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Technical textiles for monitoring applications in construction

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Abstract:

The fields of activity in civil engineering are subject to a permanent change. Thereby, maintenance strengthening and monitoring of existing buildings have become more important. An increasing number of carbon fiber reinforced polymer (CFRP) applications could have been observed. In some of those applications, properties that are inherent to CFRP's like brittleness and low bonding ductility between the CFRP and concrete has been pointed out to be a challenge, which is considered to refrain this promising technique from a wider range of use.

In this paper, an optical strain sensor applied on FRP system is presented. Thereby optical fibers containing fiber Bragg grating sensors (FBG) are used, being directly integrated in the FRP systems. The recent work is focused on the investigation of reliable fixation and alignment techniques for the silica fibers in order to create a reliable, industrial-grade compound between the sensing FBG element and the FRP system. The paper describes the approach for setting the sensing silica fiber directly on the reinforcing fiber material with an adapted embroidery technique.

An embroidery machine was modified in order to align and fix the optical fiber accurately to the reinforcement carbon fiber. By using such machines, a very high degree of production yield and efficiency has been demonstrated for sample FRP structures that were applied to several objects per a manual lamination technique. The FRP system's potential was thoroughly evaluated in multiple four-point beam bending tests, and long-term interrogation in field tests.

Key words: CFRP, GFRP, Fiber Bragg Grating, Embroidery, Health Monitoring.

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1 Introduction

The fields of activity in civil engineering are subject to permanent changes. Thereby, maintenance strengthening and monitoring of existing buildings have become more and more important. This tends to result in smaller investments for new buildings, and in a significant cost increase for maintenance and health monitoring arrangements, which should start as early as possible and must be carefully planned and conducted. In the recent past, this convention has been more or less ignored for the majority of cases. The reasons for damages are manifold and reach from faulty construction till unpredictable natural phenomena [1]. Advanced measurement techniques can contribute to a reliable and cost effective structural health monitoring by allowing an easier assessment of the buildings actual health status, in addition to visual controls. For permanent measurements, rugged measurement systems are needed. Conventional electrical systems like strain gauges suffer from some intrinsic limitations that are a permanent stimulation for further research. Hence, optical measurement systems that have been intensively investigated during the last two decades and nowadays come to the fore.

2 From FRP to sensing composite structures

Fiber reinforced polymers have attracted more and more attention during the last decade. The fields of application are widespread and not only focused on civil engineering. The main usage of FRP's in civil engineering is the non-destructive reinforcement and repair of concrete structures. However, FRP's can be used also for other building materials, for example wood constructions. Carbon fibers are used as reinforcing material in the today's majority of cases. Reasons are the superior technical properties of carbon fibers compared to other high-strength fibers. [1]. Table 1 gives an overview about the properties of this fiber typ.

Table 1: Fiber properties used for FRP's

Fiber Type	Axial Tensile Strength	Axial Modulus of Elasticity	Strain Limit
[-]	[kN/mm²]	[kN/mm²]	[µm/m; microstrain]
Optical fiber (w/ FBG)	4.8	71.7	10.000
Carbon	3.53 - 4.90	230	15.000 - 21.000

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

Like other materials, FRP material is subject to statistical failure during its life-span. Failure types of FRP materials may have different reasons. Common failure types are reinforcing fiber cracks, matrix and bond failures, or delamination between fiber and matrix. The fiber material's modulus, the form factor, the fiber amount and orientation, the bond between fiber and epoxy matrix, as well as the matrix properties, affect the stiffness and strength of the FRP material. Besides the composite material's failure types, the bond behavior between FRP and concrete surface is a very crucial parameter. Figure 1 shows the delamination of a CFRP sheet during a displacement-controlled four-point bending test. In this case, the delamination started at the last bending crack. The failure type of a wrapped concrete column is also visible here, indicating that the crack of the reinforcing fiber (after reaching an ultimate strain level) has been the initial event for the drop out.

Figure 1: Destroyed concrete beam after failure of CFRP material.

