CFRP Systems with Embedded FBG for Structural Monitoring and Retrofitting

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ABSTRACT

The fields of activity in civil engineering are subjected to a constant change. Thereby maintenance, strengthening and monitoring of existing buildings have become more and more important. During the last ten years an increasing amount of Carbon Fiber Reinforced Polymer (CFRP) applications to rehabilitate damaged concrete or steel elements was observed. Thereby some important disadvantages of the brittle materials must be considered, for example the low ductility of the bond between CFRP and concrete and brittle failure of FRP. With embedded sensor systems it is possible to measure crack propagation and strains. In this paper a sensor based CFRP system will be presented, that can be used for strengthening and measuring. The used optical fibers with Fiber Bragg Gratings (FBG) have a large number of advantages in opposite to electrical measuring methods. Examples are small dimensions, low weight as well as high static and dynamic resolution of measured values. A Bragg Grating consists of a periodic sequence of artificial and equidistant refraction switches in the core of an optical fiber. It can be produced over emblazing of an interference pattern of ultraviolet light. The core is surrounded by cladding. The main problem during the investigations was the fixing of the glass fiber and the small FBG at the designated position. In this paper the possibility of setting the glass fiber with embroidery at the reinforcing fiber material will be presented. The direct embroider of the optical fiber (and the FBGS) clearly simplifies the fixing. An embroidery machine, using computerized support, is able to fix the fiber optical system accurately fitting at the carbon fiber material. By using computer-controlled machines it is possible to achieve a very high degree of prefabrication as well as a high productiveness. The economic industrial fabrication of smart structures can be realized. Another possibility is the direct converting at the building site by hand made lamination with an epoxy resign.

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INTRODUCTION - MONITORING AND SMART COMPOSITE STRUCTURES

Monitoring in Civil Engineering

The fields of activity in civil engineering are subjected to a constant change. Thereby maintenance, strengthening and monitoring of existing buildings have become more and more important. This tends to result in smaller investment for new buildings and significant increase for cost for maintenance and observation. These arrangements should start as early as possible and must be carefully maintained. In many cases this convention was not hold in the past. A lot of cases of damage at buildings at the age of 30 till 50 years underline this fact. The reasons for damages are manifold and reach from faulty construction till unpredictable natural phenomena [1]. Among other things natural facts have caused a stronger focus on building monitoring by publicity. One contribution for a safe structural monitoring can be given by modern measurement techniques. They allow a blanket assessment of the actual situation additionally to visual controls. Thereby a clear distinction between temporary and permanent measurement should be made. For permanent measurement rugged measurement systems are needed. Electrical systems like strain gauges are not the best alternative. Hence optical measurement systems move over to the foreground.

Structural situation in Europe – building situation

European-wide examinations prove the high importance of older existing buildings. Studies in big European countries like France or Great Britain show that the fraction of apartments in older buildings (more than 20 years old) takes a portion of 75 percent of the whole floor space. It is very important to protect these fundamental economic resources. One possibility of an effective and sustainable maintenance can be smart composite structures, which contain Fiber Reinforced Polymer and integrated fiber optical measurement systems.

From FRP to Smart Composite Structures

Fiber Reinforced Polymers (FRP) have got more and more important during the last decade. The fields of application are widespread and not only focused on civil engineering. In civil engineering the main usage of FRP is the repair of concrete structures. But also for other building materials, for example wood constructions, FRP can be used. In the majority of cases carbon fibers are used as reinforcing material. Reasons are the superior technical properties of Carbon fibers compared to other high-strength fibers like glass fibers or aramid fibers [1]. Table 1 shows the properties of different fiber types. The high modulus of elasticity and the great tensile strength of carbon can be seen clearly. The Carbon Fiber Reinforced Polymer (CFRP) arises when circa 70 vol.-% high-strength carbon fibers are embedded into an epoxy matrix. The number of products of CFRP for reinforced concrete (RC) constructions is huge. Examples are at the surface bonded CFRP laminates or sheets as well as laminates which are placed in slots at the concrete surface. Furthermore it is possible to prestress CFRP laminates. Another favorable way is to combine these different types.

Table 1. Properties of different fiber types.

