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Strain Measurement Using Embedded Fiber Bragg Grating Sensors Inside an Anchored Carbon Fiber Polymer Reinforcement Prestressing Rod for Structural Monitoring

Abdelfateh Kerrouche, William J. O. Boyle, Tong Sun, Kenneth T. V. Grattan, Jacob W. Schmidt, and Björn Täljsten

Abstract—Results are reported from a study carried out using a series of Bragg grating-based optical fiber sensors written into a very short length (60 mm) optical fiber network and integrated into carbon fiber polymer reinforcement (CFRP) rod. Such rods are used as reinforcements in concrete structures and in tests were subjected to strain through a series of cycles of pulling tests, with applied forces of up to 30 kN. The results show that effective strain measurements can be obtained from the different sensors mounted along the rod. Additionally, the tests show that close agreement with the results obtained from the calibrated force applied by the pulling machine and from a conventional resistive strain gauge mounted on the rod itself is obtained. Calculations from strain to shear stress show a relatively uniform stress distribution along the bar anchor used. The results give confidence to results from various methods of *in situ* monitoring of strains on such CFRP rods when used in different engineering structures.

Index Terms—Anchor system, carbon fiber polymer reinforcement (CFRP), fiber Bragg grating (FBG), prestressing rod.

I. INTRODUCTION

OVER the past few years, carbon fiber reinforced polymer (CFRP) composites have become increasingly accepted materials for external strengthening, in particular, as sheets and plates but also as rods, (usually as internal reinforcement in the form of rods) in concrete structures. Their uses arises from their high corrosion resistance and high strength-to-weight and stiffness-to-weight ratios which make CFRP composites very well suited to these applications, when compared, for example, to steel reinforcement rods. Systems have also been developed for prestressing, [1]. It should be noted that however, field applications for prestressing are relatively uncommon. One reason for this is the lack of cost-effective anchor systems. To anchor a CFRP tendon is more complicated than for a similar steel

system. The main reason for this is the weak material properties of the CFRP in the radial direction; the tendon is sensitive to high concentrated forces. To overcome this, it is necessary to create anchor systems that distribute the shear stresses and minimizes the peak stresses of the anchor. Research is ongoing on a new type of wedge anchor, but not presented in detail in this paper as it is the subject of an ongoing patent application [2], [3]. To investigate the shear stresses at the surface between the CFRP tendon and the wedges, fiber-optic techniques have been proposed and investigated, with the results presented in this paper.

In the development of the anchor for the CFRP rods, the aim of the work carried out within a limited timescale has been to obtain failure outside the anchor, in the tendon itself. Thus, in light of the increasing use and potential of such anchor systems for a variety of civil engineering applications, a series of novel strain measurements from CFRP rods inside an anchor system have been taken. These have been designed to allow the investigation of the strain distribution along the rod and thus (in subsequent work) coupling the results to those from a finite-element model study. The work builds upon the expertise of the investigators in the use of fiber Bragg grating sensors (FBGs) to make strain measurements along conventional reinforcement bars [4]. In this application to our knowledge, for the first time FBGs have been used for monitoring the strains in the anchor. To do so a series of FBG sensors is fabricated along a very short length of fiber to allow measurements to be taken over a minimal length of CFRP bar. FBGs are now an increasingly accepted technology offering a number of advantages for many engineering applications such as structural health monitoring, damage assessment and in monitoring engineering materials [5], [6]. Such sensors have been successfully used in several engineering fields to measure strain, temperature, pressure and monitoring applications for industrial and civil structures [7]–[10].

In this application, arising from the difficulty of measuring strain inside the anchor system, the approach of using several FBG sensors over a short length of fiber was the only possibility to enable successful measurements. The advantages here of using the FBG sensors arise from their relatively small physical size (< a few mm in length) compared to conventional strain gauges, thus making them much more suitable for embedding in structures in general or in CFRP composites in this case. In addition, the use of these sensors does not cause any significant changes to the mechanical properties of the host material. The

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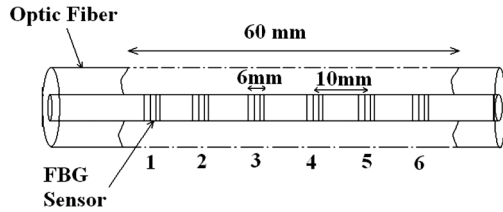


Fig. 1. Schematic of the placement of the six different FBG sensors written along the 60 mm length of the optical fiber.

details described subsequently will show that in this application, the single FBG network created shows advantages over the use of conventional strain gauges for strain measurement.