Adequate measurement systems might help to realize a reliable monitoring in order to long-term survey the strong but brittle CFRP strengthening systems. With optical measurement systems based on silica fibers, one can integrate the sensor fibers directly in the FRP material [2] that then is sometimes described as "smart" composite, which is not fully correct as such elements are lacking both analyzing and control capabilities. But if connected to a monitoring system, these structures are able to return measurement signals continuously under their normal

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operation, thus reporting their current mechanical state and integrity data without any user interaction. Among other fiber optical sensing systems, fiber Bragg grating based strain sensor systems have evolved from a predominant laboratory use to a mature technology in the current advanced health monitoring universe.

3 FBG usage in FRP for concrete structures

3.1 Possibilities for Concrete Constructions

The advantages of fiber-optic measurement systems compared to classical electric measurement procedures are known. Examples are the small dimensions and the low weight, as well as the high static and dynamic measurement resolution. Other advantages are the insensibility to electromagnetic fields and the resistance against the most common chemicals. By using of silica fibers, it is possible to integrate the sensor system directly into building materials like concrete or FRP. In Figure 2, the relative dimensions of a strain gauge, an FBG with connector, and common reinforcement steel are shown.

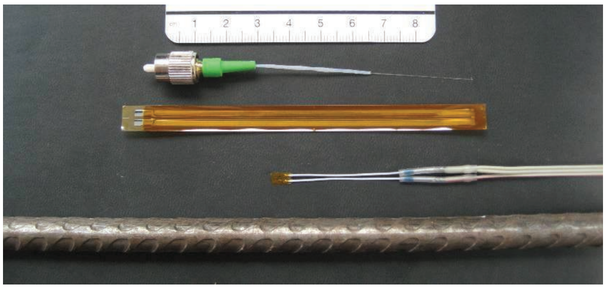

Figure 2: Relative dimensions of reinforcement steel (bottom), silica fiber with connector (top) and electrical strain gauges (middle).

Different applications for reinforced concrete constructions have been evaluated in the past [3, 4] due to some favorable properties of FBG's. So, it is possible to integrate the FBG sensor fibers in reinforcing bars. Making a groove in the reinforcing bar in which the optical glass fiber can be placed and fixed with epoxy resin can do this. The distribution of strain along the steel bar's length can be measured by multiplexing several FBG's as introduced in chapter 2.3, in order to explore non-linear effects like tension stiffening. In this scenario, the bound between reinforcing bar and optical fiber/FBG – commonly realized by an epoxy resin – defines a weak point of the matrix. So, a careful arrangement of the FGB is very important for reliable results. An FBG's direct use inside the concrete matrix is still harder because of the small long-term durability of the polymer coating around the glass fiber in an alkaline medium. Moreover, the optical glass fibers have to be especially protected because of their small diameters of 0.25 mm and hence their fragility. The fitting and adjustment of optical fibers/FBG's in concrete can only be done by experienced experts and/or the helpful use of appropriate carriers.

3.2 FBG usage in FRPs

The constraints discussed in chapter 3.1 can be overcome by using fiber Bragg gratings in fiber reinforced polymers [2]. The direct embedding in the epoxy resin attached to the structure in a thin layer allows an exact strain measurement in the material that eliminates nearly all effects that may spoil the measurement values during the monitoring. The epoxy resin ensures a defined strain translation between the structure and the FRP-FBG sensor, and besides it is 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 FBG's. Lu and Xie [5] accomplished strain measurements in smart CFRP sheets with FBG's. Additional electrical measurement with strain gauges was conducted for the optical measurement's validation. Their results showed a very good correlation and thus they were able to monitor the whole strain distribution of the profile.

4 Optical fiber alignment

For an effective production of sensing structures, it is very important to fix the optical fiber sufficiently on the FRP clutch matrix before lamination. Especially the fiber placing according to a particular design is complex and must be done carefully. One possibility to realize flexible sensor arrangement designs is the fiber's embroidering directly onto the textile carrier mesh. The carrier material consists of reinforcing fibers that are usually arranged as meshes or clutches (see the carbon fiber clutch in Figure 3). Given the case that only a uniaxial state of stress is subject to measure, the optical fiber application is easy. It can be conducted simply with epoxy resin because of the fiber's linear alignment.

