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RESEARCH ARTICLE - CIVIL ENGINEERING

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Carbon Fiber Reinforced Polymer Cables: Why? Why Not? What If?

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Abstract Cables of suspended structures are suffering due to increased corrosion and fatigue loading. Since 1980, EMPA and BBR Ltd. in Switzerland have been developing carbon fiber-reinforced polymer (CFRP) parallel wire bundles as cables for suspended structures. The excellent properties of those bundles include corrosion resistance, very high specific strength and stiffness, superior equivalent moduli and outstanding fatigue behavior. An anchoring scheme produced with gradient materials based upon ceramics and epoxy is described. For the first time, large CFRP cables were applied in 1996 on the vehicular cable-stayed Stork Bridge with 124 m span in Winterthur, Switzerland. The performance of these cables and later applications was and still is monitored with sophisticated fiber-optical systems. Up to date, these results are fully matching the high expectations. Under the assumptions that (1) the behavior of the pilot applications of CFRP cables described in this paper will be further on fully satisfactory, (2) active systems for distributed mitigation of wind-induced vibrations are going to be successful and (3) there is a need for extremely long-span bridges to cross straits like that of Bab el Mandeb, Messina, Taiwan or Gibraltar, why should the next generation of structural engineers not use CFRP cables for such extremely long-span bridges? This would open spectacular new opportunities.

Keywords Carbon fiber · CFRP · Parallel wire bundle · Cable · Anchorage system · Gradient materials · Pultrusion · Limiting span

الخلاصة

إن كوابل التراكيب المعلقة هي تحت المعاناة نتيجة لزيادة التآكل و حمل التعب . لقد قامت منذ قامت شركتا EMPA و BBR المحدودتان في سويسرا عام 1980 بتطوير حزم أسلاك مبلمرات ألياف الكربون المدعمة (CFRP) المتوازية ككوابل للهياكل المعلقة ، حيث كانت الصفات الممتازة لهذه الحزم تتضمن مقاومة التآكل والمتانة والصلابة المحددة المرتفعتين والوحدة المكافئة المتوفقة وتصرف التعب المتميز. وقد تم توصيف مخطط رسو ناتج مع مواد متدرجة أساسها السيراميك و الإيبوكسي. وتم لأول مرة تطبيق كوابل CFPR كبيرة في عام 1996م في جسر ستورك المعلق بالكوابل للسيارات مع امتداد 124 مترا في وينتثر بسويسرا. وكان التحكم وما يزال في أداء هذه الكوابل وتطبيقاتها المتأخرة يتم بأنظمة ألياف ضوئية متطورة. وإلى هذه الأيام فإن التنائج تطابقت كليا مع التوقعات المرتفعة بوجود ثلاث فرضيات: الأولى: إن سلوك التطبيقات التجريبية لكوابل CFPR الموصوفة في هذه الورقة العلمية هو مرضٍ تماما. الثانية: سوف تكون الأنظمة النشطة الموزعة للتخفيف من الاهتزازات الناتجة عن الرياح ناجحة . أما الفرضية الثالثة فتتمثل في أن هناك هناك حاجة لجسور ممتدة بشكل كبير لتعبر مضائق مثل: باب المندب وميسينا وتايون أو جيبرلاتر. إذاً لماذا لايستخدم الجيل الجديد من مهندسي البناء كوابل CFPR للجسور الممتدة بشكل كبير؟ سوف يفتح هذا الأمر فرضيات جديدة مذهلة.

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1 Why?

1.1 Introduction

Today's state of the art in cables for civil structures is the accumulation of past innovations. Much has been reached. However during the past 30 years, the bridge engineering community has experienced more and more damage on stay and hanger cables [1,2]. Cables are suffering due to increased corrosion and fatigue loading. Within the last few years, even more and more corrosion damage has been discovered on large main cables of suspension bridges [3]. Most bridge engineers seem to agree that the corrosion and fatigue resistance of cables for suspended structures have to be enhanced.

Researchers proposed already decades ago modern approaches using non-metallic, which means non-corrosive, materials in civil construction [4–7]. The introduction of carbon fiber-reinforced polymers (CFRP) instead of steel for cables has since 1982 been proposed in [8]. From the lifetime point of view, studies indicated superior results for carbon fiber composites compared to aramid or glass. It was found that the future potential of carbon fibers is highest [9]. The purpose of the following EMPA R&D work was to develop an anchorage system capable of successfully handling the huge potential of CFRP wires, to achieve a high reliability of parallel wire bundles made of such advanced composites and to apply it in pilot projects.

1.2 Carbon Fibers

The ideal construction materials are based on the elements found principally toward the middle of the periodic table. These elements, including carbon, form strong, stable bonds at the atomic level. Materials held together by such bonds are rigid, strong and resistant to many types of chemically aggressive environments up to relatively high temperatures. Furthermore, their density is low and raw materials are available in almost unlimited quantities. Carbon fibers are made by carbonizing an organic polymer yarn with a fiber diameter in the 5- to 10-μm range. The fibers mostly used within the projects described in the following sections were the Torayca T700S having a strength of 4,900 MPa, an elastic modulus of 230 GPa and an elongation at failure of 2.1%. The density is 1.8 g/cm^3. The axial thermal expansion coefficient is approximately zero.

The carbon fiber dates back to 1879. The inventor, Thomas Edison, used carbon fibers as filaments for early electrical light bulbs.

