Evolution of stay cables through the use of CFPR

Evolution of Stay Cables through the Use of CFPR

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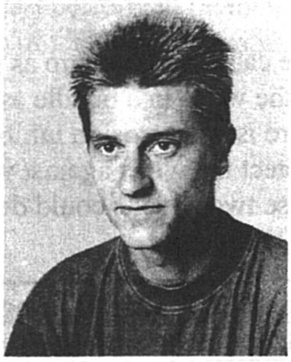

Summary

The excellent properties of the parallel wire bundles made of carbon fiber reinforced polymers (CFRP) include corrosion resistance, very high specific strength and equivalent modulus and outstanding fatigue behavior. 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 and its application on a vehicular cable stayed bridge is described.

Introduction

During the past 20 years, the bridge engineering community has experienced more and more damage on stay and suspender cables. 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. The introduction of carbon fiber reinforced polymers (CFRP) instead of steel has been proposed since the early eighties [1]. 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 [2].

CFRP Cables

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 varies between 0.6 and 2.4 %. The fiber mostly used within this study and for the bridge in Winterthur 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.

CFRP wires are produced by pultrusion, a process for the continuous extrusion of reinforced polymer profiles. Rovings (strands of reinforcement) are drawn (pulled) through an impregnating tank with epoxy resin, the forming die, and finally a curing area. 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 diameters of 5 or 6 mm.

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 attacks because the combination of these two attacks could degrade the wires. A poly-tetra-fluoroethylene sheath would be adequate for shielding.

Tensile strength σ_u (longitudinal)	3300	MPa
Elastic modulus E (longitudinal)	165	GPa
Density	1.56	g/cm^3
Fiber content	68	Vol-%
Thermal expansion (longitudinal)	0.2 x 10^{-6}	m/m/°C

Table 1: Properties of wires pultruded of T700S fibers

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. 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:

- 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 (Fig. 1a) provides the necessary radial pressure to increase the interlaminar shear strength of the CFRP wires. If the LTM over the whole length of the socket is a highly filled epoxy resin there will be a high shear stress concentration at the loadside of the termination on the surface of the CFRP wire. 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 a gradient material. At the loadside of the termination the modulus of elasticity is low and continuously increases until reaching a maximum. This way a shear peak can be avoided. The LTM is composed of aluminum oxide ceramic (Al_2O_3) granules with a typical diameter of 2 millimeters (Fig. 1b). 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 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. 1a. 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% [3]. Fatigue tests performed on the above described 19-wire cables at EMPA showed the superior performance of CFRP under cyclic loads [2]. The anchorage system is patented worldwide.

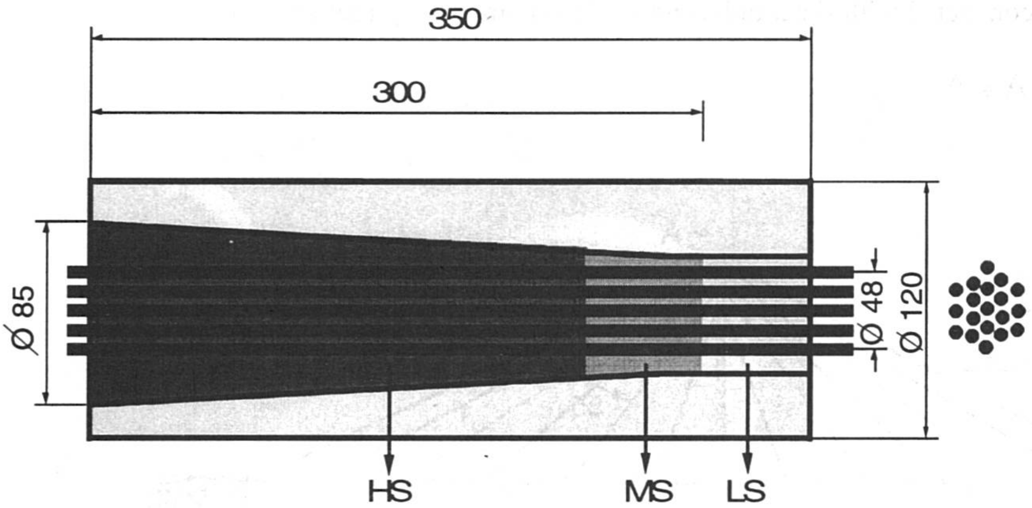

Figure 1a: Conical resin-cast termination; HS=high stiffness, MS=medium stiffness, LS=low stiffness; right side=loadside

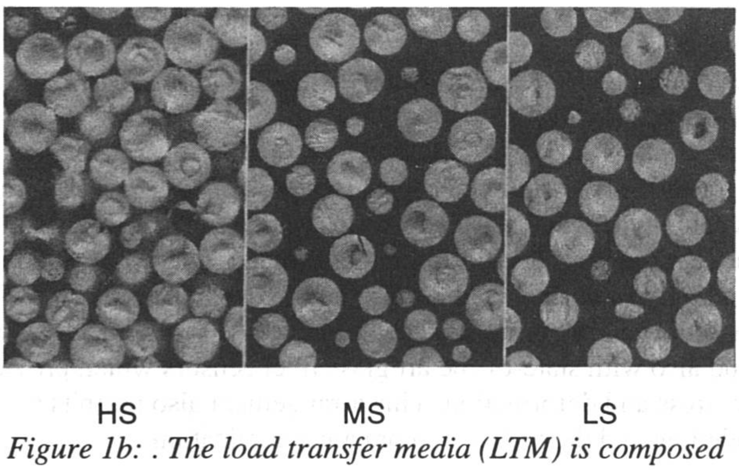

Figure 1b: . The load transfer media (LTM) is composed of aluminum oxide ceramic (Al_2O_3) granules with a typical diameter of 2 millimeters; HS=high stiffness, MS=medium stiffness, LS=low stiffness; right side=loadside

The Stork Bridge

The Storchenbrücke, erected in 1996, is situated over the tracks of the railroad station in Winterthur and has a central A-frame tower supporting two approximately equal spans of 63 and 61 meters (Fig. 2). The cables converge at the tower top and 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 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.