However, if it is necessary to measure biaxial stress conditions (or an additional temperature compensation is needed) a more difficult fiber adjustment is required. For instance, in order to avoid fiber breakage during application a minimum bend radius of 20 mm must be taken into account when the fiber's orientation changes.

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Depending on the fiber alignment pattern's complexity, a manual fiber attachment appears sometimes rather difficult. Tack-gluing the fiber with epoxy resin did not address the problem sufficiently in terms of both handling and yield. Eventually, embroidering the optical sensor fiber directly onto the CF matrix was proven to be an effective approach that led to reliable results. An adapted embroidery machine using computerized support is able to attach the optical fiber optical accurately on the carbon fiber material.

Figure 3: Embroidery of optical fiber on technical textile (carbon fiber clutch).

Using programmable machines, a very high degree of production yield and efficiency has been demonstrated for a couple of FRP sensor samples. The direct embroidery is a method that results in a reliable but still flexible mechanical link between the optical fiber and the carbon fiber clutch. The pre-formed samples can be laminated by an industrial lamination process in a further production step. In our field measurements, we have used a manual lamination technique in order to attain an exact alignment between the discrete sensor and the measurement object in order to detect the strain at the correct position (Figure 4).

Figure 4: Handling at building site

5 Experiments on smart FRP sheets

5.1 Tests in Laboratory

The developed sensor based textiles have undergone an extensive experimental program in order to evaluate their measurement reliability. Beside the strengthening properties of the FRP pads, the integrated FBG's strain measurement capabilities have been of special interest. Our investigations were focused on:

- the arrangement and integration of optical fibers on carbon and glass textile matrices and their integration into epoxy matrix to develop the FRP material,
- investigating the FBG's measurement resolution, accuracy, and zero-point stability compared to electrical strain gauges,
- various short-term and long-term tests, e.g. four-point bending-tests with static and dynamic load scenarios in order to evaluate the FBG's long-term signal integrity, including accelerated ageing experiments with sensing CFRP containing FBG's under harsh conditions (weathering),
- use of the smart FRP applied to different materials and test specimens,
- various pressure tests with FRP confined concrete columns to measure very high strains (>1,5%) beyond the FRP material's damage threshold,
- Development and test of a software supported online monitoring system.

Giving an example here, we present our investigations to concrete specimens in a four-point bending experiment. The 3 fabricated specimens have been composed of high-strength concrete with dimensions of 700 mm x 150 mm x 150 mm, together with two reinforcement steel bars (6 mm diameter).

In a first step, the test beams were loaded in a deflection-controlled four-point bending test that was driven up to a crack width of 0.40 mm. Thereby it was possible to attain a defined pre-damage by setting the beams to determined crack-state. Then we aligned the sensor-based CF sheets on the beam's tensile zone, followed by using an epoxy resin to attach the sensor pad to the beam's surface. For the deflection-controlled tests, displacement transducers were used together with load cells in order to retrieve load vs. deflection curves and load vs. strain. Figure 5 shows the entire test setup. The CFRP pads were attached to the beam's bottom in the tensile zone. The CFRP matrix incorporated an optical fiber with one FBG (uniaxial) integrated by the embroider technique described before. For comparison purposes, we added an electrical strain gauge close to the CFRP sensor.

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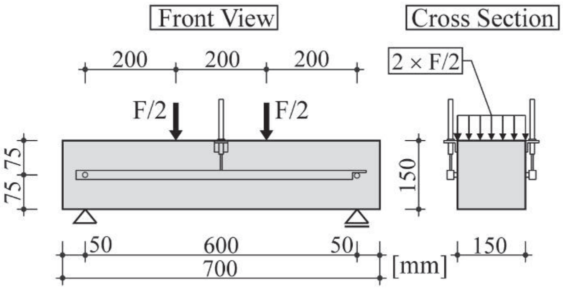

Figure 5: Experimental setup.

