.

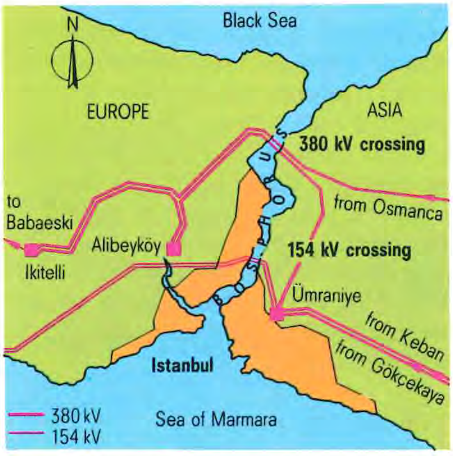


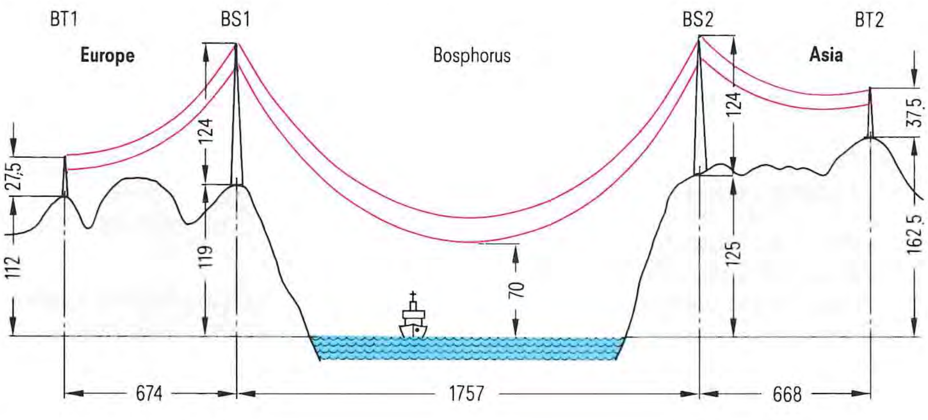
Fig. 1 Geography of the 380 kV power transmission line over the Bosphorus

Load conditions

The Turkish specifications [2] concerning design and construction of overhead lines list five climate zones. For each of these zones, the ice load on the conductors and the maximum and minimum conductor temperatures to be taken into account during planning and in the design calculations are specified. Data according to zone III was selected to serve as the basis for design of the crossing. According to the formula $3\sqrt{d}$, the conductor ice load is 23.0 N/m; and in zone III conductor sag and tension calculations have to be based on conductor temperatures of −25 °C at minimum and of +80 °C at maximum.

The wind speed increases with height above ground. To enhance

Fig. 2 Profile of the Bosphorus crossing (heights 5 : 1 out of scale)



BS suspension tower BT tension tower Dimensions in m the reliability, the wind data for the zone from 150 m to 200 m above ground was specified for the whole tower and all conductors. This yielded a dynamic pressure of 0.95 kN/m^2 on the conductors and 1.25kN/m^2 on the tower structure.

Conductors

Selection

Single conductors as well as bundle conductors would have been suitable for the transmission capacity specified [3]. After careful consideration TEK opted for single conductors, the following reasons having been decisive in favour of this solution:

- Greater reliability under ice load
- Less risk of conductor galloping
- No twisting of a bundle under ice load
- No bundle spacers.

However, these technical advantages increased the total costs of the crossing.

Under the given climatic conditions, a conducting cross-section of 1800 mm^2 per conductor is required in the case of single conductors [4]. In order to keep the sag of the conductor in the long span to a miminum, it was decided to use a conductor consisting of aluminium alloy outer layers and an aluminium clad steel core, the latter being selected for its superior resistance to corrosion [5].

A conductor with a cross-section of about 320 mm^2 and also consisting of aluminium clad steel strands was selected for the earth wires.

Information about the make-up and technical data of the conductors and earth wires is listed in **Table 1**.

		Conductor	Earth wire
Aluminium alloy cross-section	mm^2	1805.46	–
Aluminium clad steel cross-section	mm^2	227.83	318.38
Total cross-section	mm^2	2033.29	318.38
Number and diameter of aluminium alloy wires	mm	108 × 3.9 and 40 × 4.05	–
Number of aluminium alloy layers		5	–
Number of aluminium alloy wires per layer		18, 24, 30, 36, 40	–
Number and diameter of aluminium clad steel wires	mm	37 × 2.80	37 × 3.31
Number of aluminium clad steel layers		3	3
Number of aluminium clad steel wires per layer		1, 6, 12, 18	1, 6, 12, 18
Conductor diameter	mm	58.90	23.17
Conductor weight	kg/m	6.488	2.124
Modulus of elasticity	kN/mm^2	71.1	166.3
Coefficient of thermal expansion	K^{-1}	$20.3 \cdot 10^{-6}$	$13.0 \cdot 10^{-6}$
Ultimate strength, calculated	kN	847.49	393.2
Horizontal tensile stress, maximum	N/mm^2	117.6	357.9
Horizontal tensile stress at +15 °C	N/mm^2	82.88	193.4

Table 1 Conductor and earth wire make-up and data

Tensile stresses

The following criteria had to be taken into account for deciding the conductor sagging:

- The maximum horizontal tensile stress may not exceed 45% of the theoretical ultimate stress.
- At the minimum temperature of −25 °C, the horizontal tensile stress may not exceed 25% of this ultimate stress.
- In order to compensate for conductor creepage, this tensile stress may be increased to a minimum of 33% of the ultimate stress.
- The everyday stress at +15 °C is to be limited to 20% of the ultimate stress.
- At −5 °C and double ice load, the conductor tensile stress at the suspension point may not exceed 70% of the ultimate stress.

For the given spans and the selected conductors, the everyday stress criterion was decisive for sagging the conductors. The conductor tensile stresses derived therefrom are listed in **Table 1**. For the conductors, the maximum sag at +80 °C in the crossing span is 156.0 m and the maximum horizontal tension 240 kN. The horizontal tension at the annual mean temperature of +15 °C amounts to 168 kN.

Manufacture

For reliability reasons and in order to simplify the stringing work, the conductors were to be supplied in continuous lengths of about 3200 m (from tension tower to tension tower). As only few manufacturers are capable of producing conductors of these dimensions, the conductor make-up was decided in close cooperation with the potential suppliers. Special attention had to be given to the following requirements:

- Untwisting is required during the stranding of aluminium alloy wires.
- For the outer layer, 40 wires have to be stranded simultaneously.
- Each wire reel of the spinning machine must be able to carry 3200 m of wire with a diameter of 4.05 mm.
- The weight of one conductor length plus transport drum, amounting to 25 t with a drum diameter of 3.0 m and a width likewise of 3.0 m, had to be handled.

Insulators and accessories

The conductor dimensions and the long span also affect the loads on the insulators and accessories [5]. The minimum failing load of the insulator sets amounts to 600 kN for the suspension strings and 1060 kN for the dead-end sets. These values signify four times the maximum

Fig. 3 Conductor blocks and suspension saddle

loads in the case of the suspension string, and 1.25 times the theoretical ultimate strength of the conductor in the case of the tension set.

For the suspension towers a double string consisting of 2 × 22 cap and pin type glass insulators (F30) was selected. The double tension strings consist of 2 × 20 cap and pin type glass insulators (F55). The creepage paths obtained with these insulator designs are 9350 mm for the suspension string and 9200 mm for the tension string.

Special accessories had to be developed to cope with the unusually high loads, and extensive tests were necessary to validate the theoretical considerations and calculations. Saddle type clamps are used at the suspension sets. They can withstand the forces imposed by the conductors, are designed for the conductor deflection angle concerned and prevent the stresses in the conductors from exceeding the permissible limits. The suspension saddle for the conductor is 2.0 m long and weighs 180 kg. Armour rods 4.0 m long had also been fitted on the conductors before the suspension clamps were installed (**Fig. 3**).

Compression type tension clamps were used for anchoring the conductors. These clamps had to undergo trials to prove their capacity to anchor 90% of the ultimate strength of the conductor, i.e. 765 kN.

To prevent vibration damage, the selected conductor tension and the long span required dampers because of the local conditions of frequently occurring laminar air flow. In the vicinity of the suspension clamp, each conductor was fitted with five Stockbridge dampers on the Bosphorus side and with three Stockbridge dampers on the land side. Three dampers were likewise fitted ahead of each dead-end clamp. Each earth wire is fitted with ten dampers in the main span and four dampers in the adjacent spans.

Due to the exposed position of the crossing, each earth wire was provided with eight aircraft warning balls along the main span and three along the adjacent spans.

Towers

All conductors have been arranged at the same level. This configuration resulted in the lowest possible tower height, which was important to achieve for air traffic and also for aesthetic considerations (**Fig. 4**).

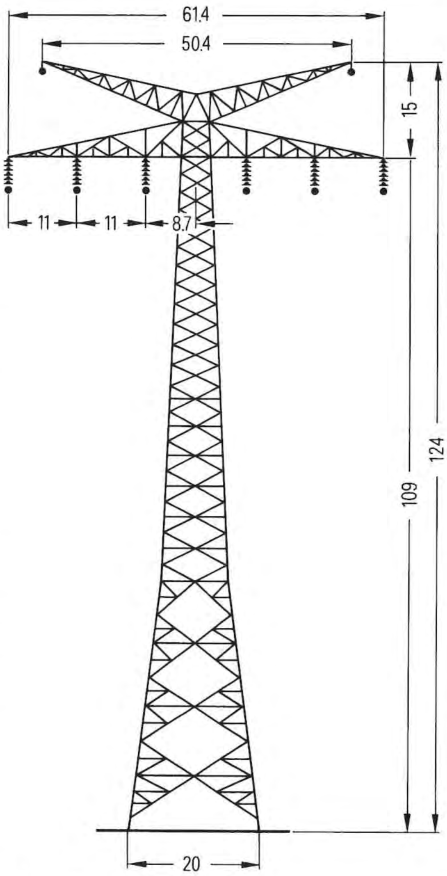
Fig. 4 Suspension towers of the Bosphorus crossing

Design

The crossarm height of about 230 m over the water level resulted from the specified clear height for shipping of 70 m, the maximum conductor sag of 156 m and the insulator string length of 5.0 m. The tower sites on the steep banks lie at heights of 119 and 124 m, and so a height of 109 m above ground sufficed for the crossing. The two earth wires are suspended 124 m above ground (**Fig. 5**). The conductor clearances were selected to prevent impermissible approach causing service breakdowns. This resulted in a crossarm length of 61.4 m.