1.3 CFRP Wires

An advanced composite material built up of parallel fibers and a matrix might seem unnecessarily complicated at first sight. Why not simply take a solid carbon rod for the parallel wire bundle of a cable? Carbon would be, as was pointed out above, a very rugged material having the outstanding properties shared by elements from the middle of the periodic table. Such materials have however seen little use as structural materials in the past due to their extremely brittle behavior. A fine notch at the surface or a small flaw within the bulk can lead to a sudden, premature and catastrophic failure of a structural element made of such a material. Considerations of the atomic structure and statistics show that the strength of carbon can be greatly increased and made highly reliable in the form of fibers.

Furthermore, the crack in a composite wire does not propagate as suddenly as in a solid body. A flaw in a fiber does not inevitably lead to the failure of a structural element. When a fiber is embedded in a polymer matrix, it can take up full load again a short distance away from a crack. For these reasons, CFRP wires are very reliable.

Carbon fiber-reinforced polymer wires are produced by pultrusion, a process for the continuous extrusion of reinforced polymer profiles. Rovings are drawn (pulled) through an impregnating bath with epoxy resin, the forming die, and finally a curing area. The fibers have a good parallel alignment and are continuous (endless up to 4 km or even more). The fiber volume content of the wires used for the described projects was in the range of 68–72%. The axial properties of a CFRP wire (modulus, strength) can simply be calculated with the rule of mixture. Measured properties are listed in Table 1. The wires used in this project have a diameter of 5 mm.

Table 1 Properties of wires pultruded of T700S fibers

Tensile strength (longitudinal)	3,300	MPa
Elastic modulus *E* (longitudinal)	165	GPa
Density	1.56	g/cm^3
Fiber content	68–72	Vol %
Thermal expansion (longitudinal)	0.2×10^{-6}	m/m/°C

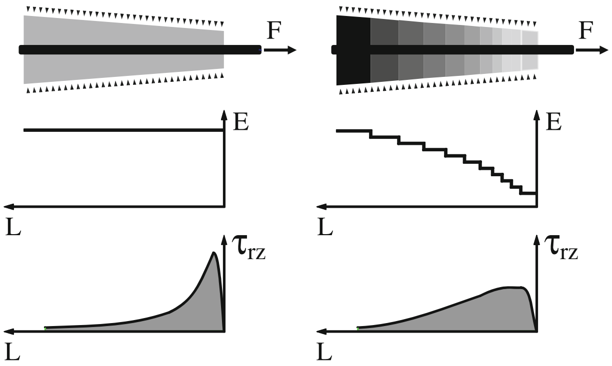

Fig. 1 Stress buildup in LTM

1.4 CFRP Cables

The cables are built up as parallel wire bundles. The principal objectives are minimal strength loss of the wires in a bundle as compared to single wires. Since CFRP wires are corrosion resistant, no corrosion inhibiting compound or grout is required. However, it is still necessary to protect the wires against wind erosion and ultraviolet radiation attack, because the combination of these two attacks could degrade the wire surfaces. A polyethylene (PE filled with carbon black) pipe was used for adequate shielding. Such pipes are very successfully applied to shield parallel wire bundles made of steel since 1972. The resistance against outdoor weathering including UV radiation is at least in Western Europe excellent.

1.5 The Anchorage of CFRP Cables

The key problem facing the application of CFRP cables and thus the impediment to their widespread use in the future is how to anchor them. The outstanding mechanical properties of CFRP wires mentioned above are only valid in the longitudinal direction. The lateral properties including interlaminar shear are relatively poor. This makes it very difficult to anchor CFRP wire bundles and obtain the full static and fatigue strength.

The EMPA has been developing CFRP cables using a conical resin-cast termination. The evaluation of the casting material to fill the space between the steel cone (in future it will be a filament-wound CFRP cone) of the termination and the CFRP wires was the key to the problem. This casting material, also called load transfer media (LTM) has to satisfy multiple requirements: (1) the load should be transferred without reduction of the high long time static and fatigue strength of the CFRP wires due to the connection; (2) galvanic corrosion between the CFRP wires and the steel cone of the termination must be avoided. It would harm the steel cone. Therefore, the LTM must be an electrical insulator.

The conical shape inside the socket provides the necessary radial pressure to increase the interlaminar shear strength of the CFRP wires. The concept is demonstrated in the Fig. 1 left and right using for this example a one-wire system. If the LTM over the whole length of the sockets is a highly filled epoxy resin, there will be a high shear stress concentration at the beginning of the termination on the surface of the CFRP wire (Fig. 1, left). This shear peak causes pullout or tensile failure far below the strength of the CFRP wire. One could avoid this shear peak by the use of unfilled resin. However, this would cause creep and an early stress rupture. The best design is shown in Fig. 1, right. The LTM is a gradient material. At the load side of the termination, the modulus of elasticity is low and continuously increases until reaching a maximum.

