CARBON FIBER REINFORCED COMPOSITES PROVED TO BE VERY SUCCESSFUL IN CONSTRUCTION DURING A QUARTER OF A CENTURY

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Keywords: carbon fiber reinforced polymers (CFRP), strengthening, post-tensioning, structural health monitoring (SHM).

Abstract
The application of carbon fiber reinforced polymers (CFRP) in civil engineering was before 1991 unknown. Therefore the authorities responsible for construction did not want to rely only on the laboratory experiments made in the 1980ties. They asked for the long-term structural health monitoring (SHM) of the pioneering CFRP applications. This was also in the interest of the involved R&D community. The results of this SHM over the last quarter of a century proved the outstanding performance and reliability of CFRP in civil engineering.

1. Introduction

The first author presented at the Symposium of the International Association for Bridge and Structural Engineering (IABSE) 1991 in St. Petersburg the paper ”Carbon-Fibre-Reinforced Polymers: Modern Materials in Bridge Engineering” [1]. In the same year world’s first application of carbon fiber reinforced polymers (CFRPs) in construction happened at Ibach Bridge near Lucerne. In the IABSE-paper were a lot of promises for CFRPs in construction like no corrosion, no fatigue, effective and efficient post-strengthening, a superior equivalent modulus for stay cables etc. The future potential of carbon fibers in construction and the limiting spans for suspended bridges [2] were also discussed. What has been reached meanwhile? To answer this question it was very important to build up high quality monitoring systems for the supervision of the early applications of CFRP in construction.

2. Methods of Structural Health Monitoring (SHM) to Establish the Long-Term Behavior of Structures with CFRP

2.1. Demec Gauges

The mechanical strain gauge system, often called “demec gauge”, was developed as a reliable and accurate way of taking strain measurements at different points on a structure using a single instrument. The system consists of an invar main beam with two conical locating points, one fixed and the other pivoting on a special knife edge. The points locate in pre-drilled stainless steel discs that are attached to the structure with adhesive. The movement of the pivoting point is measured by a photoelectric

Excerpt from ISBN 978-3-00-053387-7

incremental length measuring device, which is attached to a base plate on the invar beam. Design is such that thermal movement within the instrument is negligible. It has a digital readout of 0.001 mm resolution and can be connected wireless to a lap top computer. The mechanical strain gauge system is ideal for use on many types of structure for strain measurement and crack monitoring. The gauge length in all cases discussed in the following sections is 200 mm. Within the long-term monitoring of several objects a total of 156 demec points have been installed during a time period of 19 to 25 years. Only one single point failed. Using the described configurations all possible kinds of drifts become for the applications discussed negligible. The long term reliability of the mechanical strain gauge system used to monitor the behavior of the externally bonded CFRP strips for the strengthening of structures was instrumental to build up confidence into this novel technique.

2.2. Coin Tapping Technique

ASTM D4580 is proposing among others an electro-mechanical sounding procedure with an electric powered tapping device for the detection of delaminations of concrete overlays on bridge decks. For CFRP strips externally bonded to concrete, wood or metals the coin tapping technique is by far sufficient. It involves striking the CFRP strip with a large coin. Areas where delaminations have occurred have an audible acoustic response that contains different frequencies than areas where the adhesion is perfect. This process is subjective, but it has been proved to be very effective and efficient to check delaminations of externally bonded CFRP since 1982.

2.3. Replica Technique

Beside the long term behavior of the adherence of externally bonded CFRP strips also the outdoor weathering behavior of the CFRP strips had been doubted. Therefore a surface monitoring was needed. If it is not possible to put specimens into the scanning electron microscope (SEM), the replica technique can be employed to examine surface features. The procedure is the following: wet a strip of cellulose acetate replicating tape with acetone and apply it with light pressure to the surface of the CFRP strip. After it dries completely, strip it from the substrate, turn the replica over and tape it to a glass slide. Afterwards sputter the replicas with gold and examine it by a SEM.

