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Autor: Meier, Urs

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Extending the Life of Cables by the Use of Carbon Fibers

Prolongement de la durée de vie des câbles par l'utilisation de fibres de carbone

Verlängerung der Lebensdauer von Kabeln durch Anwendung von Kohlenstoffasern

Urs MEIER
Professor
EMPA
Dübendorf, Switzerland

Urs Meier, born in 1943, graduated in civil engineering from the ETH in Zürich. Since 1971 he has been involved in testing and research on advanced composites and he is now Director of the Swiss Federal Laboratory for Materials Testing and Research (EMPA). He is also Professor at the ETH Zürich.

SUMMARY

Since 1980 research and development has been carried on carbon fiber reinforced plastic (CFRP) cables for cable stayed and suspension bridges. The excellent properties of the parallel wire bundles include corrosion resistance, very high specific strength and equivalent modulus and outstanding fatigue behaviour. The key problem facing the application of CFRP cables, and thus their widespread use in the future, is how to anchor them. A new reliable anchoring scheme produced with gradient materials based upon ceramics and epoxy is described.

RÉSUMÉ

Depuis 1980, des recherches et développements sont réalisés pour des câbles en matière plastique renforcée de fibres de carbone (PRC) pour les ponts suspendus et les ponts à haubans. Ces câbles à faisceaux de fils parallèles présentent d'excellentes caractéristiques telles que résistance à la corrosion, résistance mécanique et module d'élasticité idéalisé et comportement à la fatigue remarquable. La difficulté de leur mise en oeuvre pratique réside dans l'ancrage des faisceaux de fils parallèles. Le présent rapport décrit une nouveau système d'ancrage fiable utilisant un matériau composite à gradient de concentration en céramique/résine époxyde.

ZUSAMMENFASSUNG

Seit 1980 werden Kabel aus kohlenstoffaserverstärkten Kunststoffen (CFK) für Hänge- und Schrägseilbrücken erforscht und entwickelt. Die ausgezeichneten Eigenschaften der Paralleldrahtbündel beinhalten Korrosionsbeständigkeit, sehr hohe Festigkeit, sehr hoher ideeller Modul und hervorragendes Ermüdungsverhalten. Die Schwierigkeit liegt bei der Verankerung der Paralleldrahtbündel. Im vorliegenden Bericht wird ein neuartiges, zuverlässiges auf einem Keramik/Epoxidharz-Gradientenwerkstoff basierendes Verankerungs-System dargestellt.

1. INTRODUCTION

During the past 20 years, the bridge engineering community has experienced more and more damage on stay and suspender cables [1]. Cables are suffering due to increased corrosion and fatigue loading. Most bridge engineers seem to agree that the corrosion and fatigue resistance of such cables has to be enhanced. Researchers proposed modern approaches using non-metallic that means non-corrosive materials [2-5]. The introduction of carbon fiber reinforced plastics (CFRP) instead of steel has been proposed since the early eighties [6]. 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 [7].

The purpose of this work was to develop an anchorage system capable of successfully handling the huge potential of CFRP wires and to achieve the high reliability of parallel wire bundles made of such advanced composites.

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 (charring) an organic polymer or pitch yarn with a fiber diameter normally in the 5-10-micrometer range. There are commercial carbon fibers available with elastic moduli ranging from 230 to 650 GPa and strengths from 3500 to 7000 MPa. The elongation at failure is varies between 0.6 and 2.4 %. The fiber mostly used within this study was the Torayca T 700S having a strength of 4900 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. In October 1994 these fibers were priced at 37 Swiss Francs (27 US $) per kg.

3. CARBON FIBER REINFORCED PLASTIC 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 wire for the parallel 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 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 chemical 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 an polymer matrix, it can again take up full load a short distance away from a crack. For these reasons CFRP wires are very reliable.

CFRP wires are produced by pultrusion, a process for the continuous extrusion of reinforced plastic profiles. Rovings (strands of reinforcement) are drawn (pulled) through an impregnating tank with epoxy resin, the forming die, and finally a curing area (e.g. radio-frequency exposure). The fibers have a good parallel alignment and are continuous. The fiber volume content of the wires used in this study was in the range of 65 to 70%. 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 diameters of 5 or 6 mm.

Tensile strength σ_u (longitudinal)	3300	MPa
Elastic modulus E (longitudinal)	165	GPa
Density	1.56	g/cm³
Fiber content	68	Vol-%
Thermal expansion (longitudinal)	0.2×10^{-6}	m/m/°C

Table 1 Properties of wires pultruded of T700S fibers

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 there is no corrosion inhibiting compound or grout 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 wires. A poly-tetra-fluoroethylene sheath would be adequate for shielding.

When a load is applied to a cable with a horizontal as well as a vertical span, the elongation consists of the material deformation augmented by a geometric deformation due to the straightening out of the cable sag. The ratio of the applied stress to the observed "strain" (elongation/original distance between the end points) is called the relative equivalent modulus. The low mass density of CFRP cables gives them an advantage in comparison to steel cables with increasing horizontal cable span. Some data are given in Table 2.