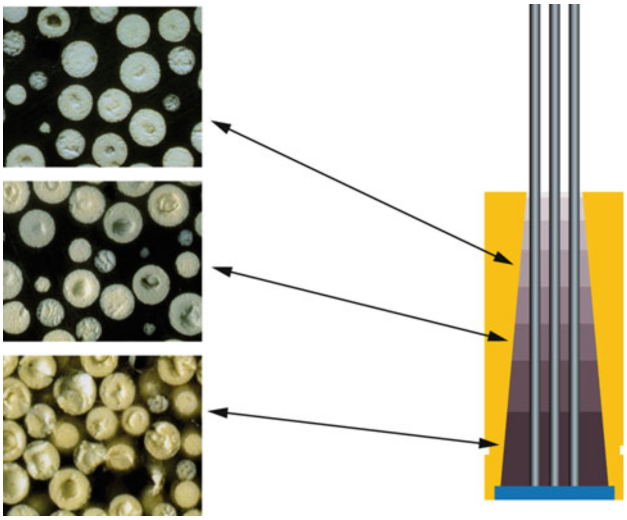

Fig. 2 Gradient anchorage system for CFRP wires

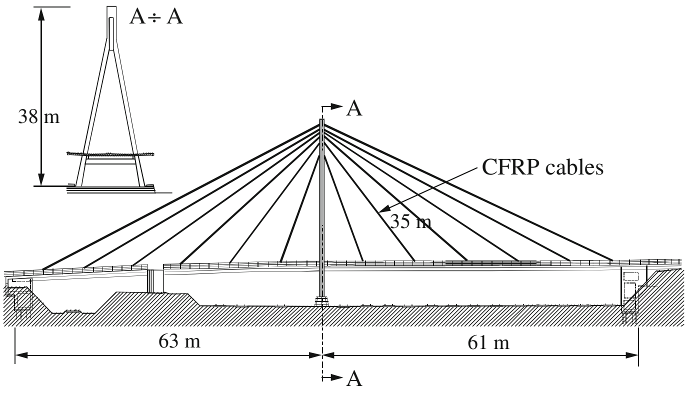

Fig. 3 Stork Bridge in Winterthur, Switzerland with CFRP stay cables

The LTM is composed of aluminum oxide ceramic (Al_2O_3) granules with a typical diameter of 2 mm. All granules have the same size. To get a low modulus of the LTM, the granules are coated with a thick layer of epoxy resin and cured before application (Fig. 2, left, top). Hence, shrinkage can be avoided later in the socket. To obtain a medium modulus, the granules are coated with a thin layer. To reach a high modulus, the granules are filled into the socket without any coating (Fig. 2, left, bottom). With this method, the modulus of the LTM can be designed tailor-made. The holes between the granules are all filled by vacuum-assisted resin transfer molding with epoxy resin.

The concept of a termination is shown on the right side of Fig. 2. Many CFRP parallel wire bundles were tested at EMPA in static and fatigue loading. The results prove that the anchorage system described is very reliable. The static load carrying capacity generally reaches 92% of the sum of the single wires. This result is very close to the theoretically determined capacity of 94% [10]. Fatigue tests performed on cables at EMPA showed the superior performance of CFRP under cyclic loads [9]. The anchorage system is patented [11]. The BBR Systems Ltd. in Schwerzenbach-Zurich got from EMPA an international license.

1.6 Stork Bridge in Winterthur: CFRP Stays—A Milestone in Bridge Construction

The Stork Bridge, erected in 1996, is situated over the 18 tracks of the railroad station in Winterthur and has a central A-frame tower supporting two approximately equal spans of 63 and 61 m (Fig. 3). The cables that converge at the tower top are rigidly anchored into a box anchorage at the apex of the A-frame. The superstructure has two principal longitudinal girders (HEM 550, Fe E 460) spaced at 8 m and supporting a

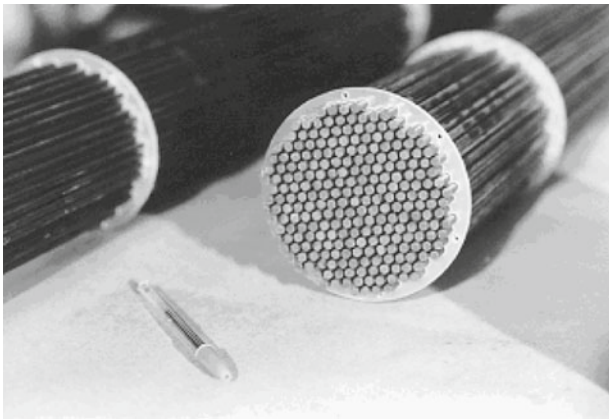

Fig. 4 CFRP Cables of 12 MN load capacity

reinforced concrete slab. At the anchorage points of the stay cables, there are cross girders (IPE 550, E 355). Longitudinal girders and concrete slabs are connected with shear bolts and work as composite girder system.

The CFRP cable type (Fig. 4) used for the Stork Bridge consists of 241 wires each with a diameter of 5 mm. This cable type was subjected to a load three times greater than the permissible load of the bridge for more than 10 million load cycles. This corresponds to a load several times greater than that which can be expected during the life cycle of the bridge.

The two CFRP cables with their anchorage and the neighboring steel cables have been equipped by the EMPA with conventional sensors and also with state-of-the-art glass fiber-optical sensors, which provide permanent monitoring to detect any stress and deformation. This arrangement also permits a comparison between theoretical modeling and the reality of a practical application.

This development project was promoted by the CTI, Commission for Technology and Innovation of the Swiss Federation, to strengthen world-wide confidence among bridge engineers in cables made from carbon fiber-reinforced polymers and thus to create a leading role for the Swiss industry in the field of stay cables.

The cable-stayed Stork Bridge will certainly be a milestone in international bridge construction, because CFRP cables do not simply have excellent behavior with regard to corrosion and fatigue, but are also five times lighter than steel cables with even higher strength properties. This high strength with low weight will permit us to build bridges in future with considerably longer spans than are currently possible, as will be discussed in the last chapter.

