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Smart CFRP systems with FBG sensors for the strengthening of reinforced concrete members

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ABSTRACT: During the last ten years an increasing amount of Carbon Fiber Reinforced Polymer (CFRP) applications was observed. Main fields of application are the strengthening of reinforced concrete members like beams or columns. 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. 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 (carbon fiber) will be presented. On the basis of four point bending tests on beams and tests on wrapped columns the potential of the Smart CFRP system is introduced.

1 INTRODUCTION

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. 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.

1.1 From FRP to smart composite structures

Fibre Reinforced Polymers (FRP) got more and more important during the last decade. In civil engineering one of the main usages of FRP is the repair of concrete structures. 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. The number of products of Carbon Fiber Reinforced Polymer (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. 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, the form, the 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 thereby the bond behaviour 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. The described failure types happen very fast and often without any previous notice. A ductile behaviour 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 decade or under dynamic load.

With adequate measurement systems it might be possible to realise 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. The name of such materials is smart composite. These structures have the ability to measure their own mechanical behaviours and to give a solid feedback. The most important representatives under the fiber optic measurement systems are the Fiber Bragg Grating Sensors (FBGS).

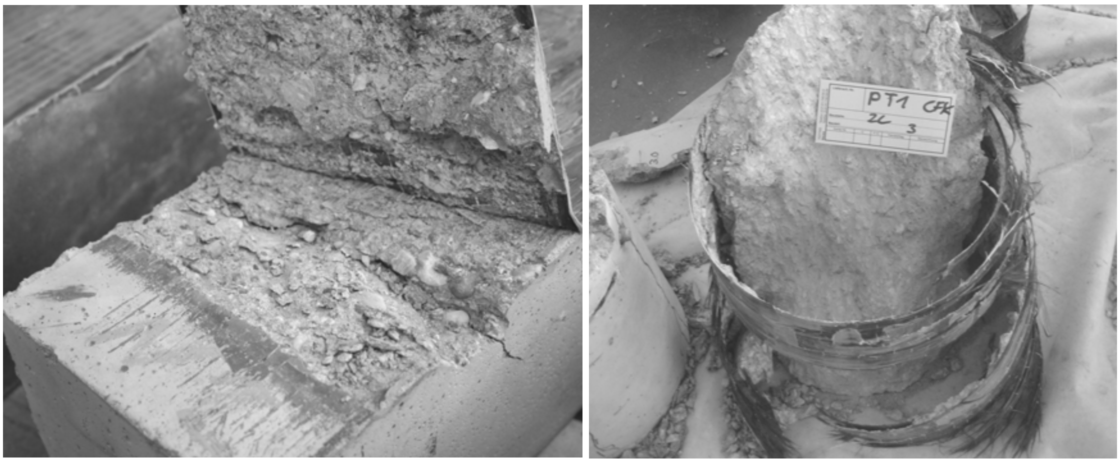


Figure 1. Destroyed concrete beam and column after failure of CFRP material.

1.2 Properties of FBG

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. 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. This means that light of inducted spectrum will be reflected which according to equation 1.

$$\lambda_B = 2 \cdot n_{eff} \tag{1}$$

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.

$$\Delta\lambda_B = \lambda_B \cdot (1 - p_e) \cdot \Delta\varepsilon \tag{2}$$

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

2 USE OF FBG IN FRP FOR CONCRETE STRUCTURES

The advantages of fiber-optic measurement systems compared to classical electric measurement procedures are great. In figure 2 the relative dimensions of different strain gauges and a glass fiber for FBG are shown. One big advantage of the fiber-optic measurement system, the small dimensions, can be seen clearly. Furthermore there is the possibility to distribute several bragg gratings at one optical fiber. The analysis of the reflected light spectrums can be done with only one spectral measurement system. Other advantages are the insensibility towards electromagnetic radiance and the most chemicals as well as the high static and dynamic resolution of measurement values. Because of the favorable properties of FBGS, different applications for reinforced concrete constructions become possible. 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 easily can be placed and fixed with epoxy resin. The distribution of strain along the length of the steel bar can be realized by multiplexing of several FBG. The results can be used to explore non-linear effects like tension stiffening.

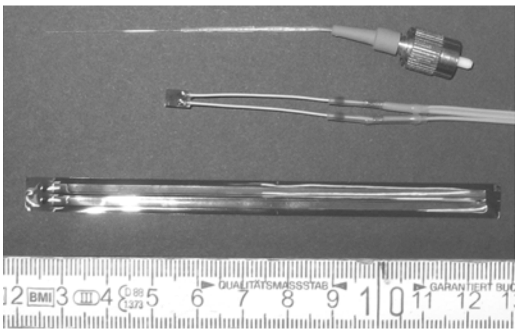


Figure 2. Optical fiber with link and different strain gauges.