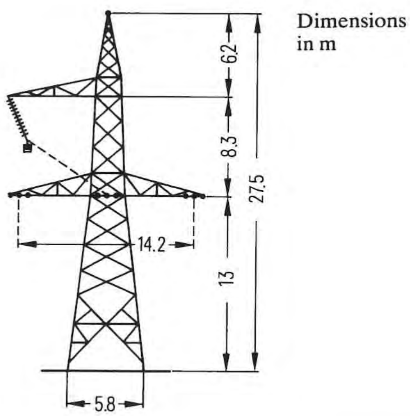
Because of the hilly terrain and the tall suspension heights at the suspension towers, the tension towers could be kept relatively low. Establishing double circuit tension towers would have meant more than 40 m long crossarms, which would have created aesthetic as well as technical problems. Therefore each circuit was provided with its own tension tower. The centre conductor of each circuit is fixed to the centre of the tension tower; the jumper is led via a pilot insulator string on an auxiliary crossarm. The conductors are terminated at the tension tower at heights between 13 and 24 m above the ground (**Fig. 6**).

Fig. 5 Suspension tower BS



Dimensions in m

Fig. 6 Tension tower BT



Temperature	Wind load	Ice load	Conductor tensile forces
Suspension tower			
+5 °C	Perpendicular to the line direction on tower and conductor	none	none
+5 °C	In line direction	none	On one side 2% of the maximum tensile forces of all conductors
+5 °C	In a quartering direction on tower and conductor	none	none
−5 °C	Reduced wind pressure; perpendicular to the line direction on iced tower and iced conductors	yes	none
−5 °C	none	yes	33% of maximum tensile force of one conductor at least favourable suspension point (broken wire condition)
−5 °C	none	yes	50% of the maximum tensile force of one earth wire
−5 °C	none	100% on one span, 50% on the other spans	Longitudinal loads due to differences in tensile forces because of unbalanced ice loads
Tension tower			
−5 °C	Reduced wind pressure; perpendicular to the line direction on iced tower and iced conductor	yes	Dead-end tensile forces of all conductors
+5 °C	Perpendicular to the line direction on tower and conductor	none	Dead-end tensile forces of all conductors
−5 °C	none	yes	Dead-end tensile forces of only 2 conductors (broken wire condition)

Table 2 Load combinations for suspension and tension towers

Load conditions

Wind loading decisively determined the suspension tower design. Each tower was designed for 1200 kN of horizontal load resulting from wind load on the conductors and on the tower. The weight of all conductors with the assumed ice load included is 1000 kN per tower. The considered load combinations are listed in **Table 2**.

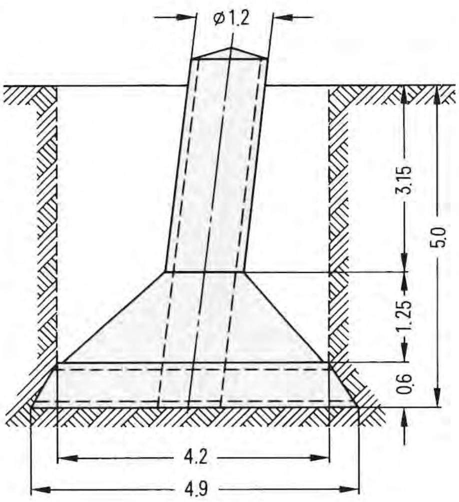
The maximum conductor tensions arise in the case of reduced wind load acting on iced conductors; under this load condition the wind pressure was reduced to 0.3 kN/m^2 for the conductors and to 0.4 kN/m^2 for the towers. Icing of the tower was taken into account by enlarging the surface projected to wind by 50%. A quartering wind load condition was the main criterion for the design of the tower leg members.

Apart from these stipulations, it was also necessary to investigate additional load conditions due to the erection procedure. The crossarms, for example, were hoisted over the earth wire peaks. Unbalanced weight loadings occurred during conductor stringing.

Each of the four tension towers was designed as a terminal tower for longitudinal conductor tensions of 835 kN [6, 7]. The load combinations are listed in **Table 2**.

The design calculations incorporated a safety factor (related to the elastic limits of the material) of 1.5 for the suspension towers in the case of broken wire condition and of 2.5 in all other cases.

Fig. 7 Foundation of suspension tower



Dimensions in m

Tower design

The towers were designed as conventional hot dip galvanized lattice structures. The width of the suspension towers at ground level was selected as 20 m in order to enable the use of conventional steel sections for the leg members. Therefore, double angles made of St 52 material crosswise welded together were suitable. The bracings are made of double angle profiles [8]. Due to the low height of the tension towers, conventional angle sections of St 52 were sufficient for their leg members.

Leg extensions were provided for each tower to match the hilly terrain. The suspension towers were coated orange and white for the sake of air safety. Obstruction lights were mounted at heights of 40 and 80 m; flashing hazard lights were fitted on the two earth-wire peaks. Access to these lights is provided by stairs mounted inside the tower. Step bolts and stirrups offer footholds to facilitate erection and coating works.

Each suspension tower weighs about 230 t, and each tension tower between 19 and 29 t depending on its height. A total of about 565 t of steel was used.

Foundations

Soil investigations revealed weathered andesite, schist and clay. Unlike the 380 kV Elbe crossing [9], no special measures were necessary for the foundation works. The good bearing soil permitted use of pad and chimney foundations at all tower sites. The lower part of the foundation pit was undercut to increase the load bearing capacity (**Fig. 7**). Both the lower part of the foundation and the cylindrical chimney were steel reinforced.

The foundations have to transmit the following forces from the leg members to the soil:

Suspension towers	
Compression force	3700 kN
Uplift force	2270 kN
Tension towers	
Compression force	1425 kN
Uplift force	1285 kN

The 2.5 safety factor called for foundation depths of 5.0 and 4.6 m and widths of 4.9 and 4.3 m in the

case of suspension and tension towers, respectively. A total of 103 m^3 of concrete was required for each suspension tower, and 45 m^3 for each tension tower. All foundation chimneys measure 1.2 m in diameter.

Progress of erection work

The foundation works were carried out in the period from August to December 1982. In conformity with standard practice in overhead line construction, tower stubs fitted with anchor cleats were embedded in concrete. The stubs extend to the bottom of the foundations. In order to keep their correct position, the lower sections of the towers were already erected up to the first horizontal braces before pouring the concrete. Auxiliary struts stabilized the lower section during this procedure.

Tower erection commenced right on schedule in March 1983 and was finished in June 1983. The towers were erected with the aid of a 25 m long gin pole arranged in the centre of the tower body [10]. The earth wire peaks, each of which weighs 6 t, were hoisted utilizing the gin pole and then tilted into their final position. The 10 t crossarm halves were hoisted in three parts to their final position, the hoisting rope being passed through a snatch block fixed to the earth wire peak.

Conductor stringing was the most challenging work of the project. Special measures were necessary because the earth wires and the heavy conductors had to be strung in spans of 1757 m across the Bosphorus with maximum safety and minimum interference with shipping. The procedure finally adopted, the mechanical equipment used and the necessary tools mostly had to be newly developed to meet the demands of this project [11]. Conductor stringing began in July 1983 and was finished at the end of October 1983, and so the complete crossing could be handed over to the owner right on schedule.

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Metin Giray and Friedrich Kießling

Selection and rating of the conductors, insulators and fittings

General

Electrical energy can be stored only to a very small extent. However, energy is always needed and, therefore, has to be generated, transmitted and distributed at the same time. Significance of electrical power transmission increases as the distance between the locations of generation and the consumers increases. In the Anatolian part of Turkey there were favourable possibilities of producing electrical energy from water power and lignite. The Keban hydraulic power plant, the Elbistan lignite power plant and the planned Karakaya and Atatürk hydraulic plants should be mentioned in this context. They are situated in the eastern part of Turkey, more than 1000 km away from the load centres mainly to be found in the Ankara area and around Istanbul and Edirne in the European part of Turkey (**Fig. 8**).

In order to supply the European part of Turkey with energy from the Anatolian power plants an overhead transmission line operating at 154 kV had been built across the Bosphorus near Istanbul in 1960. This connection is not able to meet the future demand which is still rising considerably. For this reason the Turkish Electricity Authority "Türkiye Elektrik Kurumu (TEK)" planned a connection of the existing 380 kV grids with a double-circuit overhead transmission line across the Bosphorus.

Realization of this project began in 1981 with the publication of the call for tenders. The German-Turkish consortium Siemens AG, Erlangen, and Mitas, Ankara was entrusted with the contract and completed the crossing by finishing the stringing operations in October 1983.

Location of the crossing, tower design

The new overhead transmission line crosses the Bosphorus about 20 km north of Istanbul (**Fig. 1, Page 3**). Here the straits are about 1200 m wide and their steep banks rise up to about 120 m. One suspension tower is situated on the Anatolian side south of Anadolukavagi village, the other suspension tower is placed on the European side north of Sariyer town. Naturally, the transmission line was not to affect the busy international navigation on the Bosphorus which connects the Black Sea with the Sea of Marmara. Near Istanbul the well-known bridge which links Europe to Asia crosses the Bosphorus providing a clearance of 64 m. To provide this indispensable minimum and adding the required electrical clearance, the conductor height above sea level was specified to a minimum of 70 m. Thus, unhindered passage of the largest oceangoing vessels was guaranteed.