The use of CFRP in a pilot project requires long-term structural health monitoring to gain finally confidence for this modern class of materials. Structural safety and change in structural behavior of these materials are of great interest, especially because long-term experience in application is missing. Clear statements about health condition are only possible with reliable sensors and data acquisition. Forces, stresses and deformations are often monitored by strain measurements. In this case, the strain of the CFRP cables was measured using sensing systems based on fiber-optic Bragg gratings (FBGs) and electrical resistance strain gauges (RSGs) due to their high resolution, low drift and high reliability [12]. The redundant use of sensors not only increases the reliability of the measurements, but also allows drawing conclusions about the actual reliability and measurement uncertainty of the sensing systems. In conjunction with the applications, also appropriate sensor lifetime testing is performed.

Fiber-optic Bragg gratings were surface adhered to loaded wires and to dummy wires used for temperature compensation. In contrast to the Stork Bridge, all BG sensors were embedded in the CFRP wires during the industrial pultrusion process 2 years later at the Kleine Emme Bridge near Lucerne. Some FBGs were pre-strained on dummy wires (not loaded) to a level of 2,500 μm/m to monitor creep due to delamination of the fiber coating or the epoxy adhesive. The load on the CFRP wires is moderate and corresponds to an average strain of about 1,200 μm/m. The sensor system is operational since April 1996 without any reliability problems.

Important information about the reliability of the fiber-optical monitoring data on the Stork Bridge can be derived from the FBGs on the so-called dummy wires. Four of the seven FBGs per cable are installed on unloaded wires for both, temperature compensation and creep monitoring. The temporal strain evolution of the

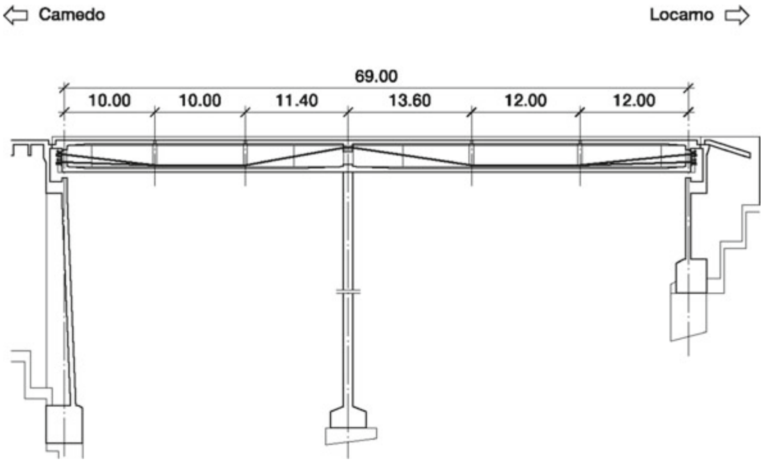

Fig. 5 Elevation of Verdasio Bridge, all measurements are in meters

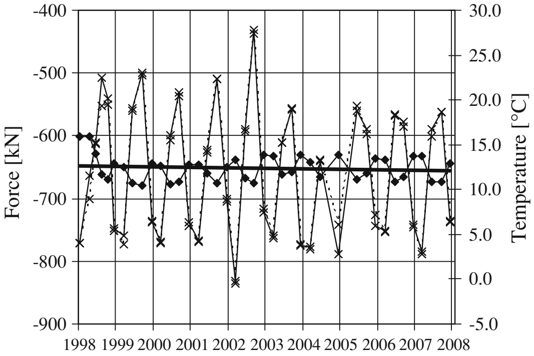

Fig. 6 Measurement of the post-tensioning force on a CFRP cable anchor head versus time at the Verdasio Bridge. Sustained stress: 1,610 MPa. The line connecting the rhombus points (*diamonds*) represents the force. The *solid horizontal line* is the corresponding trend line. There is no stress relaxation. The *line* connecting the *crosses* represents the temperature fluctuations

pre-strained FBGs corresponds to that of the unstrained FBGs. In any case of slippage or creep, the pre-strained FBGs would show a negative drift tendency. This result confirms the faultless operation.

The most important measurements are those of the relative displacement between the anchorage cones of the terminations and the load transfer media (LTM). As expected, there is a relative displacement due to creep in function of time. However, all displacement curves show clear signs of leveling out. These results fully match the earlier high expectations.

1.7 The Verdasio Bridge in the South of Switzerland

The Verdasio Bridge (Fig. 5) in the south of Switzerland is a two-lane highway bridge and was built in the 1970s. The length of the continuous two-span girder is 69 m. A large internal post-tensioning steel cable positioned in a concrete web was fully corroded as a result of the use of salt for deicing. It had to be replaced in December 1998.

The refurbishment of the Verdasio Bridge represented the first attempt to make practical use of the results of extensive experiments performed in the 1990s on continuous two-span beams post-tensioned with CFRP cables. Smooth wires were, however, used in place of the CFRP strands described in [13], with the same anchorage system as described above. Four external CFRP cables arranged in a polygonal layout (Fig. 5) at the inner face of the affected web inside of the box replaced the corroded steel cross section. Each cable was made up of 19 pultruded CFRP wires with a diameter of 5 mm. Here too, the cables are equipped with sensors to measure the post-tensioning force.