But there is a problem, because the bond 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.

2.1 FBG in FRP

The direct embedding of optical fibers with FBG in the epoxy resin of FRP materials 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 & Xie (2007) accomplished strain measurements in smart CFRP sheets with FBGS. It also was possible to get first results with fiber optical measurement systems at real constructions. Bastianini et al. (2005) were able to localize and monitor failures between concrete surface and the used CFRP system at inaccessible sites.

2.2 Setting optical glass fiber with embroidery

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. 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 (take a look at figure 3).

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. 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 (sheet) 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. The whole production of the sensor based CFRP can be seen in figure 3.

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 losess 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 were possible without problems, like the following tests will show.

Figure 3. Production of sensor based CFRP (First: embroider of optical fiber; Second: lamination by hand at building site).

3 EXPERIMENTS WITH CFRP REINFORCED BEAMS AND COLUMNS

In the context of the „regional Wachstumkern highStick" technical textiles like carbon fiber sheets (CF clutches) are to be embroidered with optical fibers, to test the effectiveness of the strain measurement of the developed smart composites. For this purpose it was necessary to create reinforced concrete beams as well as short concrete columns. In 4 point bending tests (beams) and compression tests (columns) the significant changes of strength and strain were researched.

3.1 Four point bending investigations with RC beams (test program 1)

The length of the used specimens conducted 70 cm (dimensions of 700 x 150 x 150 mm) and they consisted of high strength concrete as well as two reinforcing bars (diameter 6 mm) as bending reinforcement. All in all 3 beams were produced. At first the test beams were loaded in a deflection controlled four point bending test up to a crack width of 0.40 mm. Thereby it was possible to simulate a realistic measure of redevelopment and to bring the beams into the cracked status. Thereafter the application of the sensor based CF sheets (tensile strength: 3 900 N/mm², elastic modulus: 230 000 N/mm², thickness: 0.11 mm) followed with an epoxy resin at the surface of the tensile zone of the concrete beams. For the deflection controlled tests displacement transducer were used as well as load cells to get load deflection curves and load strain curves of the bending tests. Figure 4 explains the whole test set-up and the used equipment.

The CFRP sheets were glued (like shown in figure 4) at the underside in the tensile zone of the concrete beams. The CFRP material was appointed with an optical fiber with one FBG by use of the embroider technique. The orientation of the optical fibers carried out in longitudinal direction in the middle of the sheet. Furthermore the optical fiber was arranged parallel by use of a kink as turning point (beam 1). For checking of the optical strain measurement strain gauges were used additionally. They can be seen in figure 4 at the right hand side.

Every strain gauge was ranged alongside the particular FBG. Furthermore the nitriding optical fibers and the arrangement of the used FBG can be seen. It is also possible to recognize the good integration in the epoxy matrix. Through the arrangement of the FBG in the middle of the beams it was possible to compare the strain measurements of the FBG. Furthermore it was possible to compare the electrical measurement system (strain gauge) directly with the results of the FBG. The results of the strain measurement with the bragg gratings, because of bending stress, can be seen in figure 5.

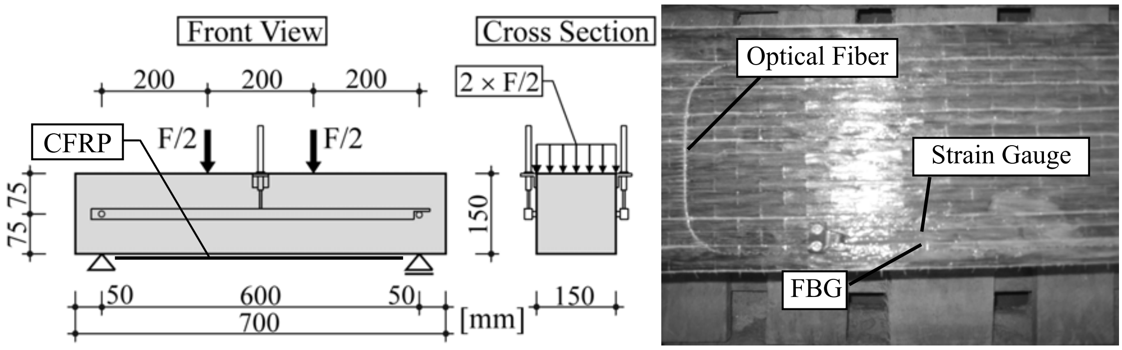


Figure 4. Test set-up of the four point bending test and arrangement of the optical fiber measurement system (Test program 1).