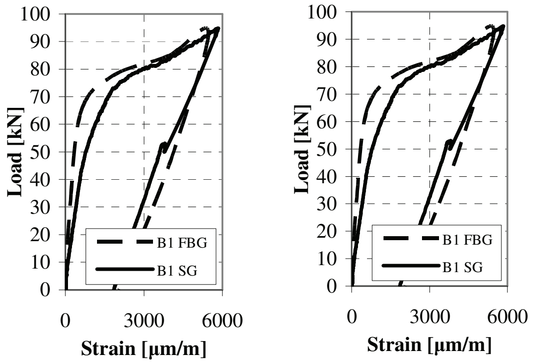

Figure 6: Load vs. strain curves of strain gauge (SG) und fiber Bragg gratings (FBG).

The comparison chart of Bragg grating strain values and strain gauge results under an applied bending force can be seen in Figure 6. We present 2 independent test cycles with CFRP sensors, each containing one uniaxial, stitched optical fiber (1 FBG). The comparison of the FBG's' strain output to strain gauge values suggests that beside small scaling effects an effective strain monitoring can be performed with CFRP sensors.

All measurements show a sufficient correlation between electrical and optical measurements for at least the 2 test beams (B1, B2). Continuing and repeating the experiments several times, we neither encountered any optical fiber damage or FBG degrading due to the embroidery process nor the laminating. All subsequent experiments underlined a good correlation between common measurement techniques like strain gauges and the FBG integrated in the smart FRP. At a glance, we summarize our main conclusions from all conducted experiments as follows:

- Embroidering optical fibers that contain FBG's on different technical textiles (carbon, glass) is possible.
- An integrated optical fiber does not negatively affect the handling of the textiles during lamination on a construction site.
- An efficient and steady strain monitoring inside the FRP sheet is provided until the FRP's strain damage limit.
- Good correlation between electrical and optical measurement methods is given in various measurement scenarios.
- Long-term load under static or dynamic forces do ostensibly not affect the FBG's stability inside the FRP in terms of drifting, creeping, or shifting, neither do harsh environmental conditions nor ageing effects.
- The use of CFRP (with/without integrated sensors) imposes a strong increase of bearing or confinement strength.
- Our investigations regarding the temperature influence on strain measurements have shown that this effect is considerably strong which resulted in the development of easy and reliable temperature compensation by using an additional FBG.
- In case that the FRP is not intended for a significant structural reinforcement, we encountered a very big potential for using GFRP sensor pads incorporating up to 3 FBG's for biaxial strain measurements.

Besides the CFRP sheets for structural strengthening with integrated strain monitoring, various configurations of optical GFRP–based sensor pads are available today that can be used as optical strain gauges patched to a variety of material surfaces for a long-term strain measurement. Consequently, we have used these sensing FBG-GFRP pads in our field tests.

5.2 Field tests

We have equipped several civil engineering structures with our developed "smart" FRP systems. As an example, we present the health monitoring of a hall's roof construction in Saxony during the winter 2012/2013.

Because of a structural pre-damage caused by a heavy snowfall incident, it became urgent to equip the roof construction with an online monitoring system providing reliable online alarm functionality. Warnings should be posted on critical load levels due to heavy snow or ice load. We installed a system based on optical GFRP strain gauges, next to a conventional electrical strain gauge system for referencing purposes. The strain gauges and the FRP sensor were installed locally in the tension zone of the endangered roof elements allowing a direct comparison between the classical electrical strain gauges and newly developed "smart" FRP sensor. In Figure 7 the installation of the monitoring systems at the roof element (trapezoidal sheet) can be seen. In a loading test after installation, the roof construction was intentionally loaded until the roof elements' deflections reached critical states in order to correlate both electrical and optical strain gauge signals to that said critical strain.