II. THE EXPERIMENTAL ARRANGEMENT USED

A. FBG Sensor Writing and Sensor Arrangement

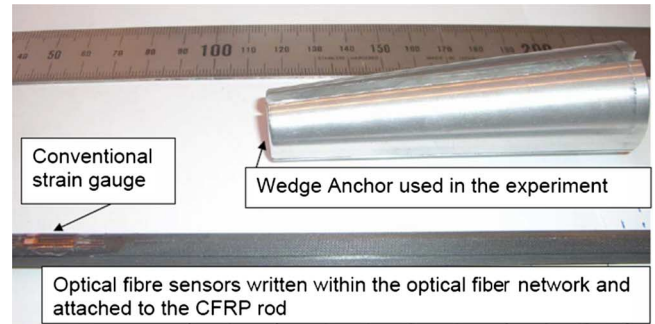
For this application, six FBG sensors were fabricated, in-house, on a very short length (60 mm) of stripped optical fiber to enable strain measurements to be made over that same short length of CFRP rod to which the fiber would be attached. It was, therefore, a key (and difficult) challenge to overcome to create the right fiber network of this type of relatively short length. To do so, the following procedure was employed.

Initially, the required length of fiber into which the different FBG sensors were to be written was stripped and, using phase mask technique [5], all the sensors were written manually by shifting the fiber by 10 mm on each occasion, while at the same time changing the corresponding phase mask to allow a series of different sensors at wavelengths separated by ~ 5 nm to be written. Fig. 1 shows this schematically. In practice, the stripped fiber is very fragile and considerable care has to be taken to allow the short network to be created. This also makes it very difficult to install the network onto the CFRP rod and for this reason, the packaging and installing of sensors onto such a rod requires particular care to avoid damage to the fiber and thus the sensors.

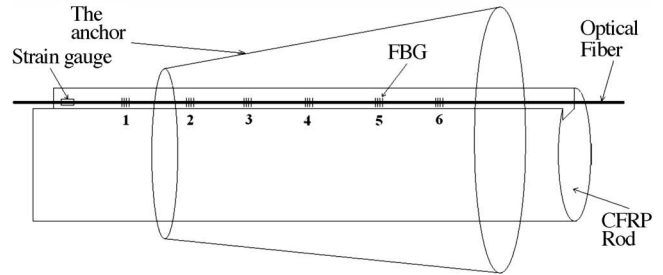
B. Sensor Attachment to the CFRP-Anchor System

A CFRP rod of nominal diameter of 8 mm was employed using the newly developed wedge anchor system with a copper sleeve to prevent crushing of the fibers due to direct contact between the wedges and CFRP rod. The optical fiber, with the six FBG sensors written into it, was glued (using a cyanoacrylic adhesive) inside a groove of 2 mm wide and 1 mm deep which was cut along 50 cm rod to hold and protect the optical fiber. The optical fiber was placed in such a way that the five FBG sensors are located *inside* and one FBG sensor *outside* the anchor system.

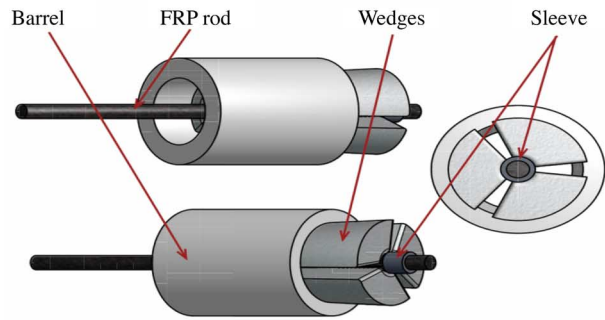
For comparison, a single electrical resistance strain gauge was fixed onto the CFRP near the wedge end of the anchor and several such gauges were also placed *outside* on the steel casing of the anchor system to provide some comparative measurements. Given its size, the only realistic option available to take measurement inside the anchor was via optical fiber. Schematic diagrams of the arrangements used are shown in Fig. 2(a)–(c).