The main problem in this application was to tension the cable around relatively tight bending radii of 4.5 m, as CFRP wires are sensitive to transverse pressure due to their composition. However, a series of as yet

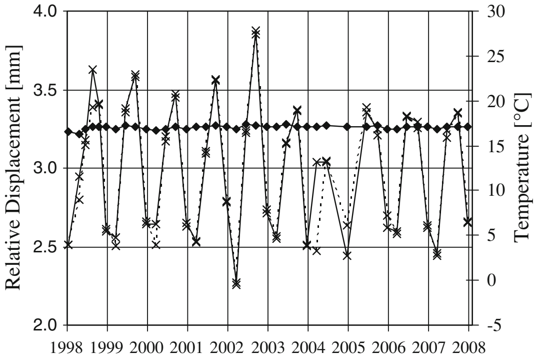

Fig. 7 Measurement of the relative displacement between the anchorage cone and the load transfer media according to Fig. 2 versus time for the same anchor head as in Fig. 6. The *line* connecting the *crosses* represents again the temperature fluctuations

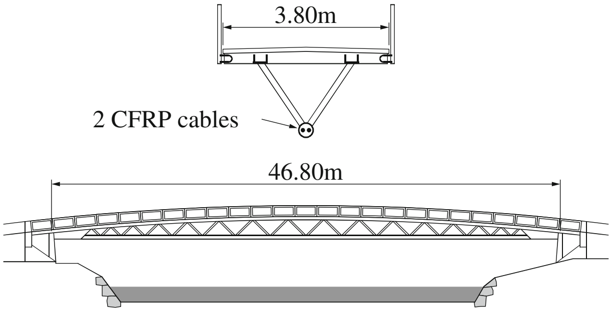

Fig. 8 Cross section and elevation of the "Kleine Emme" bridge

unpublished EMPA experiments with 3.0 m radii suggest that a satisfactory solution was found to this problem in Verdasio.

Also in the case of this bridge, the relative displacement within the anchorages and the cable load in function of the time were measured. This project was as far most interesting as in this case the nominal post-tensioning stress on the cable cross sections is as high as 1,610 MPa. The main questions were about stress relaxation (Fig. 6) and relative displacement (Fig. 7) due to this high sustained loading. The long-term results demonstrate also in this case that the relative displacement in the anchorage is also under this high creep load leveling off. There is also no stress relaxation in the CFRP wires.

1.8 The "Kleine Emme" Bridge Near Lucerne

The bicycle and pedestrian single span bridge (Fig. 8) crossing the River "Kleine Emme" near Lucerne was built in October 1998. The bridge deck is 3.8 m wide, 47 m long and is designed for the maximum load of emergency vehicles. The superstructure is a space truss of steel pipes in composite action with the steel rebar reinforced concrete deck. The bottom flange, a tube of 323-mm diameter, was post-tensioned with two CFRP cables inside the tube. Each cable was built up with 91 pultruded CFRP wires of 5-mm diameter. The post-tensioning force of each cable is 2.4 MN. Therefore, the CFRP wires are loaded with a sustained stress of 1,350 MPa.

This project saw the first ever use of CFRP wires with integrated fiber-optic Bragg gratings (FBGs) for this kind of application. The continuous monitoring and optimization of future production processes for high-grade CFRP wire will obviate the need for time-consuming final quality checks. Where the projected application requires incorporation of sensors in the CFRP wires, these may be integrated at the production stage for process monitoring. For the bridge over the Kleine Emme, "endless" optical fiber sensors with Bragg gratings have been incorporated in the CFRP wires during the continuous pultrusion process. The strain and temperature signals from the sensors were monitored and analyzed already during production.

The parallel wire bundles were produced in Dubendorf by EMPA and BBR, wound onto 2.5-m-diameter reels and transported to the bridge site in Emmen. Since October 1998, these cables have tensioned the bottom chord of the new bridge over the Kleine Emme River. The sensors used for process monitoring during production now serve to monitor cable strain and thus the post-tensioning force in the bottom chord.

Also in the case of this bridge, the relative displacement within the anchorages and the cable load in function of the time were measured. This project was as far also interesting as in this case the nominal post-tensioning stress on the cable cross sections is 1,350 MPa. Main questions were also here about stress relaxation and relative displacement due to this high sustained loading. The results give proof that the relative displacement in the anchorages also in this case is leveling off and there is no stress relaxation.

1.9 The Dintelhaven Bridge in Rotterdam

In order to stimulate the application of fiber-reinforced plastics in civil engineering structures in the Netherlands, in April 1994 the Preliminary Advisory Committee PC97 was established under the auspices of The Centre for Civil Engineering Research and Codes (CUR). The goal of the committee was to render an account about the feasibility of a pilot project with the application of FRP reinforcing elements in concrete. In April 1996, the Civil Engineering Division of the Dutch Ministry of Transport and Public Works proposed the application of a limited number of external Carbon FRP (CFRP) pre-stressing elements in the Dintelhaven Bridge in the Harbor of Rotterdam. For guiding the activities involving the project, in November 1996 CUR Research Committee C97A was established.

The Dintelhaven Bridge consists of two concrete box girders in the harbor of Rotterdam. The three span continuous girder, in which the CFRP pre-stressing elements have been applied, has a main span of almost 185 m and has been erected by using the balanced cantilever method.