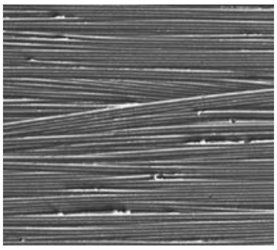

Figure 1. SEM image of negative replica of surface of CFRP strip after 18 years of outdoor-weathering under the soffit of the Ibach Bridge, fiber diameter 5μm.

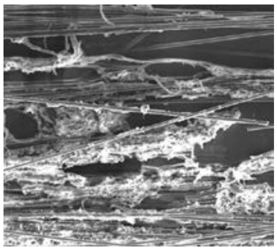

Figure 2. SEM image of negative replica of surface of CFRP strip after 18 years of outdoor-weathering exposed to the sun on a inclined rack, fiber diameter 5μm.

In the case of the CFRP strips of the Ibach Bridge (see 3.1) this technique with negative replicas has been used. At the same time when the CFRP strips had been installed on the soffit of Ibach Bridge in summer 1991 the same type of strips had been placed on inclined racks oriented at the sun. These racks are at an angle of 45 degrees in the southerly direction on a roof of the Empa laboratories in Dübendorf. Fig. 1 (CFRP strip from the soffit of Ibach Bridge where UV rays can be neglected) shows the fiber-print on the outermost layer of EP matrix which has been pulled off by the replica technique. The visual and light microscopic inspection revealed not any damage due to outdoor weathering. In Fig. 2 with the same type of CFRP strip, however exposed to the sun since 1991, the situation is

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different. Contrary to Fig. 1, fibers and UV-degraded epoxy matrix have been pulled off. However this is only about one layer of fibers that means 5µm per 18 years. It does not really have influence on the structural properties of the CFRP laminate. It can be avoided, as experimental results proved, with a layer of paint.

2.4. Fiber Bragg Grating (FBG) Sensors and Resistive Strain Gauges (RSG)

Fiber optic sensors are potentially very well suited for such applications. Measurable variables are mainly temperature, electrical current, strain and pressure. Optical fibers and sensors are often promoted to work in electromagnetic fields, at high temperature and humidity, or in aggressive chemical environment. Especially fiber Bragg grating (FBG) sensors have been demonstrated to operate in applications from airplanes to civil infrastructure like dams and bridges [3, 4].

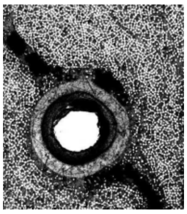

Figure 3. SEM image of CFRP wire with a Bragg grating sensor, Ø 100 µm. The fine white dots are the carbon fibers.

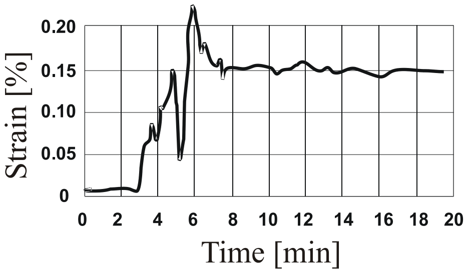

Figure 4. Strain signals from Bragg grating during pultrusion of 5 mm CFRP wires.

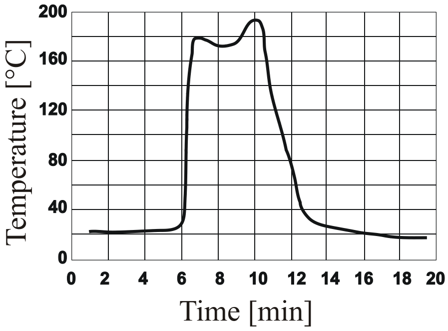

Figure 5. Temperature signals during pultrusion.

The long-term SHM program of Empa saw the first ever use of CFRP wires with integrated fiber optic Bragg gratings (FBGs) [4]. They have been directly embedded during the pultrusion process in the middle of the CFRP wires (Fig. 3). This procedure allows placing FBGs not only in the free span of the wires but also in the critical zone of the anchor socket with the critical strain decay. Where the projected application requires incorporation of sensors into the CFRP wires, these may be integrated at the production stage for process monitoring. The strain (Fig. 4) and temperature (Fig. 5) signals from the sensors were monitored and analyzed already during production.