Figure 7: Laminated GFRP sensor and installation at the roof construction

The critical strain value (serviceability limit state) was reached at an approximate FBG strain of 400 to 500 macrostrains. Figure 8 shows an example for the GFRP's pad #2 strain gradient during the critical-weight test.

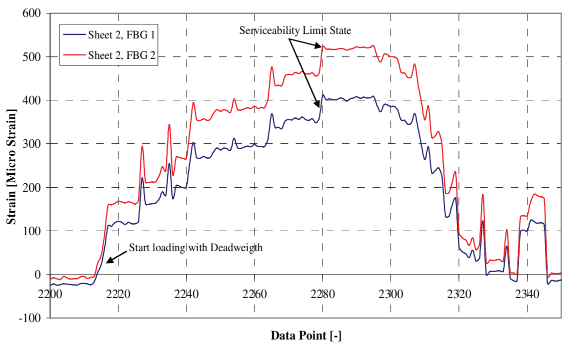

Figure 8: Strain distribution vs. time during critical weight test GFRP pad #2.

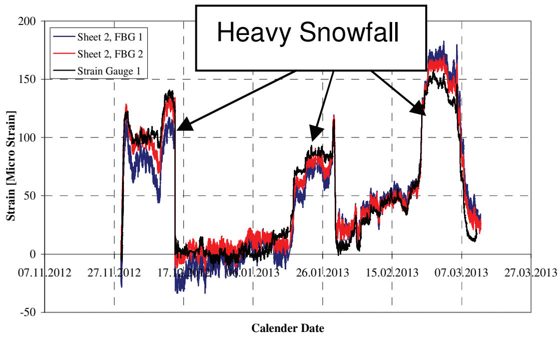

Figure 9: FBG strain versus electrical strain gauge, FRP Sheet #2, over a period of 3 months.

The difference in values between the two FBG's can be explained by an location difference of about 15mm along the tension zone of the trapezoidal sheet. After the critical weight tests we initialized the long-term online in order to acquire the strain gradients of the common strain and the FBG-GFRPs. For storage of data we used sophisticated, server based online monitoring software (GKSpro).

6 Conclusions

Structural monitoring will become more important due to an expected rapid aging of existing civil structures. The precious economical resource building-asset must be monitored and repaired carefully. We have presented a reliable and efficient technology to monitor and reinforce existing concrete structures by embedding optical fibers with FBG strain sensors in glass or carbon fiber reinforced polymer. The small proportions of optical glass fibers allow very flexible strain and temperature measurements inside of the FRP material while the common advantages like the FRP's high tensile strength will not be negatively affected by the FBG sensor system. Moreover, our presented embroidery technology first time clears the way for an accurate alignment and a reliable, highly reproducible application method for FBG sensors attached to civil structures.

7 Acknowledgments

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8 References

[1] S. Käseberg; T. Müller; H. Kieslich; K. Holschemacher; Faser-Bragg-Gitter-Sensoren: Einsatzmöglichkeiten im Betonbau, *pp 233 - 256 in Betonbau im Wandel, Holschemacher, Editor,* Bauwerk Publishers, 2009.

[2] K.-T. Lau; L.-M. Zhou; J.-S. Wu; Investigation on strengthening and strain sensing techniques for concrete structures using FRP composites and FBG sensors, *Materials and Structures 34*, 42 – 50, 2001.

[3] V. Saouma; D. Anderson; K. Ostrander; B. Lee; V. Slowik; Application of a fiber Bragg grating in local and remote infrastructure health monitoring, *Materials and Structures 31,* 259 – 266, 1998.

[4] C.L. Wong; P. A. Childs; R. Berndt; T. Macken; G.-D. Peng; N. Gowripalan; Simultaneous measurement of shrinkage and temperature of reactive powder concrete at early-age using fibre Bragg grating sensors, *Cement and Concrete Composites 29,* 490 – 497, 2007.

[5] S. Lu; H. Xie; Strengthen and real-time monitoring of RC beam using "intelligent" CFRP with embedded FBG sensors, *Construction and Building Materials 21,* 1839 – 1845, 2007.