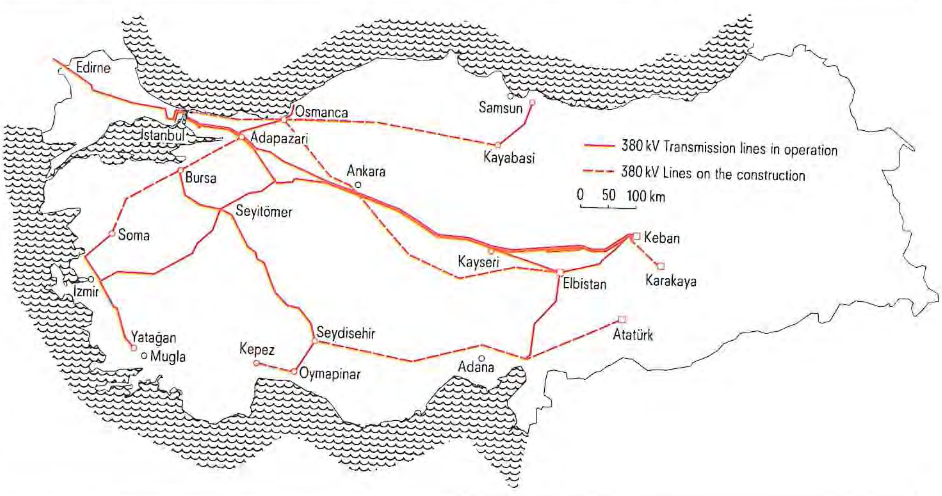
The 3100 m long crossing section (**Fig. 2, Page 3**) consists of three spans. The main span across the Bosphorus is 1757 m long; the adjacent spans between the suspension and the tension towers have a length of 674 m and 668 m respectively. The two suspension towers are located 119 m and 125 m above the Bosphorus, the tension towers have been placed on the top of hills representing the most advantageous tower sites. The height of the suspension towers depends on the choice of conductors and their sags. The two identically designed suspension towers reach an overall height of 124 m each. The conductors are suspended on insulator strings which are fixed to the crossarms 109 m above the tower foundations. Thus, the conductor suspension points are approximately 230 m above the Bosphorus. In addition to the six conductors for the two three-phase circuits, two earth wires have been strung.

The necessity of keeping the tower height as low as possible resulted in the horizontal arrangement of the two circuits with a phase-to-phase clearance of 11 m (**Fig. 5, Page 5**). With regard to aesthetic impacts and in order to avoid the difficulties of portal-type structures each circuit was provided with a separate tension tower at both ends of the crossing. In consequence four tension towers with heights between 28 m and 39 m were required (**Fig. 6, Page 5**). The tension towers also have a horizontal configuration of phase conductors. The upper crossarms serve the only purpose of supporting the jumpers.

Electrical design

The transmission line was built with two 380 kV circuits, each hav-

Figure 8 Important power plants and 380 kV transmission lines in Turkey



ing a transmission capacity of 1400 MW limited by the permissible conductor temperature. This results in an electric current of 2200 A. Suitable conductors also able to meet the expected mechanical loads had to be chosen for the purpose of carrying this current.

Selection of conductors

The conductors transmit the electric current and as the electrically active parts they thus represent the most important component of an overhead transmission line. They have to bear electrical loads as well as extreme mechanical loads. Therefore, special attention must be paid to their selection and rating with regard to their operating reliability as well as the erection and operating costs.

High-voltage transmission lines today are generally equipped with steel-reinforced aluminium conductors with pure aluminium or high-tensile aluminium alloys as conducting material and steel wires with a correspondingly high mechanical strength in the core [1]. Such conductors are lighter and less expensive than conductors made purely of copper. Compared with conductors made of pure aluminium or high-tensile aluminium alloys they possess a superior tensile strength and show a better long-term behaviour. For these reasons steel-reinforced aluminium conductors were the only choice possible for the Bosphorus crossing.

Bundled conductors are commonly used for voltages from 380 kV upwards. In comparison to single conductors of the same overall cross-section they possess, due to a better dissipation of heat, an increased transmission capacity and reduced voltage gradients which contribute to a decrease of corona phenomena. Related to the cross-section bundled conductors can be utilized electrically to a higher extent than single conductors. A bundled conductor for 380 kV lines normally consists of two, three or four subconductors. In Turkey two or three subconductors per bundle can be found. Single conductors are only used for 380 kV lines in special cases, above all for crossings with long spans.

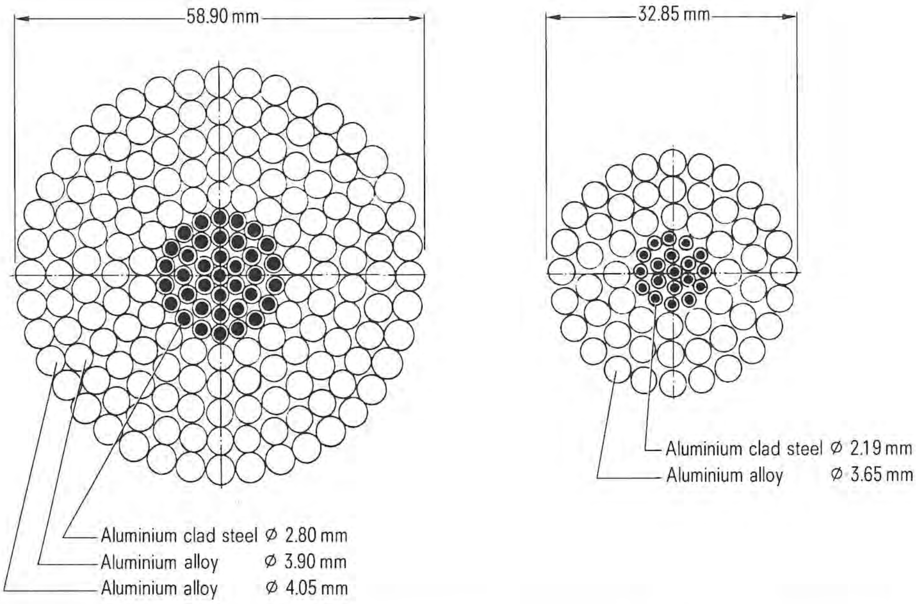
Selecting the conductors for the Bosphorus crossing involved the question whether single or bundled conductors should be used and how many subconductors in a bundle would be the most advantageous solution. Further issues concerned the materials and the conductor make-up; that is to say the ratio of conducting material to steel reinforcement, as well as the wire diameter and the number of wires. In order to solve those problems the required ampacity, the voltage gradients, the erection costs involved, as well as stranding and stringing had to be considered.

Single conductors and twin bundles were subjected to detailed examinations in consideration of the long span and the required ampacity. The respective conductors for this purpose were selected and designed accordingly. The AACSR/AC 1805/228 conductor as a single conductor consists of a three-layer core with a total of 37 aluminium clad steel wires. To produce these aluminium clad steel wires first of all aluminium is sintered onto a steel

1	Aluminium alloy cross-section		1805.45 mm^2
2	Aluminium clad steel cross-section		227.83 mm^2
3	Total cross-section		2033.29 mm^2
4	Number of aluminium alloy layers		5
5	Number and diameter of aluminium alloy wires		108 × 3.9 mm 40 × 4.05 mm
6	Number of aluminium alloy wires per layer		18/24/30/36/40
7	Number of aluminium clad steel layers		3
8	Number and diameter of aluminium clad steel wires		37 × 2.8 mm
9	Number of aluminium clad steel wires per layer		1/6/13/18
10	Total diameter of the conductor		58.9 mm
11	Weight of the conductor		6.488 kg/m
12	Theoretical Young's modulus		67,000 N/mm^2
13	Measured Young's modulus initial		63,200 N/mm^2
14	final		71,100 N/mm^2
15	Coefficient of thermal expansion		$2.029 \cdot 10^{-5}$ 1/K
16	Theoretical ultimate tensile force		847.49 kN
17	DC resistance	at 20 °C	0.0179 Ω/km
18		at 80 °C	0.0216 Ω/km
19	AC resistance	at 80 °C	0.0249 Ω/km

Table 3 Technical data of the phase conductor AACSR/AC 1805/228

Fig. 9 Cross-section of single conductor AACSR/AC 1805/228 and subconductor AACSR/AC 564/72 for twin-bundle conductor



wire and this composite wire is then drawn to the single wire diameter necessary for the conductor. In comparison to a galvanized steel wire this type of wire has a superior corrosion resistance rendering greasing of the steel core unnecessary.

Over the core there are five layers of wire made of the high-tensile aluminium alloy E-AlMgSi. Four of these layers have a wire diameter of 3.9 mm and 18, 24, 30 and 36 strands per layer, the fifth has 40 strands with a diameter of 4.05 mm each. Consequently, the conductor consists of a total of 148 aluminium alloy strands, its external diameter is 58.9 mm and its overall cross-sectional area sums up to 2033 mm^2 (**Table 3**).

In a similar way the AACSR/AC 564/72 conductor which was to be used as subconductor of a twin bundle consists of a core with 19 aluminium clad steel wires with a diameter of 2.19 mm each and three layers made of E-AlMgSi with 54 wires with a diameter of 3.65 mm each. Its external diameter is 33 mm and its overall cross-sectional area sums up to 636 mm^2. The 380 kV Elbe crossing was equipped with a conductor of the same make-up [2]. The cross-section of a twin bundle with AACSR/AC conductors 564/72 comes to 1272 mm^2, i.e. to only 63% of the area of the single conductor. **Figure 9** shows cross-sections of both conductor types.