(a)



(b)



(c)

Fig. 2. (a) Photograph showing the wedge anchor, the optical fiber sensor network and the conventional strain gauge. (b) Schematic of the CFRP-anchor showing its position relative to the optical fiber sensors used and FBG2-6 within the anchor with FBG1 outside. (c) View of the wedge anchor showing barrel, wedges, and sleeve.

C. The Sensor Interrogation System Used

The FBG network in this application was interrogated by using the well known wavelength division multiplexing (WDM) approach, which uses the different characteristic sensor wavelengths to identify one sensor from another along the network. This was similar to that used by the authors previously [11], [12], where the array of sensors was illuminated by light from a broadband source and detected using an optical spectrometer containing a Fabry–Perot tuneable filter that scans the narrow band light from the source and sweeps over wavelength of the gratings in the array. Such an approach allows for the identification of the characteristic wavelength change with strain of each of the sensors reflecting back a signal—the Gaussian peak of the signal is used to indicate the wavelength.

In this tests carried out, one of the available 8 channels from the optoelectronic interrogation system discussed previously (based on WDM technology) is used [8]. This incorporates a 20 mW 1520–1560 nm broadband light source, a Fabry–Perot

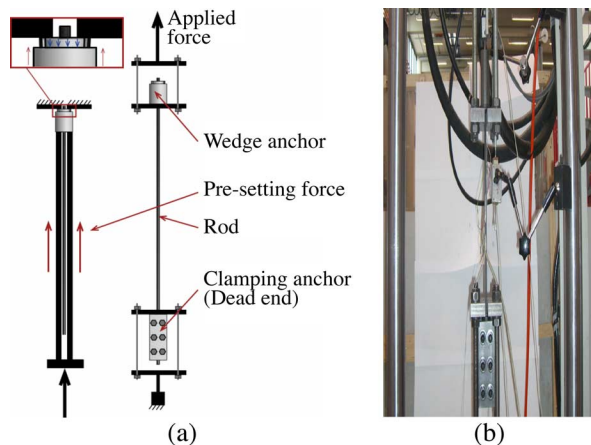


Fig. 3. (a) Left schematic of the CFRP rod containing the strain sensors loaded in the pulling machine and (b) photograph of the rod actually loaded into the machine used for this test.

spectrometer, an eight-way optical fiber splitter, an eight PIN photodiode detectors, an eight-analogue channel digital sampling processor DSP (AdwinGold), and is connected to the computer via the USB port for data storage, analysis, and transfer. The wavelength of the sensors and thence from the calibration the value of the strain (and the data to enable the required temperature correction measurements to be made from an unstrained sensor) are determined. LabView-based programming is used to undertake the analysis by determining the position of the peaks in the optical spectra obtained from the light reflected back from each sensor.

III. EVALUATION OF THE SENSOR SYSTEM UNDER LOADING

A. Installation in the Pulling Test Machine

A series of tests to evaluate the effect of loading created through installing the CFRP rod, as shown in Fig. 2(b). In a computer controlled load machine which is used to pull and thus strain the CFRP rod. The pulling force is increased linearly under computer control from 0 to 30 kN, this being held for some time before releasing and allowing it to return back to 0 kN. Similarly, a second test was carried out over a lower force range from 0 to 20 kN but this is repeated five times over a short period. Fig. 3 shows the CFRP rod installed in the pulling machine (INSTRON 8200), both schematically (on the left) and in an actual photograph.

B. Results of the Pulling Tests

Data were obtained from a series of tests carried out and the following graphs show strain measurement taken during the pulling tests, using forces up to 20 and 30 kN, respectively. Fig. 4 shows one cycle of data obtained from the 0–30 kN test—and data from four of the sensors FBG 1–4. (It was discovered after the tests began that one of the sensors did not give a reading—this may have been due to a problem created during the fabrication. It was, however, decided to continue with the tests given the functionality of the other grating sensors and the likelihood of obtaining useful data from them).

The results obtained from the working sensors (in total) show that the strain varies across the rod itself with different values

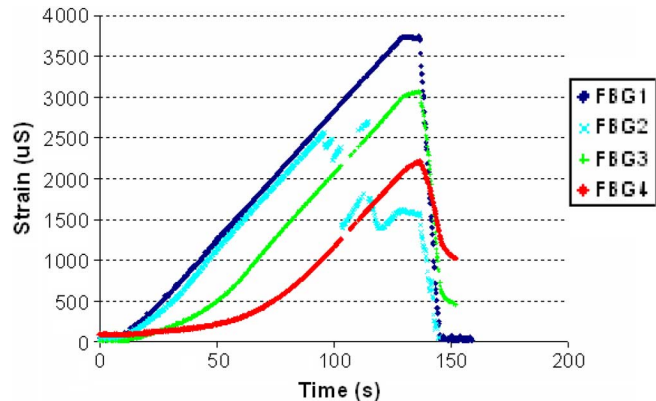


Fig. 4. Strain measurement from one cycle of the 0–30 kN test for FBG 1–4.