Fiber type	Density	Axial tensile strength	Axial modulus of elasticity	Breaking strain
[-]	[g/cm³]	[kN/mm²]	[kN/mm²]	[%]
Glass	2.57	2.60	75	3.50
Aramid	1.45	3.00	110 - 125	2.40 - 2.70
Carbon	1.80	3.53 - 4.90	230	1.50 - 2.10

For example the combination between prestressed and in slot bonded laminates can be realized. Main fields of application are strengthening of RC beams under flexural tension and shear as well as the retrofitting of columns with wrapped CFRP sheets.

Failure types of FRP materials can differ. Main types of failure can be the cracking of the reinforcing fiber or matrix and the bond failure or delamination between fiber and matrix. The stiffness of the fiber material, form, amount and orientation of fiber, the bond between fiber and epoxy matrix as well as the matrix properties affect the stiffness and resistance of the FRP material. Besides the types of failures of the composite material, the bond behavior between FRP and concrete surface is very important. In particular this contact zone is critical for the design of CFRP strengthened concrete structures. Above all in structures under bending moment the small tensile strength of concrete is the most important parameter for the bond bearing strength. Figure 1 shows the delamination of a CFRP sheet during a displacement controlled four point bending test. The delamination started in this case at the last bending crack. In figure 1 also the failure mode of a wrapped concrete column can be seen. In this case the cracking of the reinforcing fiber (after reach of ultimate strain) was the failure type.

Figure 1. Destroyed concrete beam and column after failure of CFRP material.

The described failure types happen very fast and often without any previous notice. A ductile behavior of the strengthened structural element can not be achieved under this term. But assurance is essential in civil engineering. Furthermore it is not comprehensively clarified if the constancy of the bonding between the different partners will be assured over a long time or under dynamic load.

With adequate measurement systems it might be possible to realize a safe monitoring to control the powerful but brittle CFRP strengthening systems. With optical measurement systems, which base on glass fibers, one can integrate the sensor system in the FRP material [2]. The name of such materials is smart composite. These structures have the ability to measure their own mechanical behaviors and to give a solid feedback. The most important representatives under the fiber optic measurement systems are the Fiber Bragg Grating Sensors (FBGS).

PROPERTIES OF FIBER BRAGG GRATING

Configuration and Assembly

A Bragg Grating consists of a periodic sequence of artificial and equidistant refraction switches in the core of an optical fiber [3]. It can be produced over emblazing of an interference pattern of ultraviolet light. The core is surrounded by cladding. The refraction index of both is different and this results in total reflection of inducted light λ.

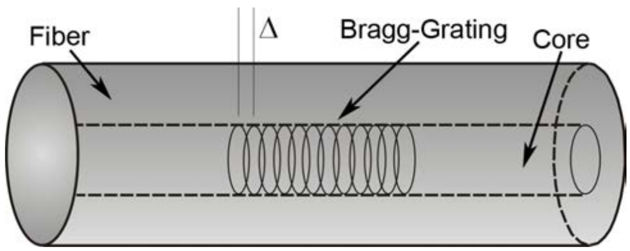

Figure 2. Glass Fiber with Bragg Grating.

For mechanical protection the glass fiber gets an additional coat of synthetic material. This coating can consist of polyimide and prevents the infiltration of water and hydrogen. The maintenance of the safety function is very important, in order to guarantee an error free and durable FBG unit. For the production of FBG in optical fibers it is necessary to have powerful ultra violet laser with wavelength of circa 240 ... 250 nm. These will be apportioned in two bales. This generates a pattern with a period Δ. This period is addicted by the angle of the laser. Δ describes thereby the distance between two interference maxima in the pattern. At every maximum a change of the refraction index will happen, whereby the actual pattern develops. The coating must be removed before producing the FBG. This means an additional stress for the optical fiber. Particularly a decrease of strength in these areas might be possible. It is also possible to write the FBG into the optical fiber during the production of the optical fiber.

Theoretical background

Because of the emblazed interference pattern a reflection of inducted appointed light wavelength is possible. Light with the Bragg wavelength λ_B will be reflected [3]. This means that light of inducted spectrum will be reflected according to equation (1).

$$\lambda_B = 2 \cdot n_{eff} \cdot \Delta \qquad (1)$$

where λ_B = Bragg wavelength, n_{eff} = effective refraction index and Δ = period of diffraction grating.