Ampacity of the conductor

Current flowing through a conductor in a steady state, i.e. at a constant temperature, can be determined by balancing the energy input and output of the conductor (according to [3])

$$I_D = \sqrt{\frac{N_s + N_k - N_{so}}{R_{t\sim}}} \text{ in A} \qquad (1)$$

$R_{t\sim}$ represents the alternating-current resistance in of Ω/m.

The energy input is due to the Joule effect and solar radiation (N_{so}) and the energy output to radiation (N_s) and convection (N_k). For determination of these components please refer to [3]. Their amounts mainly depend on the ambient conditions and the conductor temperature.

For the evaluation of the ampacity of the conductors it was assumed that the wind velocity amounts to 1 m/s and the ambient temperature

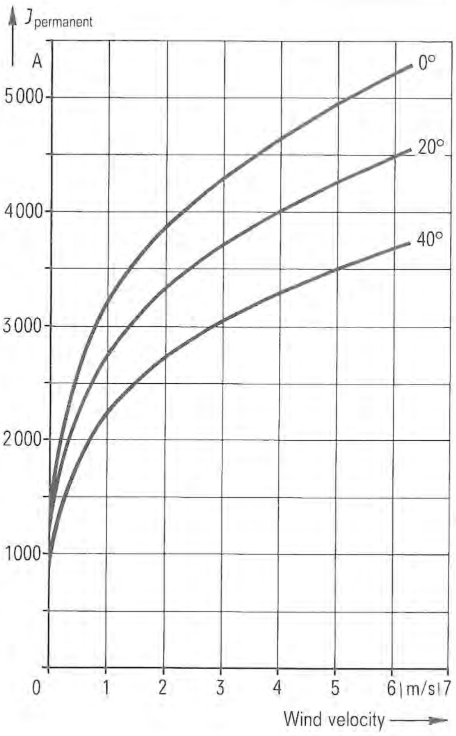


Fig. 10 Ampacity of the conductor AACSR/AC 1805/228 depending on ambient temperature and wind velocity

is 40 °C; the maximum permissible conductor temperature was 80 °C.

The alternating-current resistance of the single conductor exceeded the direct-current resistance by about 15% as a result of the skin effect appearing to be unfavourable. The conducting cross-section of a subconductor of a twin bundle completely supports the current transmission because of the smaller diameter. **Figure 10** shows the ampacity of the AACSR/AC 1805/228 conductor depending on the ambient temperature and the wind velocity. For the assumed design criteria, a permissible permanent current of 2250 A results. If the wind velocity rises or the ambient temperature decreases the current capacity will increase rapidly. It will be more than doubled at wind velocities of more than 5 m/s and at an ambient temperature of about 0 °C.

With respect to the ampacity the considered twin bundle corresponds to the conductors of the 380 kV River Elbe crossing [2], being able to transmit permanently a current of 2300 A. At the crossing site, the wind velocity of 1 m/s may be exceeded more or less permanently, the air temperature will only rarely rise above 30 °C. So far as the power capacity is concerned, the conductor had been conservatively selected; the nominal value of 2200 A represents a lower limit. The single conductor AACSR/AC 1805/228, as well as the bundled conductor AACSR/AC 564/72 are suitable for being considerably overcharged by electric current.

Permanent operation of an overhead line at its ultimate capacity is not economic since the associated losses due to the Joule effect are very high. As a rule, it can be said that aluminium conductors will operate at an optimum if the current density is about 1 A/mm^2. Therefore, an economic transmission capacity of about 1200 MW per circuit results for the Bosphorus crossing equipped with single conductors and 800 MW per circuit if twin bundle conductors had been adopted.

Corona behaviour

The corona behaviour of a conductor essentially depends on the voltage gradient. The mean value of the three conductors of a circuit is 13.2 kV/cm in case of single conductors and 16.2 kV/cm in case of bundled conductors with a distance of 600 mm between the subconductors. Mean values of voltage gradients up to 17 kV/cm can be tolerated since they do not create any corona effects which might result in considerable disturbances. In this respect the single conductor proves to be advantageous due to the lower voltage gradient. Even with equal voltage gradient the conductor system with less subconductors would be preferable with respect to the corona behaviour [4].

Mechanical stresses under everyday conditions

As to the investigated conductors the stress under everyday conditions, which should not exceed 20% of the ultimate strength, determined their sagging. This limit is called "everyday stress" [5] and controls the behaviour of the conductor under vibration. The intensity of vibrations increases with the conductor tension (see "Vibration protection", **Page 17**).

The comparison of several alternative conductors has shown that a ratio of 8 : 1 between the cross-sections of conducting layers and the steel core represents an economic optimum for the design of the crossing. This is true of single conductors, as well as of twin-bundled conductors. As to conducting material a decision had to be made between pure aluminium or aluminium alloy with increased tensile strength (E-AlMgSi, Aldrey). The latter increases the total strength of the conductor considerably. Since the permissible everyday stress had to be chosen relatively to the total strength, the material for the conducting layers has a significant influence on the sag. The use of an AACSR/AC conductor with the mentioned ratio between the cross-section of conducting material and reinforcement results in a maximum sag of 156 m, whereas the use of an ACSR/AC conductor would have meant a sag of 215 m representing an increase of 60 m and consequently resulting in towers taller by 60 m. They would have imposed an unfavourable visual impact on the surroundings and would have raised the total costs of the crossing. Therefore, only aluminium alloy could be considered as conducting material.

Mechanical stresses under ice loads

Ice or snow on the conductors cannot be excluded, particularly in a humid climate close to the sea shore if temperatures fall below the freezing point. They increase the conductor loadings and, consequently, the stresses on conductors and structures significantly. **Figure 11** demonstrates that the ultimate tensile capacity of a conductor AACSR/AC 1805/228 would be reached if an ice load of 300 N/m occurred. For a conductor AACSR/AC 564/72 this limit would already be attained with an ice load of 100 N/m. The rating of the crossing was based on a design ice load of 17.2 N/m according to

$$g_E = 3\sqrt{d} \text{ in N/m} \qquad (2)$$

where d = diameter in mm. Compared with the design value, an ice load of 100 N/m represents such a high value that any risk of damage can be excluded for the conductors and structures. However, the reliability of the single conductor and, therefore, of the whole crossing will be significantly higher.

Behaviour of conductors under wind-induced vibrations

Due to the exposed site and the necessarily high sagging forces aeolian vibrations often occur on conductors of river crossings under everyday conditions. To avoid vibration damage the conductors have to be damped by suitably designed devices. The smaller the conductor cross-section the more simply and more reliably the damping devices will protect the conductors. A bundled conductor would, therefore, be favourable with respect to the behaviour under everyday conditions.

Transmission line conductors may gallop under extreme conditions if covered with thin layers of ice and if winds conducive to this phenomenon blow. They oscillate with large amplitudes. Amplitudes up to 12 m have already been observed. It is well-known that bundled conductors are more prone to galloping than single conductors [6]. Favourable behaviour under galloping was one of the reasons for selecting single conductors for the 380 kV crossing over the River Schelde [7]. The risk of damage due to galloping can be limited by adopting appropriate clearances. The horizontal arrangement of all conductors has proved to be advantageous.

Peculiarities of bundled conductors

Bundled conductors need special fittings to keep the subconductors in a constant distance. These spacers can be damaged by aeolian vibration and may cause other troubles for example by ageing. Bundled conductors may tilt under unequal icing causing twisting of the subconductors. After melting of the ice they may under certain conditions fail to return into their original position and, therefore, necessitate service outages. Even if this were a very rare event [4], it would create very severe trouble in the given case since the conductors are rather difficult of access high above the Bosphorus.

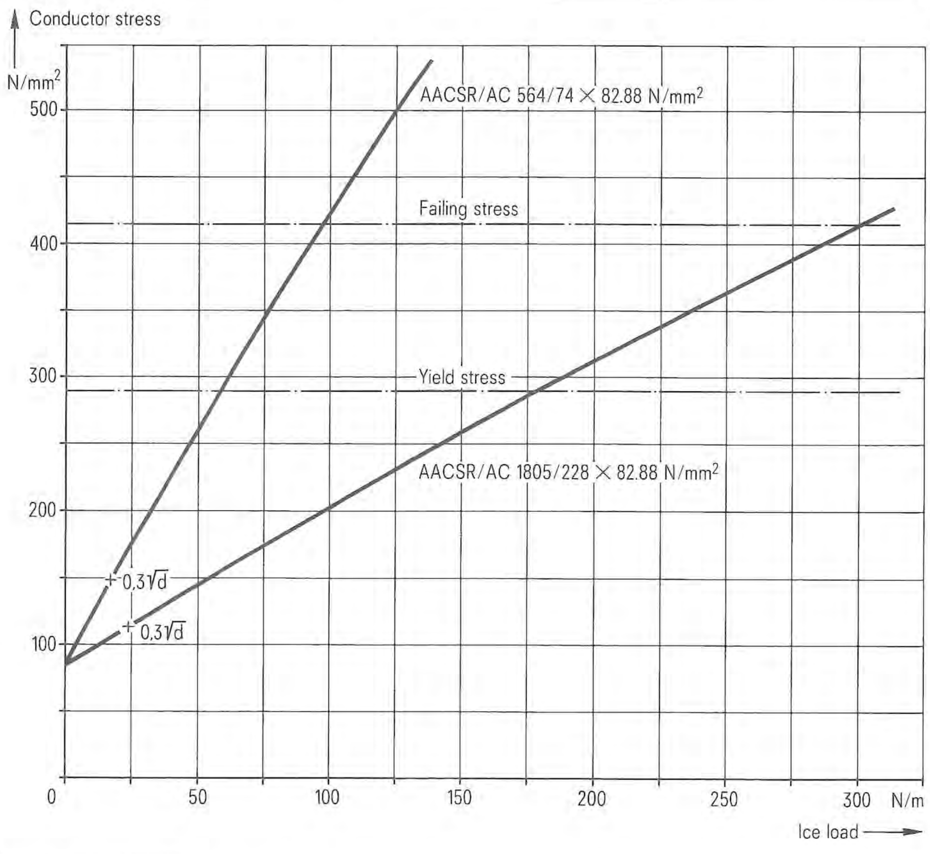
Manufacturing, stringing, costs

The described mechanical and electrical advantages of the single conductor had to be set of against the greater effort involved in supply and stringing, since the bigger cross-section, the complicated manufacturing procedures and the higher material consumption increase the costs per unit length significantly.