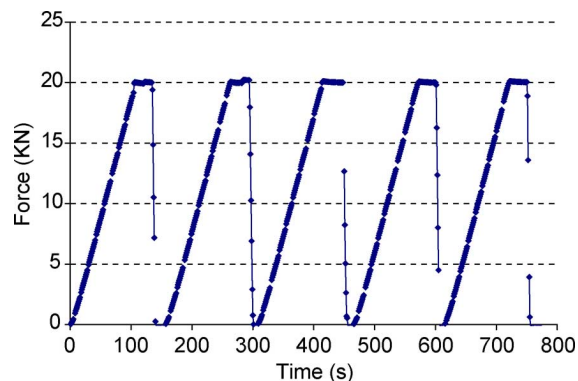


Fig. 5. Graph showing the data from the pulling test machine indicating the force applied in the 0–20 kN test: five cycles over a period of 750 s is used.

of peak strain for the different sensors. Also, the results from FBG2 seem anomalous, showing a different profile from that of the other sensors. That could be due to partial debonding of the sensor to the CFRP rod over the few millimeters of the sensor length due to the very high level of force applied or a poorer writing of the grating and thus a different optical response from the sensor. Given the consistency of the response of the other three sensors, the data from this sensor can be ignored in this test.

Fig. 5 shows the temporal profile of the force applied (data read out from a on-board computer to the INSTRON 8200 machinery) for the 5 cycle, 0–20 kN test that was carried out on the test piece containing the FBG-based sensors. Given the problem seen previously with FBG 2 and the possible damage to the sensor due to the high force (30 kN) used, the pulling forces were decreased but several cycles of testing were used, to investigate the recovery of the sensors under this smaller loading. The results and the failure of one of the FBGs after this test suggest that the maximum force of 30 kN is excessive for the bonded gratings used.

The system software is designed to monitor the wavelength shift of the FBGs and thus determine the applied strain using data obtained from determining either the transmission spectral peak or the Gaussian reflection peak. As can be seen from data from the five sensors positioned differently along the fiber and thus inside the rod (labeled FBG 1–4 and FBG 6—sensor FBG 5 failed to function), the strain level varies with the position of

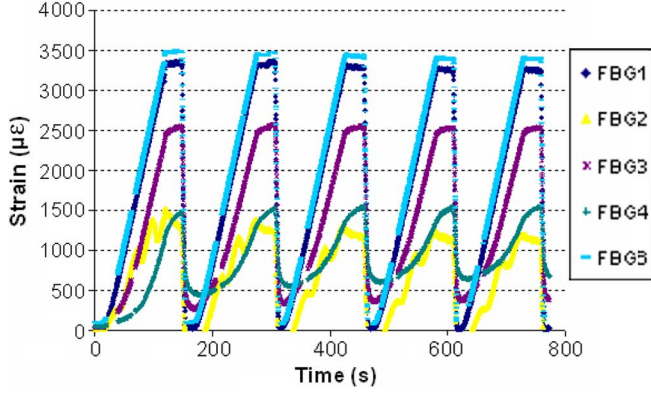


Fig. 6. Strain measurement from the 5 cycle \times 0–20 kN test, showing the responses of the different sensors placed along the CRPF rod.