This term of the light spectrum will be missing in the penetrated array. With equation (1) it is possible to clarify the measuring principle of FBG. A change of the period of diffraction grating results in an adjustment of the Bragg wavelength. Now other spectra of light will be reflected. These modifications can be activated by strain or temperature and then changes can be measured. The change of strain in the optical fiber can be explained with equation (2).

$$\Delta\lambda_B = \lambda_B \cdot (1 - p_e) \cdot \Delta\varepsilon \qquad (2)$$

where $\Delta\lambda_B$ = change of Bragg wavelength, p_e = photo elastic component ≈ 0.22 and $\Delta\varepsilon$ = change of strain.

Besides the monitoring of strain in structural elements the temperature measurement will be of interest. Also in this area FBGS can be used. With equation (3) the change of temperature can be considered.

$$\Delta\lambda_B = \lambda_B \cdot (\alpha + \xi) \cdot \Delta T \qquad (3)$$

where α = thermo-elastic coefficient, ξ = thermo-optic coefficient and ΔT = change of temperature.

Equation (3) shows that the simultaneous change of strain and temperature results in a modification of wavelength. With equation (2) and equation (3) the following combination is feasible in which strain and temperature are considered.

$$\Delta\varepsilon = \frac{1}{1 - p_e} \cdot \left(\frac{\Delta\lambda_B}{\lambda_B} - (\alpha + \xi) \cdot \Delta T \right) \qquad (4)$$

For explicit strain measurements it will be necessary to perform a compensation of the temperature influence. One possibility is an additional FBG only for temperature measurement in mechanically decoupled areas. These FBG can be emblazed at the same optical fiber.

Multiplexing of several Fiber Bragg Grating

One important reason for continuing propagation of Fiber Bragg Gratings should be seen in the ability of Multiplexing [4]. One FBG can measure strain or temperature changes only at one point. But there is the possibility to distribute several Bragg Gratings at one optical fiber. The geometrical arrangement along the length of the fiber can be varied. In figure 3 such a disposition is shown.

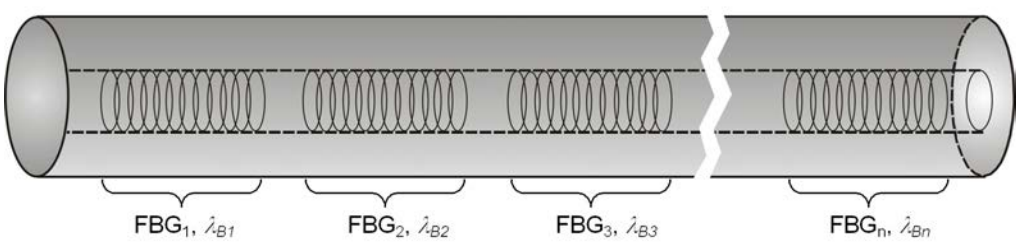

Figure 3. Multiplexing.

At every single Bragg Grating light spectrums will be reflected, which obey equation (1). A determination of the different Bragg Gratings is possible because of the variation of the period of diffraction grating between the various FBG. In such a way a distributed and wavelength coded sensor is developed.

The variation of the period of diffraction means that a preferably wide-band light spectrum must be inducted into the optical fiber. This works with strong light emitting diodes and with laser technique. The analysis of the reflected light spectrums can be done with different methods. Thereby a differentiation in active and passive optical filters as well as interferometric and spectral measurement systems is possible. The spectral analysis is possible with a spectrometer and allows the direct measurement of the Bragg wavelength.

USE IN FRP FOR CONCRETE STRUCTURES

Possibilities for concrete constructions

The advantages of fiber-optic measurement systems compared to classical electric measurement procedures are great. Examples are the small dimensions and the low weight as well as the high static and dynamic resolution of measurement values. Other advantages are the insensibility towards electromagnetic radiance and the most chemicals. By the use of glass fibers, in which the FBG are emblazoned, it is possible to integrate the sensor system directly into building materials like concrete or FRP. In figure 4 the relative dimensions of a strain gauge and a FBGS plus reinforcement steel are shown.