Many well-known suppliers of transmission line conductors were not in a position to manufacture the conductor AACSR/AC 1805/228 of the required continuous length of 3200 m without a joint, while for the production of a subconductor AASCR/AC 564/72 of the investigated twin bundle several bidders were available.

The conductor AACSR/AC 1805/228 can only be strung with special equipment which is not suit-

Fig. 11 Stress of the conductors depending on the ice load



able for stringing work on conventional lines. Especially designed fittings are necessary for the single conductor AACSR/AC 1805/228 while the bundled conductors AACSR/AC 564/72 could have been suspended and terminated by conventional, approved fittings. Detachable wedge-type tension clamps are suitable for their termination [8].

The bigger cross-section of the single conductor causes greater forces and higher loadings on the towers and foundations which will be more expensive. The required custom-tailored equipment raises the costs of conductor stringing.

Decision on the line conductors

Carefully setting the advantages against the disadvantages of the investigated solutions TEK as owner decided to use single conductors AACSR/AC 1805/228. The higher reliability with respect to ice load and absence of problems concerning spacers and twisting of subconductors expected in case of ice load were decisive for the selection of single conductors. Economic aspects were less significant.

Comparison of the selected conductors with those used in other transmission lines with long spans

When selecting the conductors for the Bosphorus crossing it was natural to draw a comparison with the conductors of similar installations erected elsewhere. **Table 4** shows important data of some of such installations.

Designed for four circuits, the 380 kV River Elbe crossing passes over the Lower Elbe which is frequently navigated by oceangoing vessels at the crossing site [9]. In order to meet the future needs the Nordwestdeutsche Kraftwerke AG stipulated a maximum capacity of 3000 MW for each circuit in a final stage, which results in a current of 4600 A in each phase. In a first stage, a conductor system suitable for half of this capacity was strung. Bundled conductors are necessary to transmit 4600 A permanently. Investigation of many suitable conductor alternatives finally resulted in the selection of a quadruple bundle with subconductor AACSR 564/72 (called Finch according to Canadian standard) which was also considered for the crossing of the Bosphorus. This conductor can permanently transmit 1150 A [2].

In the first stage twin bundles were strung which can be joined to form quadruple bundles in the final stage. The river banks of the Lower Elbe are flat. Advantages of the terrain as given on the Bosphorus with its steep banks, could not be utilized for this crossing. Although the span amounts only to 1200 m the towers of the River Elbe crossing are 227 m tall, 100 m taller than that of the Bosphorus crossing. This is due to the disadvantageous terrain and the design of the towers for four circuits. During five years of operation the bundled conductors have not caused any difficulties up to now. All other components adopted there proved their qualification in service. At the crossing site high winds very often occur, ice loads on the conductors have to be expected every winter season. Trouble due to galloping has not been experienced up to now.

A double circuit 400 kV line crosses the River Thames in Great Britain. This transmission line with a maximum span of 1370 m has single conductors ACSR 1300/680 of 56.1 mm diameter with a smooth surface. The outer layer does not consist of round-shaped wires but of specially shaped profile wires [10]. As a reason for the selection of these single conductors with smooth surface it was mentioned that expected difficulties of sagging the bundled conductors could be avoided.

In Belgium there is a double circuit 400 kV line over the River Schelde [7]. This line has been equipped with single conductors made of aluminium alloy and steel and with a smooth surface, too. The overall diameter amounts to 52 mm, the ratio between aluminium alloy and steel cross-sections is approximately 6:1. The maximum span over the main shipping lane reaches 1170 m.

During erection of the 735 kV network in the Canadian province of Quebec, Hydro-Quebec installed several large river crossings. For the 735 kV level single conductors proved in no way adequate. Bundled conductors were found essential. All the erected lines involve one circuit only. The St. Lawrence River is crossed several times downstream of the city of Quebec as well as in the vicinity of Montreal [11]. The maximum span over a fjord-like valley amounts to 1800 m.

The subconductors of the chosen quadruple bundle are 34 mm in diameter and have a ratio between aluminium alloy and steel of 3:1. All layers consist of conventional round-shaped wires. Any difficulties typical of bundled conductors have not yet been experienced. This example, too, proves the feasibility to string bundled conductors over long spans and adjust them pre-

Table 4 Conductors of some lines with long spans

Description	Country	Voltage kV	Number of circuits	Phase conductors	Span length m	Everyday stress N/mm^2	Everyday stress %	Diameter mm	Remarks
Elbe crossing I	Germany	220	2	AACSR 340/110	1140	79.4	17	28.1	
Schelde crossing	Belgium	380	2	AACSR 1396/246	1170	108.8	11	51.9	smooth surface
Severn crossing	Great Britain	275	2	AACSR 515/601	1618	245.2	27	43.0	
Thames crossing	Great Britain	400	2	ACSR 1300/680	1371	163.5	25	56.1	smooth surface
Fjord crossings	Norway	275	1	ACSR 766/97	1431	76.1	25	38.3	
	Norway	275	1	ACSR 770/318	2889	210.9	37	42.9	
	Norway	275	1	ACSR 772/558	4570	306.0	41	47.7	
Crossing over the St. Lawrence River	Canada	735	1	4 × AACSR 482/163	1585	154.0	25	33.0	
Natura crossing	Japan	187	1	AACSR 97/635	1716	425.6	30	35.2	
Elbe crossing II	Germany	380	4	4 × AACSR 564/72	1185	71.5	18	32.9	

cisely. There will be no trouble due to galloping or twisting of the bundles if the clearances between the individual conductors, as well as the components are properly selected.

Above all the comparison shows that the cross-section of the conductor selected for the Bosphorus crossing exceeds that of the conductors of the examples mentioned. In Europe, this size was used in a transmission line for the first time. The everyday stress amounting to only 20% of the ultimate strength seems to be conservative.

Manufacturing and testing of the conductors

The conductors for the Bosphorus crossing had to be manufactured and strung without a joint in individual continuous lengths of 3200 m. This requirement, very important for the reliability of the crossing, was again and again categorical emphasized by TEK. This may seem to be self-evident but it created a series of severe problems regarding manufacturing, transportation and stringing.

One continuous conductor length of 3200 m weighs 21 t, the reel necessary for transport and stringing is 3 m in width and 3 m in diameter. The stranding installation must allow the use and handling reels elling of such.

Stranding of aluminium alloy can only be carried out on machines which involve complete untwisting in order to avoid prestresses in the conductor. The stranding equipment must be capable of processing 40 wires simultaneously with each reel suitable for at least 3200 m of 4.05 mm diameter aluminium alloy wire with a total weight of 110 kg, since routine welding joints on the individual wires could not be tolerated.

All over the world only a few suppliers of transmission line conductors can meet these requirements. The Vereinigte Metallwerke Ranshofen-Berndorf AG, Werk Berndorf/Austria cooperated in the conductor design and supplied them. The outer aluminium alloy layers were stranded in the works of Kabelwerke Brugg AG, Brugg/Switzerland.

During manufacturing, comprehensive quality checks supplemented the thorough design in the case of this extraordinary instal-

Fig. 12 Conductor AACSR/AC1805/228 after loading to failure

lation. A 200 m long sample of the conductor was produced and tested comprehensively prior to approval of manufacturing of the whole batch. This sample was also used for the development and testing of the necessary fittings. Important conductor characteristics such as ultimate strength, modulus of elasticity and long-period behaviour under load (creepage) were measured on this specimen.

The tensile strength of the aluminium alloy wires used should be at least 315 N/mm^2, that of the aluminium clad steel wires 1370 N/mm^2. The theoretical ultimate tensile force was evaluated according to DIN 48203, Part 12, by

$$S_t = A_{Al} \cdot \sigma_{Al} + 0{,}9\, A_{Ac} \cdot \sigma_{Ac} \qquad (3)$$

where

A_{Al} Cross-section of aluminium alloy
A_{Ac} Cross-section of aluminium clad steel
σ_{Al} Tensile strength of aluminium alloy wires
σ_{Ac} Tensile strength of aluminium clad steel wires

and resulted in 847.5 kN. The actual final load of 852 kN measured in a tension test (**Fig. 12**) confirmed this value and exceeded the minimum requirements which were 95% of the theoretical ultimate capacity.

The tensile tests carried out on all wires before and after stranding showed an average strength of the aluminium alloy wires of 325 N/mm^2 and of 1470 N/mm^2 for the aluminium clad steel wires. The theoretical ultimate tensile force of the conductor evaluated from these mean values was 906 kN. The stranding caused a reduction of 6% which represents a value in line with experience attained from other measurements.

The initial loading of the conductor showed a modulus of elasticity of 63200 N/mm^2 whereas the final loading cycles resulted in a mean value of 71100 N/mm^2.

The testing of the behaviour of the conductor under load according to the everyday stress carried out over a period of 1000 hours allowed the extrapolation over a period of 50 years. A creepage elongation of about 0.7‰ can be expected during this period. However, a creepage elongation of 1‰ was allowed for in the conductor sagging to be on the safe side. The provisions for creep elongation have only a relatively low influence on the conductor sag and stresses.