Horizontal cable span [m]	Relative equivalent modulus [GPa]	
	Steel	CFRP
0	210	165
500	196	165
1000	163	163
1500	128	162
2000	98	159

Table 2: Relative equivalent modulus for 720 MPa

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 a 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 similar. The evaluation of the casting material to fill the space between the metallic 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:

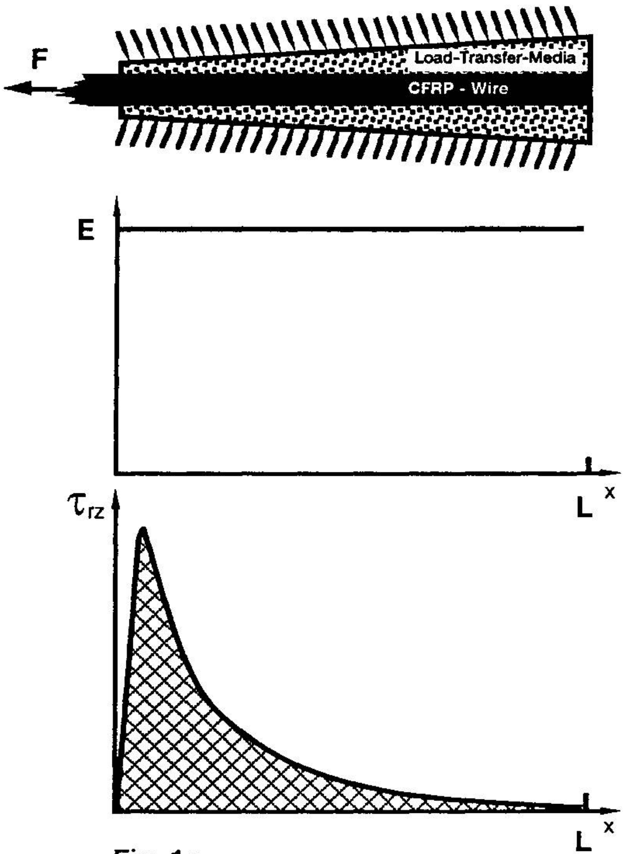

Fig. 1a

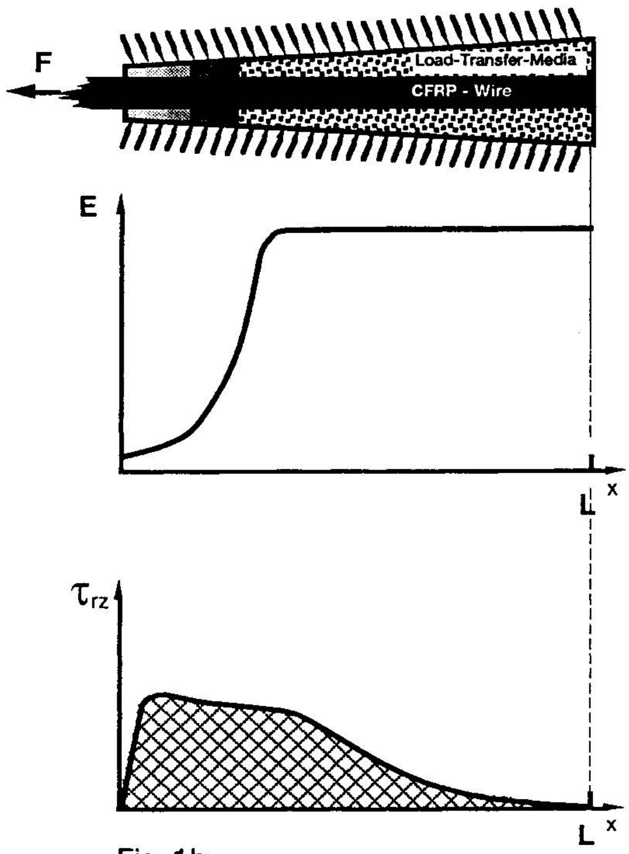

Fig. 1b

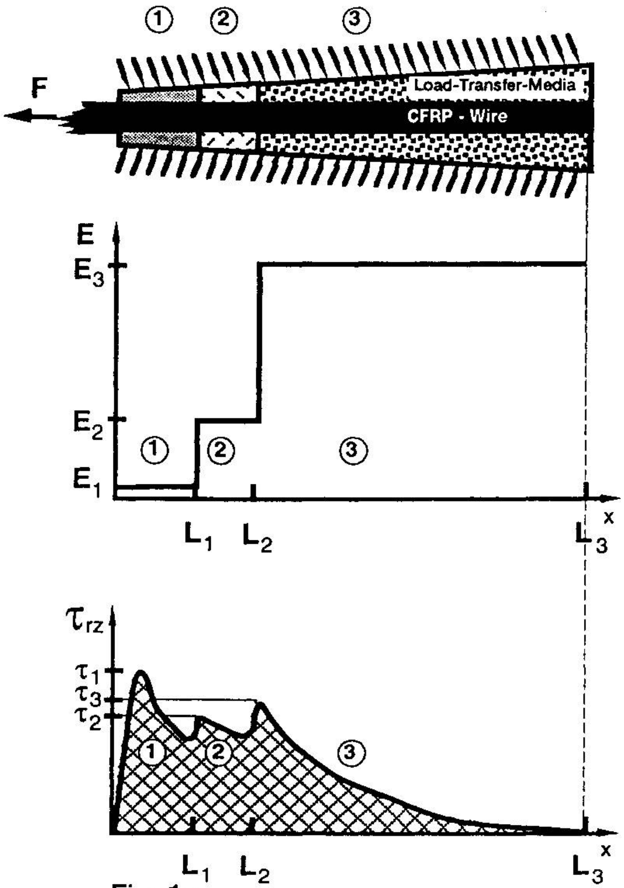

Fig. 1c

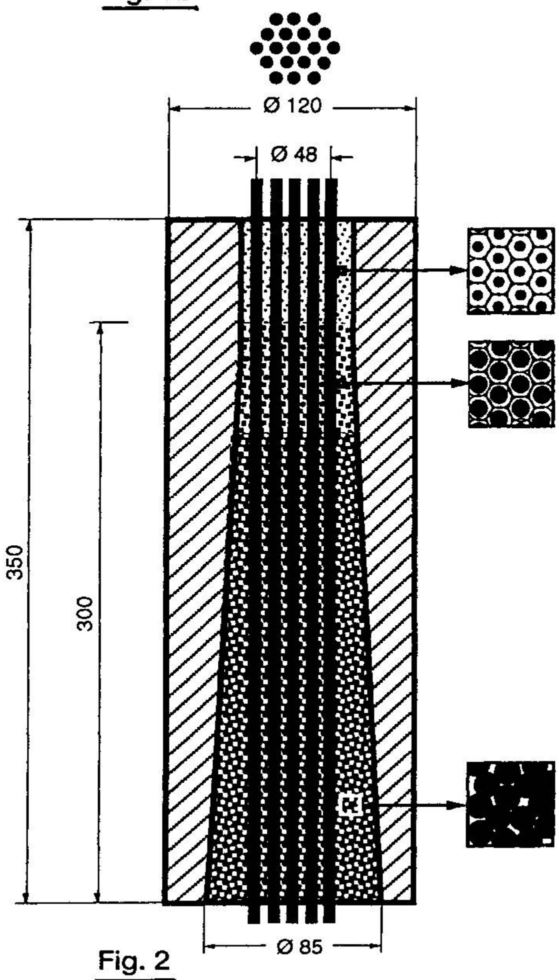

Fig. 2

- The load should be transferred without reduction of the high long time static and fatigue strength of the CFRP wires due to the connection.

- Galvanic corrosion between the CFRP wires and the metal cone of the termination must be avoided. It would harm the metal 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 Figures 1a to 1c 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. 1a). This peak causes pullout or tensile failure far below the strength of the CFRP wire. We 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 b. The LTM is a gradient material. At the beginning of the termination the modulus of elasticity is low and continuously increases until reaching a maximum. This way a shear peak can be avoided. Experiments at EMPA have demonstrated that the 3-step-modulus LTM shown in Fig. 1c is the optimum design from the technical and economic point of view . The LTM is composed of aluminum oxide ceramic (Al_2O_3) granules with a typical diameter of 2 millimeters. 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. 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 (Fig. 2) without any coating. With this method the modulus of the LTM can be designed tailor-made. The holes between the granules are filled by vacuum-assisted resin transfer molding with epoxy resin.

The termination of a 19-wire-bundle is shown in Fig. 2. Many such 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% [8]. Fatigue tests performed on the above described 19-wire cables at EMPA showed the superior performance of CFRP under cyclic loads [7]. The anchorage system is patented (CH 01'270/94-3).

6. CONCLUSIONS

Suspenders in suspension bridges are regularly replaced throughout the world. Stay cables caused very high maintenance costs in the past 20 years. Many such cables are in need of replacement. There is no doubt that from the technical standpoint CFRP is today the best suited material for suspenders and stay 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 within the next five years to a level of 25 Swiss Francs (18 US $) per kg (1 kg CFRP is 5.2 times lighter than steel) it will be very difficult for CFRP cables to compete unless the entire life is considered in the costs. A few clients for bridge cables such as the Department of Transport 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 %. CFRP cables benefit considerably compared with steel in such comparisons.

The most important factor to remember is not the cost per kg of materials, but rather the cost effectiveness of the finished product, installed, considering the life expectancy and the costs of the alternatives. This has worked to the advantage of the CFRP sheet bonding technique for rehabilitation of structures [9] and there is a high probability that this will also be the case for CFRP cables in future.

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