Four CFRP cables with a length of 75 m are pre-stressed at a load of 2.65 MN each. The location is in the negative moment zone above the supports. The cross sections of the cables and the materials are the same as described above in the case bridge over the “Kleine Emme”. The TNO-Report [14] concludes: (1) The pre-stressing elements were assembled successfully. Besides some difficulties related to the quality and the length of the wires, no irregularities were detected. (2) From the evaluation it was found that most problems that have occurred during the installation of the elements in the bridge were attributed to the novelty of the material. It is expected that if CFRP is used more frequently, additional protections when using the material will become more common. (3) From the measurements during and after tensioning of the pre-stressing elements in the Dintelhaven Bridge, it was found that the anchorage settlements, as well as the load development in time, was comparable to the long-term experiments performed in the laboratory. (4) Despite the fact that the behavior of the pre-stressed CFRP elements was as expected, it is recommended to continue the measurements in the bridge as long as possible (even after completion of the bridge).

1.10 Another Advantage of CFRP Cables

Carbon fiber-reinforced polymer cables have a very high specific strength and stiffness, do not corrode, show outstanding performance under fatigue loading, do not relax, do not suffer stress corrosion and are very lightweight. Light weight is on one hand a great advantage for the stiffness performance of long stays and on the other hand for extremely long-span bridges (will be discussed later). The stiffness of a cable-stayed bridge depends largely upon the tensile stiffness of the stay cables. The displacement of the end of a free-hanging stay cable under an axial load depends not only on the cross-sectional area and the modulus of elasticity of a cable, but to a certain extent on the cable sag, as described in [15]. The relative equivalent modulus of elasticity E_e/E, of a cable is defined as:

$$\frac{E_e}{E} = \frac{1}{1 + \frac{(\rho l)^2}{12\sigma^3} E} \tag{1}$$

where E_e is the equivalent modulus, E the modulus of elasticity, l the horizontal span of the cable, ρ the density of the cable material and σ the applied cable stress. Figure 9 gives a comparison between steel and CFRP stays.

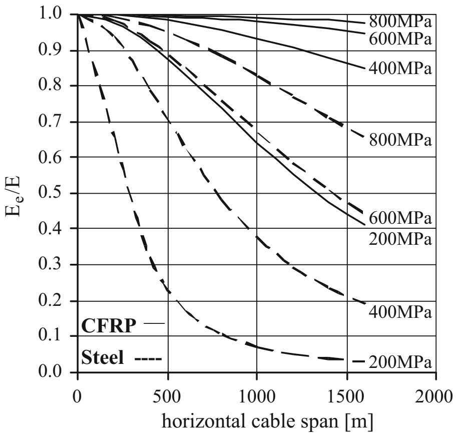

Fig. 9 Relative equivalent modulus of elasticity E_e/E versus the horizontal cable span for CFRP and steel cables according to Eq. 1. The applied cable stress is given as a parameter. The constants are: E_{steel} = 210 GPa; E_{CFRP} = 165 GPa; ρ_{steel} = 7.8 t/m^3; ρ_{CFRP} = 1.6 t/m^3

1.11 Conclusion for the State of the Art

Steel hanger cables of suspension bridges are regularly replaced throughout the world. Stay cables, post- and pre-tensioning cables made of steel, have caused very high maintenance costs in the past 30 years. Many of such cables are in need of replacement. There is no doubt that from the technical standpoint, CFRP is today the best suited material for such cables. However, since initial cost is the major and often the only parameter used by bridge owners in decision making, it is very difficult for CFRP to compete against steel. Even if the carbon fiber price would decrease further within the next few years, it will be very difficult for CFRP cables to compete unless the entire life cycle of a bridge is considered in the costs.

A few clients for bridge cables such as some departments of transportation increasingly require more and more life cycle costing to be carried out. This takes into account the predicted inspection and maintenance costs over the lifetime of the bridge, usually taken as 100 years. Costs are evaluated by calculating the net present value of the expenditure stream using a cash discount rate of typically 6% [16]. CFRP cables benefit considerably compared with steel in such comparisons.

The most important factor to remember is not the cost per kilogram of materials, but rather the cost effectiveness of the installed cables considering the life expectancy and the cost of the alternatives. This has worked to the advantage of the CFRP strip and sheet bonding technique for rehabilitation of structures [17,18] and there is a high probability that this will also be the case for CFRP cables in the future.

2 Why Not?

As mentioned above, much has been reached. However, if we do not go forward, we go backward. As engineers, we must be innovative, so that tomorrow's world will be better. Innovation starts with the questions "Why?" as shown in the chapter above and "Why not?" The question "Why?" gave us the opportunity to challenge the status quo. The question "Why not" taps into a new emphasis on rather old-fashioned kind of civil engineering ingenuity. Think, for example, about the Great Pyramid of Giza, the Pantheon in Rome, the Roman aqueducts and the Brooklyn or the George Washington Bridge. Many of our "why-nots" are counterintuitive—or maybe we should say temporarily counterintuitive. Ideas that never before occurred to us often reveal and explain themselves with as little as a single question like "Why not carbon fiber-reinforced polymer (CFRP) cables?"

Let us assume that the behavior of the pilot applications of CFRP cables described in the previous chapter is further on fully satisfactory and there is a need for extremely long-span bridges to cross straits like that of Bab el Mandeb, Messina or Gibraltar. Why should the next generation of structural engineers not use CFRP cables? This would open spectacular new opportunities.

It has been shown in a feasibility study already in 1987 [19] that from a static point of view, which means not considering the dynamic wind loading, a crossing of the strait of Gibraltar at its narrowest site with a suspended bridge of a center span of 8,400 m seems viable.