Insulators and fittings

A large variety of components is necessary for suspending and terminating the conductors on the structures by means of insulator strings, for example suspension hinges for fixing of the insulators to the towers, joining fittings for the connection of the individual insulators in the insulator strings, arcing protection fittings, suspension clamps and tension clamps. Only those components which are directly connected with the conductors are treated here in detail.

Tension fittings were necessary to connect the conductors at the end of the crossing section by insulators to the tower structures. These fittings have to transmit the tensile force of the conductor which acts in the direction of the conductor. Additionally they may have to conduct the electric current depending on the design of clamp. Their task at the end of the conductor leads directly to the stipulation that they should have about the same failing strength as the conductor itself.

The conductors are fixed at the suspension towers in such a way that only forces resulting from dead weights and wind loads acting perpendicularly to the conductor occur during normal operation. But no forces act in the direction of the conductors. The suspension fittings have to withstand those forces but do not have to conduct the electric current.

Suspension fittings

Relatively simple suspension clamps are used to carry the conductors on towers in a straight line when erecting conventional transmission lines. The suspension sets can move in the direction of the conductors. Therefore, compared to dead-end sets only small forces can act in this direction. On these suspension clamps the conductors are guided in grooves which have to be shaped to suit the cross-section and the expected curvature of the contuctor. In most cases, these suspension clamps are connected to the insulator sets by a horizontal pivot. They will have sufficient mechanical strength if they can carry the loads due to dead-weight, ice and wind with sufficient reliability. The high vertical forces which occur in long spans and which lead to steep slopes of the conductor, however, produce a considerable curvature of the conductor and, therefore, additional mechanical stresses. This is especially true if the diameter of the conductor is unusually large as in the case in question. Simple suspension clamps behave unfavourably with respect to their reaction to aeolian vibration of the conductors. Vibration damage of individual strands of a conductor often occur within the clamps or in their vicinity. The design of the suspension set using suspended dead-ends as carried out in case of the River Elbe crossing [8] avoids such an unfavourable behaviour. If this suspension design is used the conductors will be fixed by dead-end clamps as in the case of conductor terminations. They are connected to the suspension insulators by straps and yoke plates. This type of suspension design does not create any additional stress due to conductor curvature and is suitable for any value of conductor deviation. It proves to be more advantageous in the case of aeolian vibration than the conventional suspension clamps.

This solution, however, was not suitable for the Bosphorus crossing. Since the selected conductor with five aluminium alloy layers can be terminated with a force corresponding approximately to its failing load only by fixing separately the aluminium clad steel core and the aluminium alloy layers with accordingly designed components. Such a dead-end clamp could only be installed by completely cutting the conductor, a procedure which would have violated TEK's basic stipulation, to install each conductor without a joint. However, both stipulations, namely to install continuous conductors and to use wedge-type tension clamps in order to obtain a suspension configuration which subjects the conductor to little stress and tends to suppress vibration, could be met for the River Elbe crossing [9]. For conductors used there wedge-type clamps can terminate the conductor with its failing strength [8]. Wedge-type clamps, however, cannot reach the capacity required for conductors with big diameters and more than three layers of aluminium alloy.

In cooperation with Richard Bergner GmbH & Co, Schwabach, who supplied the fittings for the Bosphorus crossing a suspension system using a custom-tailored suspension clamp was developed **(Fig. 13)**. The conductor is carried as on a saddle and passes through the clamp without being cut. The suspension clamp was designed mainly with respect to static requirements. The shape and the dimensions of the saddle resulted from the conductor data and the strain limits in the individual strands. The total strain should not exceed 2000 µm/m that means 0.2%. It consists of a static and a dynamic component, the latter caused by the aeolian vibrations.

Taking a modulus of elasticity of 60 kN/mm^2 as being valid for aluminium alloy a strain of 0.2% gives a tensile stress of 120 N/mm^2. About 110 N/mm^2 of this results from the tensile force in the conductor and the static bending , the rated

Fig. 13 Suspension set of the Bosphorus crossing with saddle-type clamp

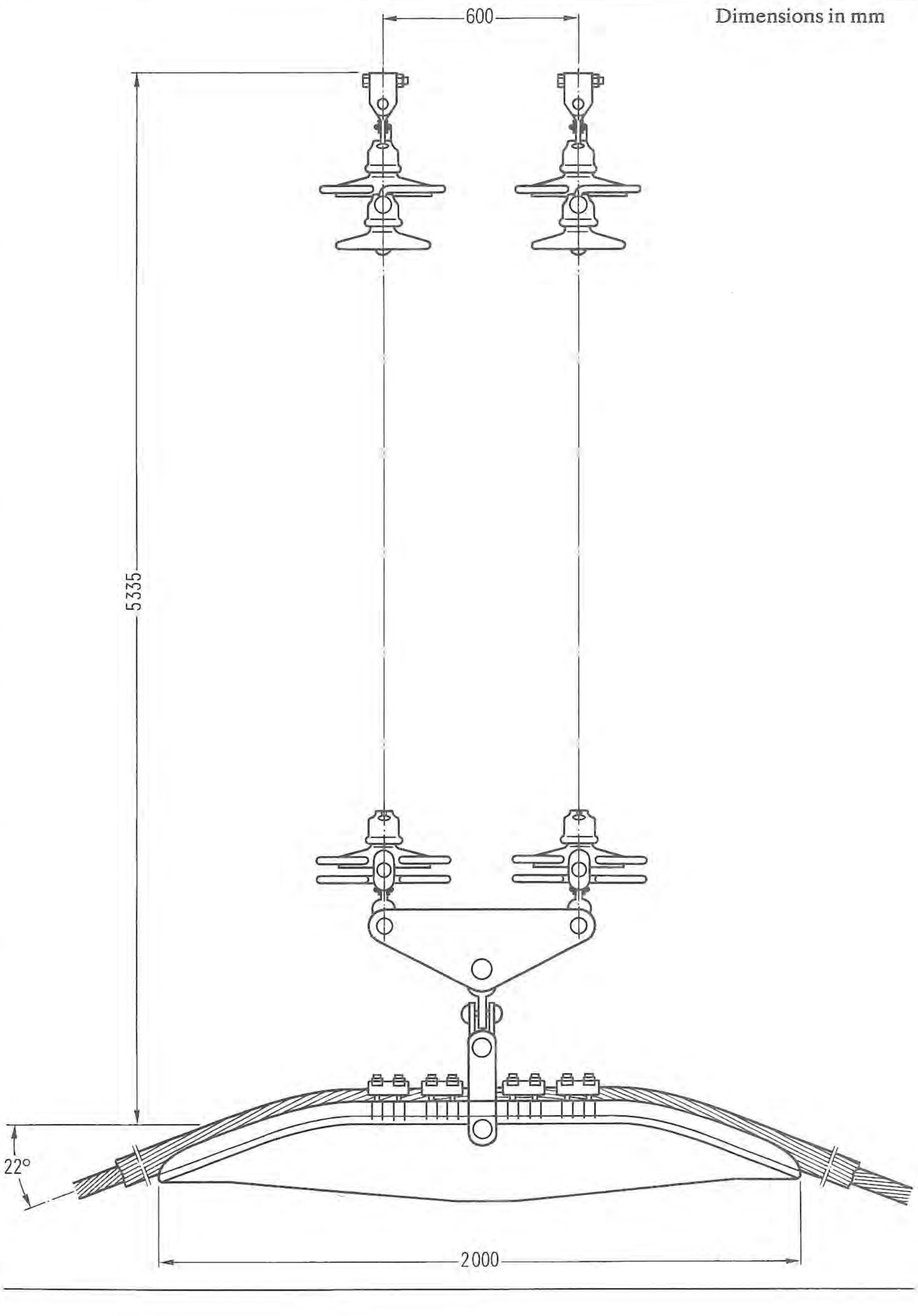


Fig. 14 Saddle-type suspension clamp installed

Fig. 16 Insulator sets at the suspension tower after completion of erection

tensile strength of the aluminium wires being 315 N/mm^2.

The angle between the tangent to the conductor axis and the horizontal reaches 18° at the suspension point of the conductor due to the sag and to the terrain conditions. To allow for additional vibration the clamp was designed for a slope angle of 22°.

The middle part of the saddle-type clamp is approximately 700 mm long and straight (**Fig. 14**). The ends are circular arcs with the stipulated radius of curvature and a length corresponding to the slope angle. Clamping pieces have been provided in the middle part which keep the conductor in place with a longitudinal force corresponding to one third of the maximum tensile force of the conductor under service.

The resultant of the vertical and horizontal loads amounts to 145 kN perpendicular to the conductor. 140 kN of this is due to the deadweight, including the ice load, and 35 kN to the wind load. To protect the conductors additionally in the vicinity of the suspension clamp, approximately 4 m long armor rods have been wound around the outer layer of the conductors (**Fig. 15**). The suspension clamp groove has a radius of 40 mm to suit the diameter of the conductors with armor rods installed.

The conductors are attached to the suspension towers using insulator sets consisting of two strings with 22 cap and pin type glass insulators F 30 (minimum failing load 300 kN) (**Fig. 16**). Out of the variety of electrical characteristics only the creepage distance which amounts to 9200 mm should be mentioned here. The creepage distance represents a measure for the capacity of the insulators to withstand the power-frequency operating voltage under pollution. The specific creepage path amounts to 22 mm/kV and copes with the requirements in an area prone to medium or heavy pollution [12].