2.5. Self-Sensing System for Unidirectional CFRP Wires

Carbon fiber reinforced polymers are composed of the electric conductive carbon fibers and the matrix polymer, which is an insulator. In section 3.5 an application of the electrical resistivity for SHM on highly pre-stressed unidirectional CFRP wires is going to be discussed.

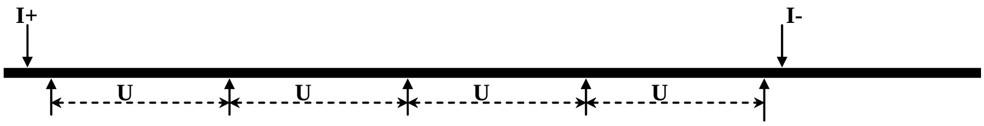

Figure 6. Principle of the strain measurement on CFRP wires.

Fig. 6 shows the measurement principle of the self-sensing system. A current is guided through the CFRP wires with contacts at the positions I+ and I-. Several electrical connections allow the measurement of the voltage drop along the wires. After painting epoxy-based silver paint on the locally polished wire contact surfaces, the silver paint dried and conventional lead wires of copper were placed on the electrodes. Silver paint was used here again for fixing the wires at the silver paste electrodes. After this, the electrodes were covered with epoxy resin and finally with a sealing compound to protect them. The system is equivalent to a four wire resistivity measurement. Low resistance values and high temperature dependence of the resistivity are main obstacles. The resistance

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per section is around 0.8Ω. A strain of 1 µm/m corresponds to a voltage change of about 0.2 µV. To improve resolution and also to compensate thermo electrical voltages, the current was reversed continuously and long integration times were used and a high stability current source was constructed with a short time stability of a few ppm. Also the temperature has strong influence on the measurement. The temperature coefficient of resistivity is around -430ppm/K corresponding to an apparent strain of ca. -200µm/m/K. To compensate temperature effects a dummy tendon has to be installed in an appropriate place [5].

3. Selected Case Histories of CFRP Applications in Construction

3.1. Ibach Bridge: Very Reliable Since a Quarter of a Century

The Ibach Bridge was in 1991 world's first bridge being post-strengthened with CFRP strips and it was also world's first application of CFRP in civil engineering. It crosses over the National Highway A2 (connecting Germany through Switzerland with Italy) beside the Emme and Reuss rivers. The bridge is designed as a continuous beam structure with 7 spans and a total length of 228 m. In the span which crosses the six lanes of the A2 Highway a post-tensioning cable in a web was accidentally cut.

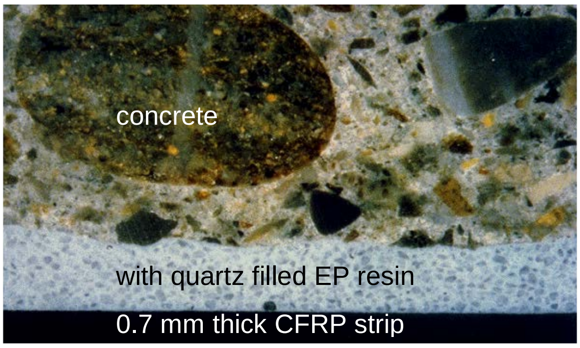

Figure 7. Longitudinal cross section of an externally bonded CFRP strip.

Figure 8. Ibach Bridge during loading test after application of externally bonded CFRP strips.