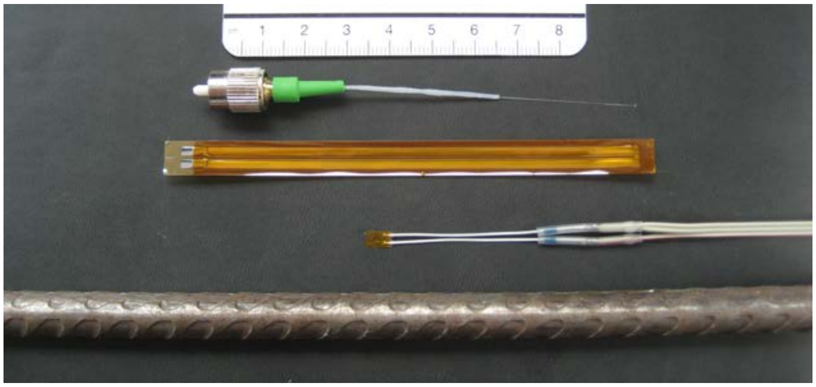

Figure 4. Relative dimensions of reinforcement steel, glass fiber and strain gauge.

Because of the favorable properties of FBGS, different applications for reinforced concrete constructions become possible [5, 6]. So it is possible to integrate the FBG sensor system in reinforcing bars. This can be done by making a groove in the reinforcing bar in which the optical glass fiber can be placed and fixed with epoxy resin. The distribution of strain along the length of the steel bar can be measured by multiplexing of several FBG as introduced in chapter 2.3. The results can be used to explore non-linear effects like tension stiffening. But there is a problem, because the bound between reinforcing bar and optical fiber/FBG must be realized by the epoxy resin. So careful arrangement of the FGB's is very important for realistic results.

The direct use in the concrete matrix is still harder because of the small long term durability of the coating around the glass fiber in alkaline medium. Moreover the optical glass fibers have to be especially protected because of their small proportions. The fitting and adjustment of the optical fibers/FBGS in concrete must be done with care.

Use in FRP

The problems discussed in chapter 3.1 can be avoided with the use of Fiber Bragg Gratings in Fiber Reinforced Polymers [2]. The direct embedding in the epoxy resin allows exact strain measurement in the material. So mistakes are minimized during the monitoring. The epoxy resin is thereby an effective protection for the optical fiber.

CFRP systems for retrofitting of concrete structures with optical sensors have already been discussed in several publications. It could be shown that the reinforcing function of the CFRP can be ideally combined with the measurement and monitoring functions of the optical sensors like FBGS. Lu and Xie [7] accomplished strain measurements in smart CFRP sheets with FBGS. The sheets reinforced the tension zone of concrete beams, which were also arranged with FBGS sensors in the compressive zone and the reinforcing bars. For control extra electrical measurement with strain gauges was carried out. The results showed a very good agreement and it was possible to monitor the whole strain distribution of the profile. So it is possible to get better understanding of the non-linear behavior of CFRP reinforced concrete beams. It is a chance for more safety and sustainability.

It also was possible to get first results with fiber optical measurement systems at real constructions. Bastianini et al. [8] were able to localize and monitor failures between concrete surface and the used CFRP system at inaccessible sites. FBGS can measure lateral stress and cracks in cross direction in FRP.

There is no information about damage of the CFRP laminate in publications. Consequently it is possible to develop intelligent smart structures, which are able to reinforce concrete structures because of their potentials to measure a multitude of mechanical states over a long time.

SETTING THE GLASS FIBER WITH EMBROIDERY

Sensor-based textile clutch

For an effective production of smart structures, it is very important to fix the optical fiber sufficiently during the production and the lamination of the FRP material. Especially the placing of the fiber in a particular design is complex and must be done carefully.

One possibility to realize any designs of sensor arrangements can be seen in embroidering the optical fiber directly on a carrier material. In this case the carrier materials are the reinforcing fibers which are often arranged as webs or clutches (for example carbon fiber clutch, like in figure 6). If only a uniaxial state of stress has to be measured, the fixing of the fiber can be easily done. The fixing can be realized with epoxy resin, because of the linear direction of the fiber. But if it is necessary to measure biaxial stress conditions (or if temperature compensation is needed) more difficult fiber courses will be required. Some minimum radiuses must be applied if the direction of the fiber changes. So the stress, caused by breaks, for the fragile fibers can be minimized. The adaptation at the designated courses of the optical fiber by hand is now very difficult. The selective fixing (epoxy resin) causes a lot of problems, and often it does not bring the optimal results. The direct embroider of the optical fiber (and the FBGS) clearly simplifies the fixing. An embroidery machine, using computerized support, is able to fix the fiber optical system accurately fitting at the carbon fiber material.