All parts of the suspension sets were rated for a tensile force of 600 kN according to the failing load of the insulators. Therefore, sufficient safety compared with working loads is available. All components separately and the insulator set as a whole were tested mechanically. These tests demonstrated that the minimum failing load of a complete insulator set exceeds 600 kN. The insulators failed at a load of 715 kN and proved to be the weakest link. The clamping force in the direction of the conductor was found to be 160 kN which exceeded considerably the required minimum.

Fig. 15 Installation of armor rods

Dead-end fittings

In order to guarantee that the terminations of the conductors do not represent a weak link it is necessary that the fittings installed there can hold the conductors with approximately their failing load. Based on this condition it was stipulated for the dead-end clamp that it should keep the conductor with 90% of the conductor failing load over a period of one minute without damage either to the conductor or to the clamp. The 90% value means a force of 765 kN. Since the clamp must also conduct the electric current this requirement is difficult to meet. Detachable or non-detachable dead-end clamps are currently in use for transmission line conductors. Detachable clamps, for example wedge-type clamps, had to be excluded due to the large cross-section of the conductor and the required capacity. Nondetachable termination of the conductors by casting the end of the conductor into a metal cone as used on ropes for cableways could neither be adopted because the tensile strength of the aluminium alloy and, therefore, of the total conductor would have been reduced. The use of a compression-type clamp offered a practical solution. The compression-type clamp fixes and connects the aluminium clad steel core and the aluminium alloy layers separately by friction.

Figure 17 shows its design. A steel body provides the connections with the insulator sets. The aluminium clad steel core is directly connected to this steel body by being compressed in a sleeve. The aluminium alloy wires are indirectly connected by an aluminium alloy sleeve pushed over them. A lug welded onto the sleeve provides a current carrying connection to the jumper. Since a compression-type clamp for the conductor AACSR/AC 1805/228 was not available commercially, it had to be custom-tailored and to be thoroughly tested.

When designing the compression clamp care had to be taken of the fact that at a load of 90% of the ultimate strength of the conductor the aluminium clad steel core as well as the aluminium alloy layers reach the plastic range associated with considerable elongation. It is self-evident that the installation of the clamp was not to impair the strength of the conductor.

The stipulated force can only be obtained if the core and the aluminium alloy layers share their portion of load optimally. The aluminium clad steel core must be held with its failing load and the aluminium alloy layers must simultaneously carry their portion of load without slipping. The dimensions and strength of the sleeve which also transmit the current and the free section of the aluminium clad steel core had to be determined accordingly.

The total tensile force transmitted by the clamp is constituted by the force in the aluminium clad steel core F_{Ac} and the force in the aluminium alloy sleeve F_{Al}. The elongation of the aluminium clad steel core must be equal to that of the aluminium alloy sleeve due to the rigid bonding. Assuming that all wires of the conductor remain immovable up to the end of the compression sleeve the elongation of the aluminium clad steel core can only occur on its free section between the end of the aluminium alloy layers and the beginning of the sleeve at the steel body. The length of this free section of the aluminium clad steel core amounts to 120 mm. The part of the aluminium alloy sleeve which can be elongated freely, amounting to approximately 400 mm, is significantly longer. The dimensions and the strength of the aluminium alloy sleeve had to be so rated as to avoid premature failing of the aluminium clad steel core because of too large an elongation.

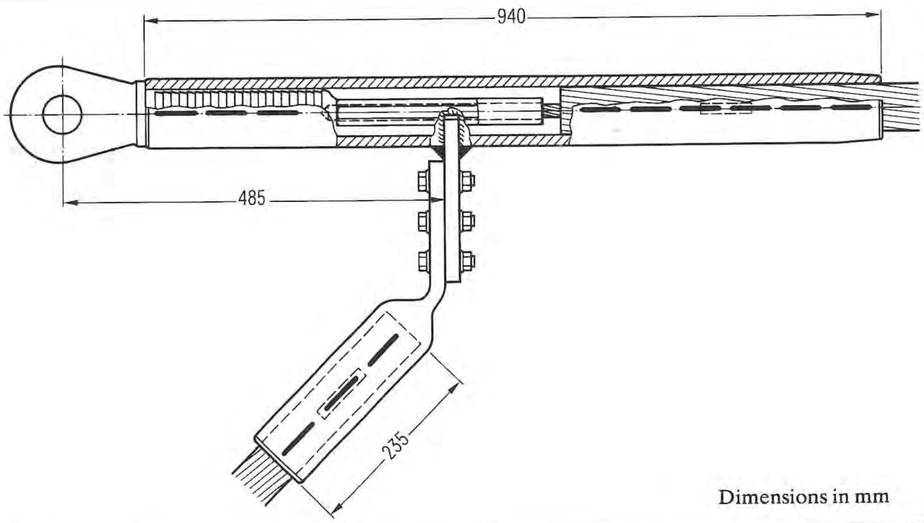


Fig. 17 Cross-section of the compression dead-end clamp

Fig. 18 Stress-strain diagram of the aluminium clad steel core

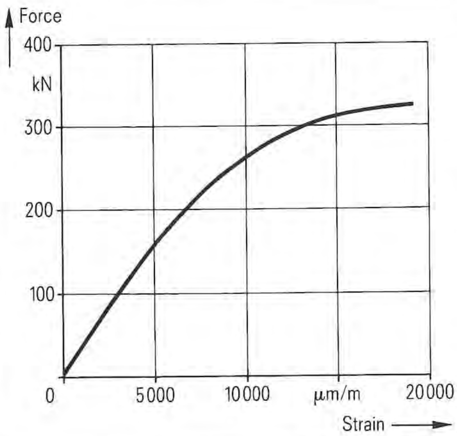
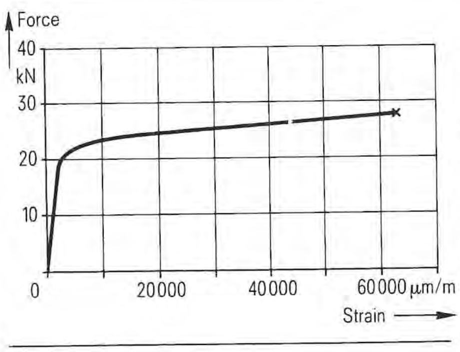


Fig. 19 Stress-strain curve of a test piece of the aluminium alloy sleeve



When treating the problem theoretically attention had to be paid to the fact that the aluminium clad steel core, as well as the aluminium alloy sleeve, work in the plastic range when the ultimate load is reached. The necessary relations between stress and strain were gained by measurements of the stress-strain curves of the aluminium clad steel core (**Fig. 18**) and of the material for the aluminium alloy sleeve (**Fig. 19**).

Theoretical considerations and practical tests resulted in a sleeve diameter of 86 mm and a wall thickness of 12 mm. The artificially ageing malleable aluminium alloy AlMgSil F 22 with a tensile strength of 220 N/mm^2 proved to be appropriate. The overall length of the clamp amounts to 1100 mm. The compression operations were carried out utilizing a press capable of 1500 kN compression force (**Fig. 20**). This commercially available press could have handled sleeves up to 90 mm diameter.

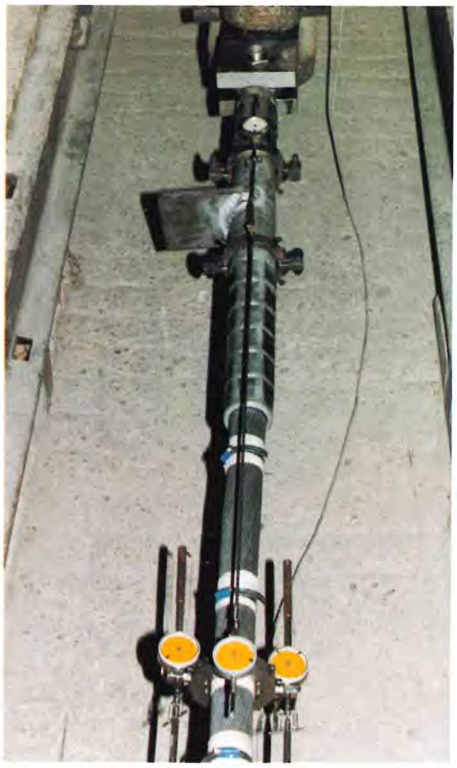
The tensile test (**Fig. 21**) of the clamp finally decided on demonstrated that the stipulated load of 765 kN could be held for one minute without disadvantageous effects either on the clamp or on the conductor. Aluminium alloy wires failed at a load of 818 kN at the end of the clamp. The failing load of the clamp was found theoretically to be 848 kN.

With the exeption of the tension clamp a minimum failing load of

Fig. 20 Pressing of the compression dead-end clamp, pressing force 1500 kN

1100 kN was required for the tension insulator set. This stipulation ensured that the insulator set would be designed for a higher load capacity than either the conductor or the tension clamp. The required minimum failing load and the electrical characteristics could be met by double strings utilizing twenty cap-and-pin-type glass insulators F 55 (**Fig. 22**), which have a minimum failing load of 550 kN and represent the strongest commercially available insulators. The electrical characteristics especially the specific creepage path agree with the data of the suspension strings. The cap-and-pin-type glass insulators failed at a total load of 1200 kN when the tension set was tested.

Fig. 21 Testing of the dead-end clamp



Vibration protection

Different types of vibration can be observed on transmission line conductors, the frequency of occurrence, the oscillation frequency and amplitude of which depend on the local conditions and the tensile stress. Conductor galloping due to aerodynamic instability because of ice load and simultaneously acting wind forces are the most spectacular. Amplitudes up to 12 m [13] have been observed at frequencies less than 1 Hz. This phenomenon is related to specific weather conditions and occurs relatively rarely. Up to now it is not possible to control conductor galloping by any damping devices. In order to take precautions against possible damage caused by this phenomenon all conductors were arranged horizontally and the clearances between them were chosen to exclude risks as far as possible.