The agreement between the FBG strain measurements of the three beams was good by trend. The beams 1 and 2, which were loaded up to the failure, presented a good agreement, especially before and after the failure. The beams 2 and 3, in these cases the arrangements of the optical fibers were the same, showed in the strain area in range from 1 000 to 4 000 µm/m a very good agreement. The comparison of the results of the FBG strain measurement with the results of the strain gauges (figure 5) show, that an efficient monitoring of the strain development inside of the CFRP Sheets was possible. The curves present a good convergence between electrical and optical measurement methods at the three test beams (B1, B2, B3). The achieved results clarify the capability of the nitrogenized FBG sensor system. A damage or detraction of the optical glass fiber because of embroider or of the laminating did not appear.

3.2 Four point bending investigations (Test program 2 and 3)

After the satisfying tests with optical fibers with only one FBG, new experiments with three FBG at one fiber should be investigated at three concrete beams with same setting as in chapter 3.1. For this purpose the optical fiber was again arranged parallel by use of a kink as turning point. The control of the optical strain measurement was once more realized with a strain gauge, which was arranged in the middle of the CFRP sheet. FBG 1 and 2 were used for strain measurement in the middle of the beam at each side. The FBG 3 was arranged in the turning point to realize temperature compensation.

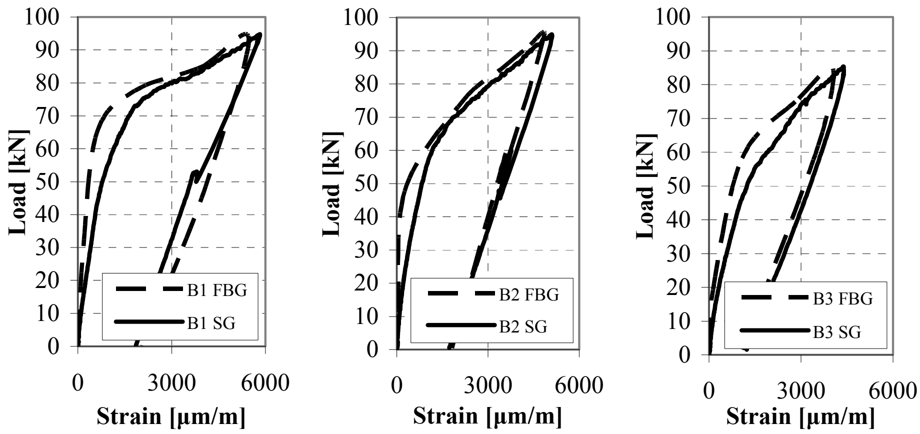


Figure 5. Load strain curves of strain gauge (SG) und Fiber Bragg Grating (FBG) (Test program 1).

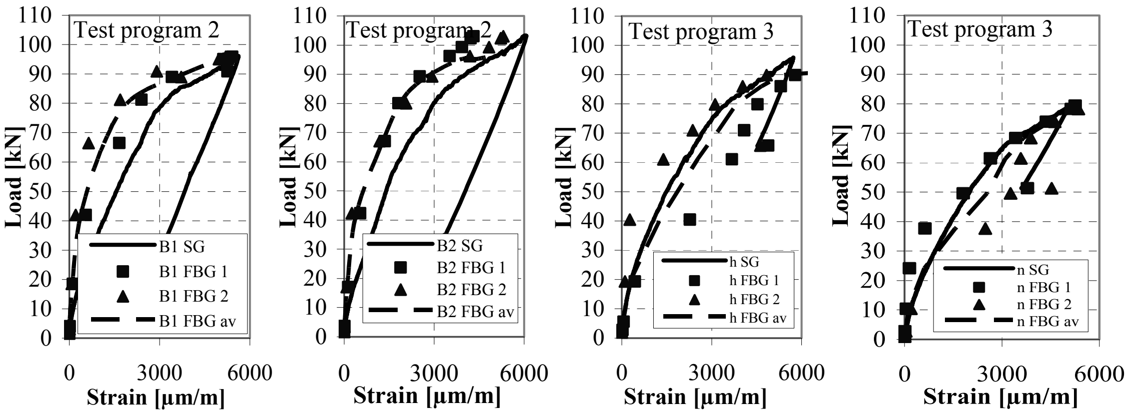


Figure 6. Load strain curves of strain gauge and FBG by use of concrete C60/75 (h) (Test program 2 and 3) and C30/37 (n) (Test program 3).