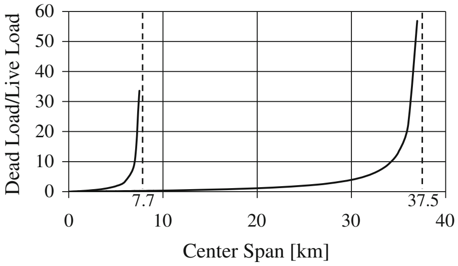

Fig. 10 Specific design loads versus main span for the classical form of suspension bridges. The limiting span for steel constructions is 7.7 km that for CFRP 37.5 km

Table 2 Assumptions for the calculation of the graph in Fig. 10

Type\property	$\sigma_{\text{allowable}}$ (MPa)	Density ρ (kg/m^3)	Systems coefficient α (m/s^2)
Steel cables	1,000	7,800	1.66
CFRP cables	1,000	1,600	1.66

Table 3 Examples for specific design loads

Bridge	Center span, ℓ (m)	Specific design load, g/p	
		Steel	CFRP
Verrazano narrows	1,300	0.5	0.04
Messina	3,000	2.0	0.06
Gibraltar	8,400	∞	0.29

2.1 Multiplication of the Limiting Span of Suspended Bridges

The dead load of a suspended superstructure increases with the span, and there is for any type of bridge a limiting span beyond which the dead load stresses exceed the assigned limit of allowable stresses. The use of CFRP cables would allow a multiplication of the limiting span of suspended structures in comparison to steel cables. In Fig. 10, the specific design loads versus the center span for the classical form of suspension bridges made of steel are compared with those made of CFRP according to Eq. 2. The specific design load is defined as the dead load g of the superstructure divided by the live load p. The calculation of the specific design load as a function of the span is as follows according to [20]:

$$\frac{g}{p} = \frac{\ell}{\left(\frac{\sigma_{\text{allowable}}}{\alpha\,\rho} - \ell\right)} \tag{2}$$

whereas g is the dead load of structure (kN/m), p is the live load (kN/m), ℓ is the center span (m), σ is the allowable stress (N/m), α is the systems coefficient (m/s^2), and ρ is the density (kg/m^3).

The limiting span ℓ_{lim} is calculated as follows:

$$\ell_{\text{lim}} = \frac{\sigma_{\text{allowable}}}{\alpha\,\rho} \tag{3}$$

The uniaxially loaded cables and hangers are mainly responsible for determining the allowable stress in Eq. 2. This permits the use of the allowable stresses for steel and CFRP cables (Table 2).

The assumptions used for Fig. 10 given in Table 2 can, to some extent, be questioned, e.g., the allowable stress of 1,000 MPa for CFRP cables might be too low compared with the ultimate strength of 3,300 MPa. However, this would not have any fundamental influence on the qualitative statement of Fig. 10.

Table 3 gives examples for specific design loads of existing and planned bridges, e.g., for a possible steel cable suspension bridge crossing the Strait of Messina, the dead load is twice the live load per unit length.

In [19] is has been demonstrated that the "break-even span" for a bridge made of CFRP is approximately 4,000 m. The "break-even span" is the span at which cost for a bridge made of steel or of CFRP are the same. This implies that only superstructures with main spans in the range of 4,000 m and greater will be the domain CFRP.

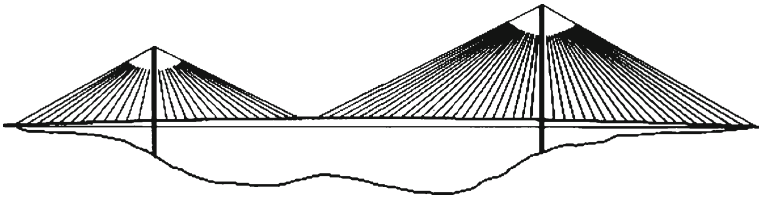

Fig. 11 Proposal for a carbon fiber-reinforced composite bridge across the Strait of Gibraltar at its narrowest site according to Meier (1987) as cable net structure. Spans: 3,100, 8,400 and 4,700 m. The heights of the towers are approximately 850 and 1,250 m above sea level

2.2 Feasibility Considerations

In [19] is a proposal for the bridging of the Strait of Gibraltar at its narrowest site with a cable-stayed bridge of CFRP. Compression forces in the deck must be avoided. This can be reached by the cable-net concept with large CFRP main cables integrated in the deck and anchored in the ground at the abutments. This would be a highly challenging civil engineering task. This is true not only for the superstructure, but also for the towers, the foundations and the anchorages. Employing building materials currently used for superstructures, this challenge cannot be met. The development step from the previously designed longest center span of 1991 m (Akashi-Kaikyō Bridge) utilizing steel to the proposed span of 8,400 m (Fig. 11) or greater can only be achieved with advanced composites. Indeed, CFRPs seem predestined, above all for the cables which would comprise approximately 70% of the weight of the superstructure, since the outstanding properties of strength and stiffness of unidirectional fiber composites can be used to full advantage.

The application of CFRP cables is today, as shown in previous sections, state of the art. The girders and decks could be built out of fiber-reinforced polymers like CFRP and/or GFRP (glass fiber-reinforced polymer) as shown by in [21,22]. Lightweight steel or aluminum decks and girders are also viable, since for such extreme spans the limiting span is mainly controlled by the dead load of the cables.

Another obstacle would be the financing of an extremely long-span bridge made of CFRP. Surely no contractor is willing to build such an object without being able to estimate the risk. This is only possible after years of practical experience on objects of medium span. Therefore, pilot projects like that of the Stork Bridge are of very high importance.