The repair work was undertaken in the summer of 1991. Three CFRP strips with a total mass of 6.5 kg were externally bonded with epoxy adhesive (Fig. 7) to the soffit of the bridge girder replacing the cut steel cable. In order to have obtained the same results with steel plates, 175 kg would have been necessary. Results of loading tests (Fig. 8) show that experimentally measured strains agree with the calculated values. For the loading test and the long term strain monitoring program, 32 as called "demec points" (see 2.1) have been attached to the soffit of the bridge girder with adhesive. Eight gauge lengths were on concrete and the other eight pair wise in parallel on one of the three CFRP strips. During the last twenty five years one "demec point" that means one of sixteen gauge lengths was lost due to adhesive failure of a point on concrete. Long term strain measurements (the method will further be explained in 3.2) and the coin tapping technique have been applied during inspections. Critics predicted in 1991 early failure based on debonding of the epoxy due to fatigue as well as temperature and humidity change, vandalism, UV-aging etc. Nothing like that happened. Until now the CFRP post-strengthening technique performed perfectly well during a quarter of a century and is fully matching all the very high expectations.

3.2. Oberriet Bridge

The two-lane-bridge, build in 1963, crossing the border between Switzerland and Austria, links Oberriet to Meiningen. It crosses the river Rhine in 3 spans, 35-45-35 m as continuous steel/concrete composite girder (Fig. 9). Thorough investigations had shown that beside regular maintenance the concrete bridge deck was in need of transversal strengthening. This was obviously due to the fact that

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in 1963 the deck was designed for the standard 140 kN truck load. In 1996 this standard truck load was 280 kN for this type of bridge. A total of 160 CFRP strips, each 80 mm wide, 1.2 mm thick and 4.2 m long were applied to the soffit of the deck with a spacing of 75 cm. The project is described more detailed in [6].

Figure 9. Oberriet Bridge during inspection.

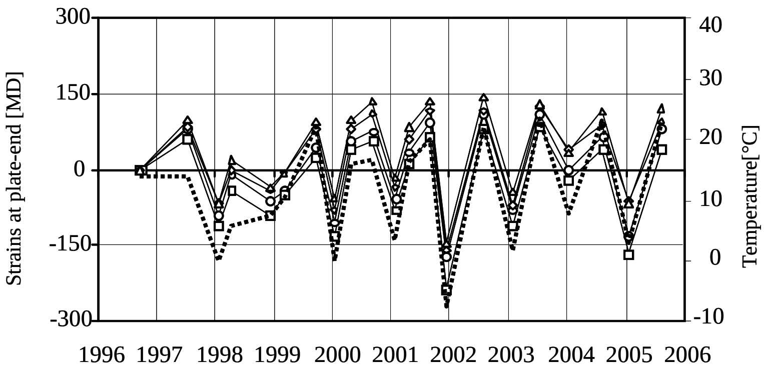

Figure 10. Typical results of strain measurement over a period of 10 years. The dashed line corresponds to the temperature. The solid fine lines connecting circles, triangles and squares correspond to strains. Note: MD = micro strains; 1000 MD = 1 0/00

The change in strain as shown in Fig. 10 is due to change in temperature from summer to winter. As long as all strain lines proceed parallel there is perfect composite action between the concrete soffit and the CFRP strips. In general there is a good correspondence of the strain with the temperature as can be expected.

3.3. Stork Bridge: CFRP stay cables since twenty years fully satisfactory in operation

Figure 11. Cable stayed Stork Bridge in Winterthur with CFRP stays.

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The cable stayed Stork Bridge in Winterthur (Fig. 11) and the CFRP cables used are described in detail in [7]. The CFRP cable type used consists of 241 wires each with a diameter of 5 mm. This cable type was in the laboratory subjected for more than 10 million load cycles to a load three times greater than the permissible load. There was not any damage. The requirement for steel cables is 2 million cycles with a maximum load that is equal with the permissible load. Such a steel cable is even accepted when it is losing 5 % of the cable cross section due to fatigue.