Higher frequency vibration in a range between 5 and 50 Hz and with amplitudes up to the diameter of the conductor occurs more frequently than conductor galloping with large amplitudes. Aeolian vibration and its effects on transmission line conductors has gained extensive consideration in literature. An explanation of this phenomenon according to recent knowledge is given in [14].

If aeolian vibration lasts for longer periods fatigue failures of the aluminium or aluminium alloy strands and, therefore, deterioration of the conductors will be caused [15]. An enhanced risk of damage due to aeolian vibration exists in transmission lines over large wareas of water [16]. The conductors are situated relatively high above the water level and, therefore, are frequently prone to laminar wind flows. A fjord-like valley like the Bosphorus straits channels the wind and therefore, it frequently flows perpendicularly to the line. The risk of vibration failures additionally increases with diameter and tensile stress.

High tensile stress increases the frequency and intensity of vibration, as well as reducing the endurance capability [17]. The practically rigid fixing of the conductors in the described saddle-type clamp of the suspension sets raises the risk of vibration damage in the vicinity of the suspension clamps additionally.

For these reasons special attention had to be paid to the protection of the conductor against damage due to aeolian vibration. Appropriately designed damping devices reduce the vibration amplitudes and, therefore, the risk of failure. The conventional Stockbridge damper consists of two weights which hang on a steel rope and are clamped to the conductor by a special clamp. In principle, Stockbridge dampers act as resonance dampers. The friction in the steel rope converts mechanical energy into heat when moving and extracts it from the conductor which keeps motionless.

Non-ferrous materials do not have a sharp limit for the permissible alternating bending stress [17]. Therefore, vibration stresse can result in failures of components made of these metals if they continue for a long period. The risk of damage due to aeolian vibration in the case of aluminium and aluminium alloy wires will practically be very small if the strain of the wires does not exceed 150 μm/m [18]. Based on an extensive theoretical study five and three Stockbridge dampers were arranged on the conductors in the vicinity of the suspension clamps on the water side and on the land side respectively. The first one was arranged at a distance of three meters from the pivot of the clamp, the others follow at intervals of one meter. The high impedance of

Fig. 22 Dead-end insulator sets at the terminal towers

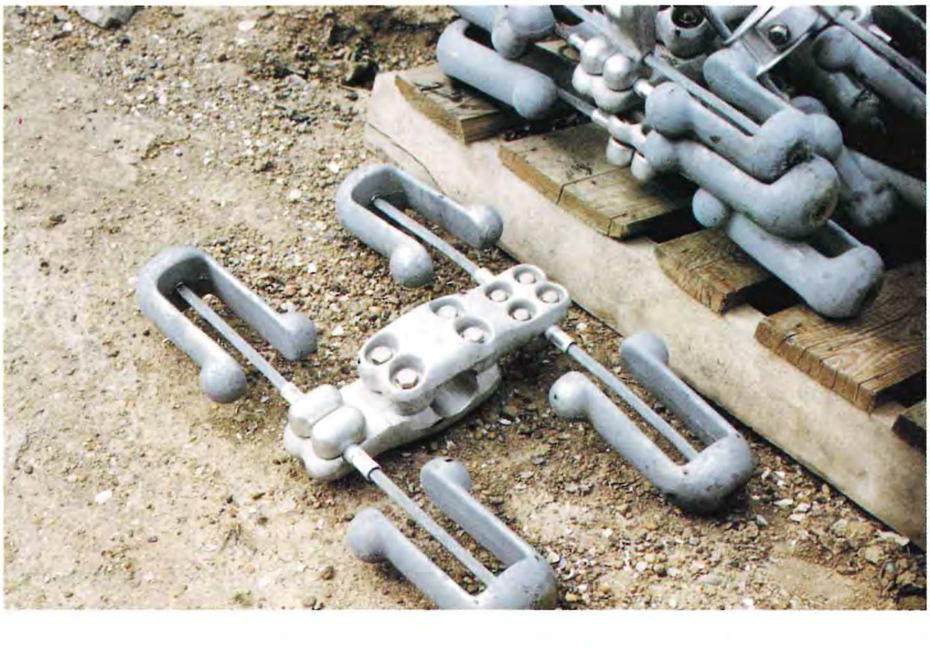
the conductor required a corresponding impedance of the dampers which, therefore, were designed with two pairs of weights (**Fig. 23**). The remaining strain of the conductor in the vicinity of the clamp was evaluated from the balance between the wind input energy and the damping energy of the conductor and the dampers.

Fig. 24 compares the vibration of the conductors with and without dampers. With an alternating bending strain of 600 µm/m without dampers the vibration stress level would have been extraordinarily high and would have caused damage within a short period. With dampers on the conductors, however, the strain within the significant section of the conductor keeps well below the mentioned limits.

Tests in the laboratory to demonstrate the qualification of the dampers could not be carried out due to the large diameter of the conductor. Therefore, vibration sensors were mounted on the conductors immediately after stringing. The measured data can be transmitted to a recorder installed at the tower base by cable since only one of the two circuits is in service initially.

In moderate winds extraordinarily intensive vibrations of the conductors were observed after stringing as had been originally feared in consideration of the conductor characteristics and the topographical conditions. However, after installation of the dampers the conductors remainds quite motionless, thus demonstrating the proper selection of the dampers. The measurements carried out since commissioning have confirmed the effectiveness of the protection measures.

Fig. 23 Damper for the phase conductor equipped with twin weights



Conclusion

In August 1982 the erection of the crossing started with foundation works [19]. The tower erection followed. The tension towers were able to be finished in autumn 1982, the progress of the erection of the suspension towers allowed commencement of conductor stringing [20] right on schedule in June 1983.

In order to close the shipping lane of the Bosphorus for only as short a period as possible a method of stringing twin service ropes by one service rope using a running board was adopted. In contrast to the method used for example for conductor stringing on the river Elbe crossing [21], only one service rope for each circuit was hauled from the drum site in Anatolia and from the winch site in Europe over the earth wire peaks of the suspension towers to each bank of the Bosphorus before closing of the waterway for navigation.

During closing of the shipping lane for three hours on July 19th 1983, two tugs hooked up the service ropes at the banks, pulled them to the centre of the waterway and connected them to each other. All vessels were able to resume navigation after the ropes had been tensioned as far as to provide sufficient clearance. All further stringing operations did not hinder navigation in the Bosphorus.

Each of the two service ropes pulled two identical ropes from the drum site to the winch site using a running board. One of these service ropes served the purpose of transferring a pilot rope from the drum site to the winch site while the other was used to start the stringing operation for the following phase conductor.

This method ensured a permament rope connection between winch and drum site on each circuit. A non-twisting three-strand swaged steel rope 25.4 mm diameter and a failing load of 600 kN was used to haul the phase conductors. At first, this pulling rope was hauled from the winch site to the drum site using a pilot rope and then connected there to the conductor by a temporary working clamp (**Fig. 30, Page 22**) which was designed identically to the tension clamp described above.

After stringing of each individual conductor the tension clamp on the winch site conductor end was installed on the ground without difficulties. Then, the conductor was bolted to the tension insulator set and precisely sagged.

Finally it was able to be terminated at the winch site end, too. The installation of the armor rods and the saddle-type suspension clamp on the suspension towers followed taking advantage of tandem-arranged travellers.

The conductor stringing was completed right on schedule at the end of October 1983 confirming the proper selection and design of insulator sets and clamps and proving the effectiveness of the dampers. **Fig. 25** shows the suspension towers of the crossing with the conductors installed.

Fig. 24 Vibration strain of the conductor AACSR/AC1805/228 with and without dampers

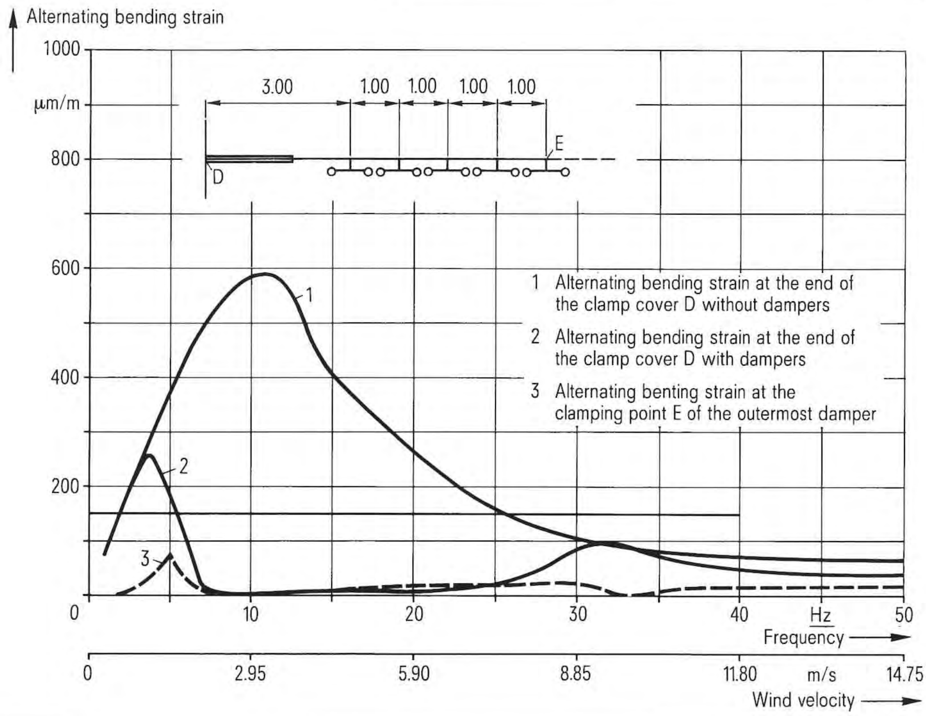


Fig. 25 Tension tower of the crossing with the phase conductors strung

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