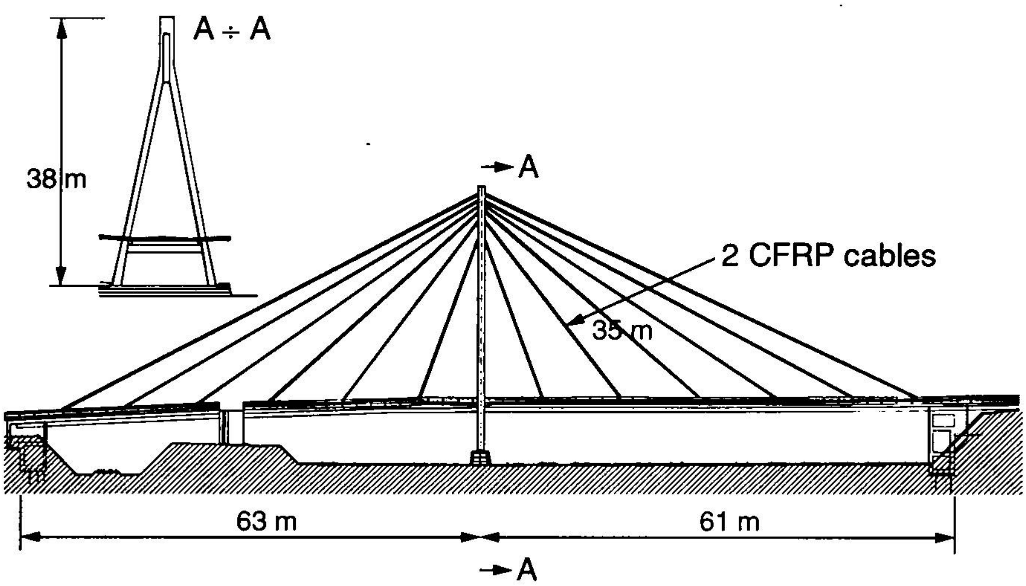

Figure 2: The Storchenbrücke is crossing 14 tracks over the railroad station in Winterthur, Switzerland.

Bridge owner: Town of Winterthur
Design: Höltschi & Schurter, Zürich,
Design and production of the CFRP cables: EMPA Dübendorf and BBR Ltd., Zürich,
Installation of the cables: StahlTon Ltd., Zürich.

The CFRP cable type (Fig. 3) used for the Storchenbrücke (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 Storchenbrücke 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 2 CFRP cables with their anchorage and the neighbouring steel cables have been equipped by the EMPA with conventional sensors and also with state-of-the art glass fiber sensors which provide permanent monitoring to detect any stress and deformation. This arrangement also permits a comparison between theoretical modelling and the reality of a practical application.

The cable-stay Storchenbrücke (Fig. 4) 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 but with the same strength properties. This high strength with low weight will permit us to build bridges in future with considerably longer spans than are currently possible [4, 5].

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

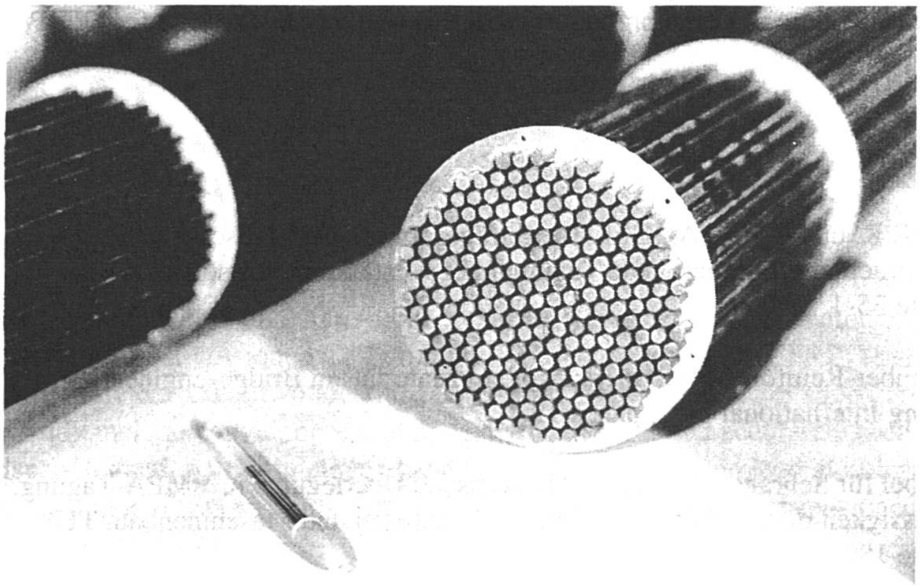

Figure 3: The CFRP cable type used for the Storchenbrücke (Stork Bridge) consists of 241 wires each with a diameter of 5 mm.

Figure 4: The cable-stay Stork bridge may be a milestone in bridge construction.

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 increasingly require worldwide 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 and there is a high probability that this will also be the case for CFRP cables in future.

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