By using computer-controlled machines, like shown in figure 5, it is possible to achieve a very high degree of prefabrication as well as a high productiveness. The economic industrial fabrication of smart structures can be realized.

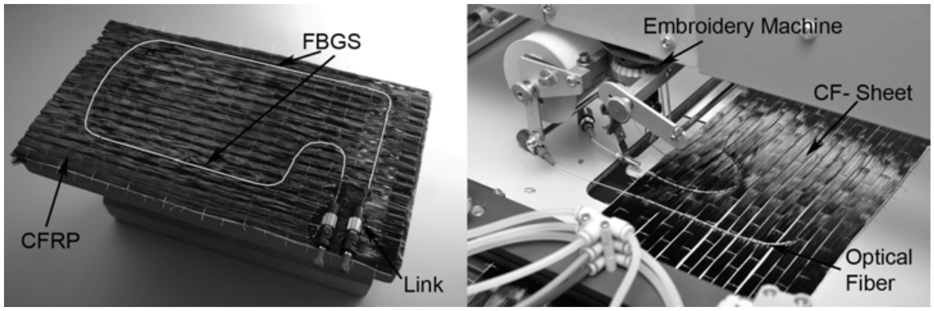

Figure 5. Courses of optical glass fibers with FBG on smart CF-composites.

In figure 5 the direction of an optical fiber with FBG for strain and temperature measurement is demonstrated. With this method it is possible to fix the Fiber Bragg Gratings close to these locations where strain monitoring is wanted. Through the embroidery method the direct mechanical bond between optical fiber and carbon fiber clutch is possible. Now the sensor based carbon fiber textile can be easily industrially laminated. Another possibility is the direct converting at the building site by hand made lamination.

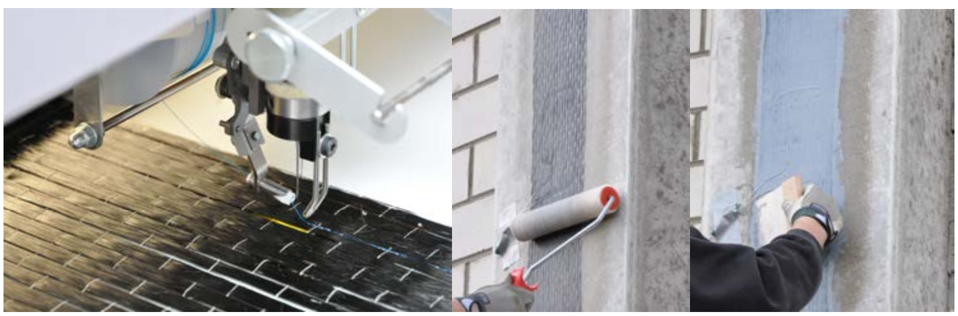

Figure 6. Production of sensor based CFRP (First: embroider of optical fiber; Second: lamination by hand at building site).

Broadband light spectrum can be inducted and the reflected light can be analyzed with connections shown in figure 6 (link). The transport of the light spectrum over long distance is possible by further using glass fibers.

Processing

The most important question during the embroider tests was, if the optical fibers or the reinforcing fibers would be damaged or influenced through the embroider procedure. With tension tests at CFRP sheets, without FBGS and with FBGS, it was possible to detect that there were only marginal losses of bearing strength and stiffness. Damages at the glass fiber and the FBG will be less if computer-controlled machines are used. With directly following spectral measurements at the fiber after the embroider procedure an effective quality check is possible. In fact the laminating processes with epoxy resin as well as the application of the sensor-based sheets at concrete structures (figure 6) were possible without problems.

CONCLUSIONS

Structural monitoring will become more important because of the increasing age of the existing buildings. The precious economical resource building-asset must be monitored and repaired carefully. One possibility to monitor and reinforce existing concrete structures is given by the embedding of optical fibers with FBG in Carbon Fiber Reinforced Polymer (smart composite). The small proportions of optical glass fibers allow very flexible strain and temperature measurements inside of the CFRP material. Advantages like the high tensile strength of the CFRP material will not be influenced by the FBG sensor system. But the arrangement and fixing of the optical fibers and the FBG at the right position is problematic. The presented embroider method enables an accurate and reproducible fixing method.

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