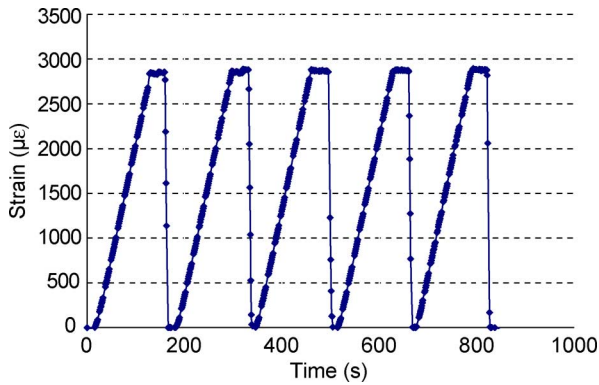


Fig. 7. Strain measurement from the single electrical strain gauge used in monitoring the five cycle 0–20 kN test.

the sensor with respect to each cycle of the pulling force applied. The results show that there is quite a difference in the strain experienced at each of the closely spaced sensors over the 60 mm distance. For example, FBG 4 shows less than 50% the maximum strain reported by FBG 6. From the following graphs it is evident that strain levels are decreasing in region 1 to 6 direction except for FBG 6 having a high strain level which was unexpected. However, FBG 2 shows typically about 30%–35% of the maximum strain experienced by FBG 6 and it seems likely from the data obtained and the profile of the response that FBG 2 had been damaged permanently by the 0–30 kN test carried out previously—a similar anomalous pattern was seen and thus the data from this sensor should be ignored. From the graph shown in Fig. 6, it is evident that strain levels are highest in FBG 1, which is positioned just outside the rod, and at FBG 6 at the end of the rod. The level of the strain for the other sensors varies as can be seen from the data on Fig. 7.

For comparison, data from the single conventional resistance strain gauge are shown in Fig. 7 for the same five cycle 0–20 kN test. This shows strain measurement where the larger electrical strain gauge is placed on the rod and located near the anchor. As expected, the data follow quite closely those of Fig. 5 (from the calibration of the pulling machine) and of the optical sensors, in particular FBG 1 (which is located physically closest to the electrical strain gauge—see Fig. 2(b) and interestingly FBG6 which, as can be seen from the figure, is located at the other end of the fiber.

TABLE I
STRAIN MEASUREMENTS FROM FIVE SENSORS CORRESPONDING TO DIFFERENT PULLING FORCES. THE SHEAR STRESS ALONG THE TENDON HAS BEEN CALCULATED AND PRESENTED IN TABLE II FOR SEVERAL SITUATIONS

Strain $\mu\epsilon \times 10^2$ → ↓Force	ϵ_1	ϵ_2	ϵ_3	ϵ_4 (sensor bonding may have been damaged)	ϵ_5 (sensor not functioning)	ϵ_6
5kN	3.6	2.1	1.8	0.90	-	4.90
10kN	11.7	5.7	4.8	1.7	-	12.7
15kN	19.9	8.9	11.5	3.2	-	21.2
20kN	33.3	15.0	24.5	12.0	-	34.8

TABLE II
SHEAR STRESS MEASUREMENTS CORRESPONDING TO DIFFERENT PULLING FORCES

Stress between FBG a (position a) and FBG b at position b	$\epsilon_2 - \epsilon_1$	$\epsilon_3 - \epsilon_2$	$\epsilon_4 - \epsilon_3$	$\epsilon_6 - \epsilon_4$
	a = 1 ; b = 2	a = 2 ; b = 3	a = 3 ; b = 4	a = 4 ; b = 6
Calculated Shear Stress → ↓Force	$\tau(\epsilon_2 - \epsilon_1)$	$\tau(\epsilon_3 - \epsilon_2)$	$\tau(\epsilon_4 - \epsilon_3)$	$\tau(\epsilon_6 - \epsilon_4)$
5 kN	-5.08×10^6	-0.85×10^6	-2.97×10^6	6.60×10^6
10 kN	-19.63×10^6	-30.03×10^6	-10.16×10^6	18.13×10^6
15 kN	-36.39×10^6	8.71×10^6	-27.32×10^6	29.63×10^6
20 kN	-60.22×10^6	31.11×10^6	-41.05×10^6	37.60×10^6

From Fig. 6, it is possible to calculate the shear stress at the surface between the tendon and the anchor. The following expression is relevant to understanding that situation [13]:

$$\tau = E_{frp} \cdot \frac{D}{4} \cdot \frac{\epsilon_{i+1} - \epsilon_i}{x_{i+1} - x_i}$$

where τ is the calculated shear stress, D is the diameter, and E_{frp} is the Young's modulus of the tendon respectively ($D = 8$ mm and $E_{frp} = 165$ GPa). ϵ_i is the measured strain in the various Bragg sensors (FBG_i, where $i = 1$ to 6) and x is the distance between these sensors. Data calculated are tabulated in Table I.