The strain of the CFRP cables was measured during the long-term SHM process using sensing systems based on fiber optic Bragg gratings (FBGs) and electrical resistance strain gauges (RSGs) [8]. The FBG sensor system is operational since April 1996 without any reliability problems. Besides sporadic FBG measurements the cables are monitored continuously with resistive strain gauges (RSG). The most important measurements however are those of the relative displacement between the cones of the anchor sockets [7] and the load transfer media (LTM). As expected there is a relative displacement due to creep in the LTM in function of time. Fig. 12 shows the cantilever gauge measuring this relative displacement. Fig. 13 demonstrates - as a typical example - that the relative displacement is leveling off. The CFRP cables of the Stork Bridge are now since twenty years fully satisfactory in operation.

Figure 12. Backside of cable anchor socket with cantilever spring gauge for the measurement of relative displacement.

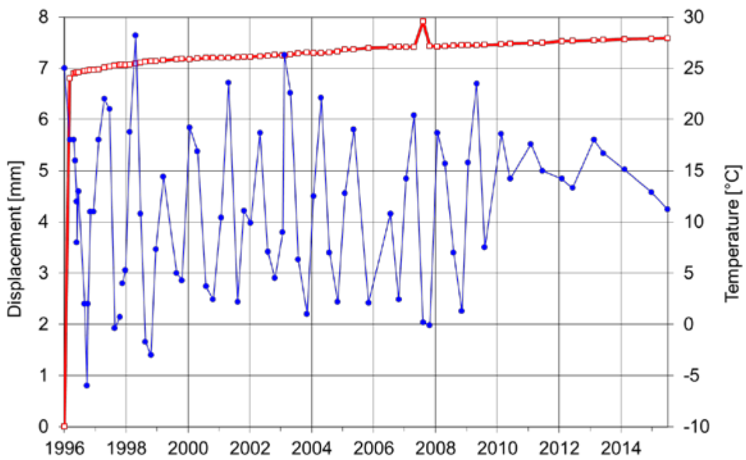

Figure 13. Relative displacements (red square markers) between the anchor cone of the upper socket 44 and the load transfer media (LTM) and temperature (blue filled dots) versus time.

3.4. Verdasio Bridge: very high sustained stresses

The Verdasio Bridge in the south of Switzerland is a two-lane highway bridge and was built in the seventies. 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. Four external CFRP cables arranged in a polygonal layout 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. The cable sockets are equipped with load cells to measure the post-tensioning force. This project is as far most interesting as in this case the sustained post-tensioning stress on the cable cross sections is in average as high as 1820 MPa and each cable is deviated around five saddles with radii of 4.5 meters.

Parallel with the seasonal temperature fluctuation there is a fluctuation of the cable force (Figure 14). The coefficient of thermal expansion for the CFRP tendons is about zero. In summertime, when the temperature is high, the concrete of the bridge girder expands. Due to that the CFRP cable force is increasing. In winter it is opposite. Most remarkable is that the trend of the cable force is a horizontal

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straight line (Fig. 15). That means there is no stress relaxation. This is surprising and unexpected from a “steel cable point of view”, but “no stress relaxation” is a typical property of the carbon fibers.

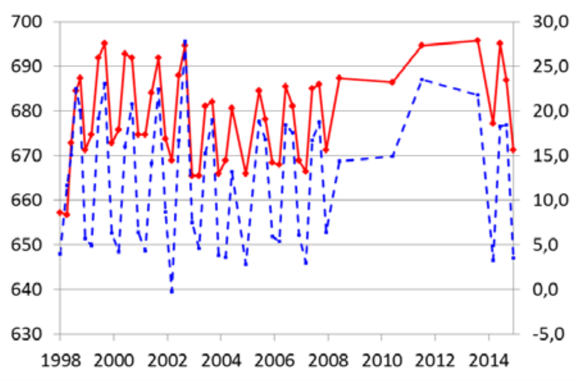

Figure 14. The post-tensioning force [kN] (vertical axis left) correlates with the seasonal temperature fluctuations (vertical axis right).