Thereby it was to analyze if the arrangement in the breaking point assures an adequate mechanical decoupling to realize an independent temperature measurement. The load strain curves explained in figure 6 (left hand side) show a good agreement between the results of the strain gauges and the average values (FBG av) of the two in lengthwise placed FBG 1 and 2. However between the FBG 1 and 2 arranged at beam 1 irregularities between the measurement results were assessed. Reasons for these results can be bending cracks near the FBG position, which create different strain states at the FBG measurement points because of the non-linear behaviour of the reinforced concrete beams (concrete, reinforcing bars, CFRP material). The results attest that it is possible to nitrogenize several FBG, grouped at one optical fiber, at a CF clutch free of failure. The analysis of all FBG was possible. Thereby it worked to create temperature compensation by the use of FBG 3 in the breaking point.

In test series 3 the effects of a concrete with normal strength (C30/37) (n) were monitored. Furthermore a new sensor arrangement at the CF sheet was sampled (figure 6 right hand side). More over all, bending cracks of concrete tension zone were investigated. These facts and a very careful laminating of the CFRP System guarantied the very good agreement between the results of the strain gauges and the average values (FBG av) shown in figure 6 on the right hand side. Bending cracks near FBG were the reasons for irregularities.

3.3 Experiments with confined short concrete columns

To test the new smart CFRP system, different concrete members were strengthened and tested.

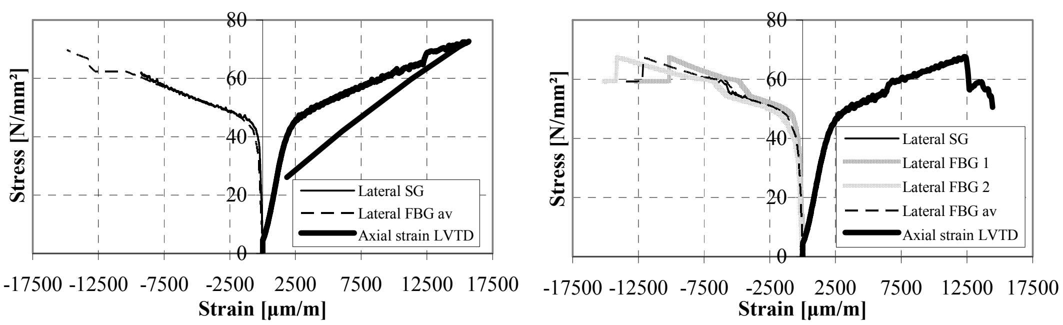
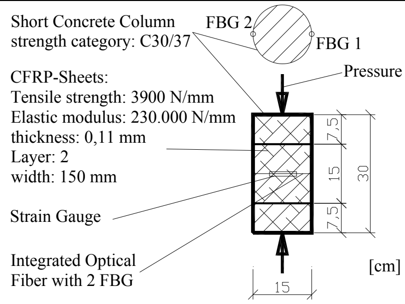


Figure 7. Stress strain curves of strain gauge (SG) and FBG average (FBG av) of column 1 and 2.

So for example short concrete columns were confined and the significant changes of strength and strain (of the used concrete) researched. In table 1 the test set-up and the main properties of the columns can be seen.

Table 1. Experimental results.

	f_{cc}	f_{cc}/f_{co}	ε_{cc}	$\varepsilon_{cc}/\varepsilon_{co}$	$\varepsilon_{l,FBG}$	$\varepsilon_{l,SG,max}$
	[N/mm²]	[-]	[‰]	[-]	[‰]	[‰]
1	72.7	1.74	15.69	7.57	14.87	9.26
2	66.4	1.59	12.40	5.99	14.10	7.72
3	68.2	1.63	14.00	6.76	16.54	7.83
	69.10	**1.65**	**14.03**	**6.77**	**15.17**	**8.27**



In figure 7 the stress strain curves of the first specimen are shown. It can be seen, that an efficient monitoring of the strain development inside of the CFRP sheet was possible. The curves present a very good convergence between electrical and optical measurement methods. Thereby only the FBG system guarantied a save measurement till the ultimate strain of the carbon fibers at nearly 1.5 % (see also table 1 $\varepsilon_{l,FBG}$). All strain gauges (SG) showed failure at approximate 0.8 % (table 1: $\varepsilon_{l,SG,max}$). Furthermore it also works to find out the area of failure inside the CFRP material, like shown in figure 7 (right side). In this case the ultimate strain inside the CFRP material was reached near FBG 2. In table 1 the ultimate stress (f_{cc}) and strain (ε_{cc}) of the three specimens in opposite to the results of plain concrete columns (f_{co}, ε_{co}) are shown. It clearly can be seen, that a high raise of strength and strain is possible with the used sensor based CFRP sheets.

4 CONCLUSIONS

By using of embedded fiber optic measurement systems, like bragg gratings, it is possible to realize an integral monitoring of the CFRP material. 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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