2.3 Open Questions

No doubt, there are still many open questions. By far, number one is the question about the dynamic behavior of an extremely long-span bridge especially under wind load. The increase in span length of bridges results in a remarkable decrease of their stiffness and natural frequencies. Due to low structural damping (the damping performance of CFRP is only a bit better than that of steel) and relatively low mass, extremely long-span bridges become very susceptible to vibrations caused by winds.

Menn and Billington [23] proposed a concept for extremely long-span bridges. The dynamic stability of such a bridge is assured by placing on either side of the deck girder a sloping cable-stayed system carried by slender pylons, which are supported by the central pylon.

Peroni and Casadei [24] suggested a three-dimensional tensile structure with a hyperboloid shape: this consists of a 3D net with the ropes interlaced to each other to form a wicker basket containing inside the deck of the bridge. The principal net rope, beginning from two towers at the extremities of the bridge, is developed around elliptic sections that gradually reduce toward the midspan of the bridge. The particular interlaced cables conformation formed a “closed system” extremely stable with respect to the horizontal, vertical and torsion effects of the wind loads.

There are more “passive systems” for the mitigation of flutter, vibrations and oscillations under discussion. Such “passive systems” will, with a high probability, not be sufficient. Advanced “active systems” and control strategies are needed. To fill this gap, the author initiated at the EMPA laboratories in the year 2000 the program “Adaptive material Systems” [25].

This program includes a project with an innovative wind-induced vibration mitigation strategy based on active control of the bridge’s aerodynamic profile. An array of adjustable winglets is installed along both edges of the girder and their angular position is controlled as a function of the current dynamic state of the structure and the local wind field measurement. This information is shared with other similar units distributed over the whole length of the bridge through wireless networking. The characteristics of the interaction between the wind field and the underlying structure (nonlinear, spatially heterogeneous, time-variant and noisy) with the additional degrees of freedom introduced by the flap system result in complex mathematical models and associated control strategies. The need for real-time coordination between various units, leading to an active control of the global aerodynamic profile of the bridge with the constraints introduced by the mechanical structure, makes the problem of mitigating vibrations at the perturbation source extremely challenging. For the mitigation of the cable vibrations, analogous systems have been considered.

The destructive effects of lightning strikes are well known. The studies of lightning and the means of preventing its striking an object or the means of passing the strike harmlessly to ground have continued since the days when Franklin first established that lightning is electrical in nature. From these studies, two conclusions emerge: firstly, lightning will not strike an object if it is placed in a grounded metal cagel; secondly, lightning tends, in general, to strike the highest objects in the area. As composite materials replace more and more metals in aircrafts, there has been an increase of risk of damage by lightning to such composite sections. CFRP is a conductor, but is relatively resistive to electricity which causes it to heat up as the current passes through it. A lightning strike has two main effects on unprotected CFRP: firstly, the main body of the CFRP becomes so hot that the epoxy resin component vaporizes; and secondly, the structural integrity of the CFRP will have been affected after the carbon cooled down. It will probably retain a considerable tensile strength, but it will lose interlaminar shear and compressive strength. Therefore, the aircraft industry developed aluminum grids which are used to protect the composite in its outermost layers. In the case of the Stork Bridge, it was decided to insulate the CFRP parallel wire bundles. It was possible to do so with very little additional cost, since the cables were anyway packed into a polyethylene pipe similar to steel parallel wire bundles. In the past, there were lightning strikes which hit the towers of the bridge without any damage for the CFRP cables.

Also for the “open questions”, there will be solutions, as just discussed. The successful development of CFRP cables was hard and took a lot of time. To resolve the open questions will be even harder and take more patience and creativity. Therefore, is “Why not?” a sustained argument against complacency?

3 What If?

However, what would happen if “somebody” would order an extremely long-span CFRP Bridge today? “What if?” keeps us humble and conservative. Today, the time is not yet ripe for very large standalone CFRP bridge projects. However, there is a need for the replacement of main cables on several large suspension bridges, as shown in previous sections. In such cases, a stepwise procedure could be performed to reduce the risk. The “25th of April Suspension Bridge” in Lisbon inaugurated in 1966 needed in 1999 additionally a lower train platform with two train tracks besides the existing upper platform with six car lanes. To accommodate this, the bridge underwent extensive structural reinforcements, including a second set of main cables, placed above the original set, and the main towers were increased in height. The original builder, American Bridge Company, was called again for the job, performing the first aerial spinning of additional main cables on a loaded, fully operational suspension bridge. Such an operation would be much easier and faster with CFRP cables. This approach could be a very efficient solution to complement the loss of cross sections on existing suspension cables due to corrosion. Such an application should be the next step in the development of CFRP cables.

4 Conclusions

We explored the basis of innovation, starting with the questions “Why?” and “Why not?” The question “Why?” gave us the opportunity to challenge the status quo, to introduce the idea of CFRP cables and overcome first restrictions with full-scale CFRP pilot projects. The question “Why not?” allowed us to discuss the future of CFRP cables. The question “What if?” will keep us humble and conservative. That is correct. As civil engineers, we have a high responsibility. However this should not prevent us to go ahead with new, promising developments in the domain of CFRP cables.

Although a great number of problems remain to be solved, the crossings of straits like that of Bab el Mandeb, Messina or Gibraltar with extremely long-span CFRP bridges appears feasible from the technical point of view within the next 30–40 years.

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