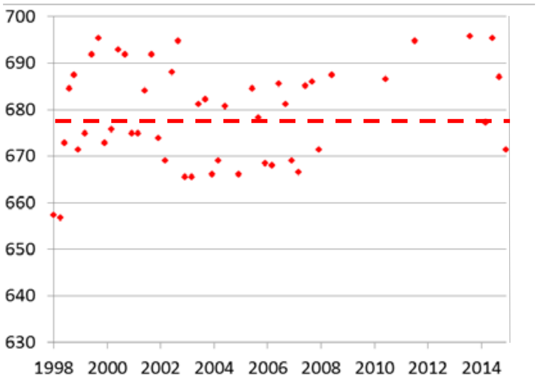

Figure 15. The trend of the post-tensioning force [kN] (vertical axis) is constant at 678 kN, corresponding to 1820 MPa.

3.5. High strength concrete pre-stressed with CFRP wires

A first full-scale field application of high strength concrete pre-stressed with CFRP wires was started in the year 2000. A 27 m high pylon was produced for a high-voltage power line using an adapted pre-tensioning-spinning process [9, 10]. One fundamental long-term aspect that had to be assessed for validating this novel technique is the loss of pre-stressing force in the CFRP wires due to creep of the concrete and potentially due to loss of bond between the CFRP wires and the surrounding high strength concrete. The monitoring method described in section 2.5 was very supportive to do so. The conical pylon had an external diameter of 847 mm at the bottom and 529 mm at the tip with an average wall thickness of 48 mm. The pylon weighed just 6’000 kg. This corresponds to a weight reduction of 40% in comparison to a traditional steel-reinforced concrete pylon for the same application. A centric overall initial pre-stressing of 1.0 MN was produced via 40 CFRP pre-stressing wires of 5.0 mm diameter. After initial pre-stress losses the following stresses were observed: 1’100 MPa on the CFRP wires, -7.5 MPa on high strength concrete at the foot and -13.8 MPa at the tip of the pylon. A rolltruded CFRP tape (0.5 to 1 mm thick, 13 mm wide) was helically wound around the pre-stressing tendons serving as shear reinforcement. The described pylon type and many other applications [9] have shown outstanding durability up to the current service time of 16 years.

3.6. Pre-stressed CFRP for Strengthening of Structures

In civil engineering today, only 20 to 30% of the strength of carbon-fiber-reinforced polymer (CFRP) strips is used when they are applied as externally bonded strips for flexural and shear strengthening or in confinement of reinforced concrete (RC) structural elements. The strips are better used when the CFRP material is pre-stressed [11]. This offers several advantages, including reduced crack widths, reduced deflections, reduced stress in the internal steel, and increased fatigue resistance. Methods and systems for pre-stressed applications have successfully been established since the 1990ties. However the number of applications is relatively low. There are two reasons: highly qualified staff is needed and the producers of CFRP strips and adhesives are not too keen since they sell fewer materials. Nevertheless pre-stressed systems are for certain applications absolutely essential and proved since 2000 to be to be very reliable. A very innovative CFRP-pre-stressing system for strengthening metallic structures is described in [12].

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4. What is the Future?

The application of carbon fiber reinforced polymers (CFRP) for post-strengthening and rehabilitation is well known and worldwide accepted today. The size of this CFRP market is similar to that of the automotive industry. In comparison to rehabilitation CFRP applications in new construction are still leading a wallflower existence. The technical performance of such applications is indeed perfect. This has been proven in several carefully monitored full-scale pilot projects as seen in the sections 3.4 to 3.5. However from an economic point of view - opposite to rehabilitation - CFRPs can in general not compete in new construction against steel as long as only the first investment costs are considered. Today most bridge owners are unfortunately not yet willing to take the whole lifecycle costs of a structure in account.

It was never and it is also today not a vision to replace steel by CFRP. However there is a future for CFRPs in new construction in commercially promising market niches like CFRP cables for suspended bridges [7], very large roofs etc. The very positive results of the SHM of full scale CFRP applications over the last quarter of a century proved the outstanding performance and reliability of CFRP in civil engineering and will support further applications in new construction.

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Excerpt from ISBN 978-3-00-053387-7