The shear stress distribution inside the anchor is plotted in Fig. 8, and from the data obtained it can be seen that shear stress is not linear along the CFRP.

IV. DISCUSSION

The tests have shown the capability of a short optical network (of length ~ 60 mm) containing six different optical fiber sensors to show the different strains experienced along a CFRP rod subjected to a series of cycles of strains of up to 20 kN and 30 kN in separate tests. Of the six installed sensors, one failed to perform (FBG 5) and one (FBG2) appeared to have been damaged or partially debonded by the first test using the largest force of 30 kN. The response shows a range of different strains along the length of the rod but overall the response of the optical sensors is seen to mirror that of the one conventional resistance strain gauge located near to the optical fiber network. Using the data

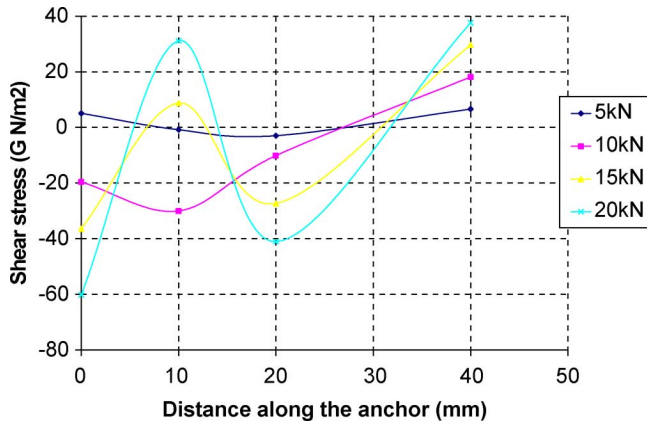


Fig. 8. The shear stress distribution inside the anchor strain measurement from the single electrical strain gauge used in monitoring the five cycle 0–20 kN test.

obtained from the sensors, the shear stress is calculated inside the anchor itself and the results have shown that this is not linear along the CFRP.

In spite of the failure of two of the FBG sensors, these results obtained from the other four shows the value of placing the series of sensors along the rod in order to obtain information about the strain profile along its length. The results confirm the value of the use of such a sensor network for the monitoring of *in situ* strains on CFRP rods used in structural reinforcement and further tests in that direction are planned. By using the measured strains in the rod it was possible to calculate the shear stress in-between the wedges and the tendon. It was shown by the developed configuration it was possible to avoid peak stresses in the anchorage.

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speaker, and over 600 papers have been authored to date. Multimillion dollar sponsorship for the work has come from industry, the research councils in the U.K., the European Union, and the Professional Bodies, with over 40 Ph.D. students graduating during that time. He is currently Deputy Dean of Engineering at City University, having been from 1991 to 2001 Head of the then Electrical, Electronic and Information Engineering Department. His research during that period was on laser systems for photophysical systems investigations, and he and his colleagues constructed some of the first of the then new category of excimer lasers (XeF, KrF) in Europe in 1976. His work in the field continued with research using ultraviolet and vacuum ultraviolet lasers for photolytic laser fusion driver systems and studies on the photophysics of atomic and molecular systems.

Prof. Grattan was Chairman of the Applied Optics Division of the U.K. Institute of Physics and President of the Institute of Measurement and Control in 2000.

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Björn Täljsten is a Project Manager for national and international construction and R&D projects. He is a specialist in the following areas: concrete structures and concrete repair, use of polymer composites in construction, structural health monitoring and risk management—in particular, technical risk management. He is an experienced project leader both in construction and R&D related projects and developed composite strengthening systems for bridges, in particular, NSMR (Near Surface Mounted Reinforcement) CFRP rods, from 1997 to the present, and carbon fiber rods that are bonded in the concrete cover in a structure. This system has today been widely accepted worldwide. We have installed it with success on several bridges in Sweden. The system can also be prestressed. He developed a completely new strengthening system, during 2005–2007, where carbon fiber tubes are bonded in drilled holes in the structure. This system was developed due to the need for strengthening without interrupting the ongoing traffic. It has so far been used on one bridge, the Frövi Bridge outside Örebro, Sweden, to strengthening a concrete slab in flexure, just under the ballast. He developed SHM (structural health monitoring) strategies for periodic and continuous monitoring of bridges both in service and for ultimate. This to optimize and bring down the need for maintenance and monitored several bridges with consideration to verify strengthening effects and performance.