SMART FRP SYSTEMS WITH EMBEDDED FBG FOR STRUCTURAL MONITORING AND RETROFITTING

K. HOLSCHEMACHER[1]*, S. KÄSEBERG[1]†

[1]*Institute of Concrete Construction, Leipzig University of Applied Sciences, Germany*

ABSTRACT

During the last ten years, an increasing number of carbon fiber reinforced polymer (CFRP) applications could have been observed that were focused on refurbishing damaged concrete or steel elements. 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, we present an optical strain sensor based CFRP system that can be used for strengthening and monitoring a wide range of structures at the same time. Thereby we have used optical fibers containing fiber Bragg grating sensors (FBG) being directly integrated in the FRP systems. This approach is known to have a number of significant advantages compared to conventional methods, e.g. small dimensions, low weight, and a high static and dynamic strain resolution. In our recent work, we have 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. We present our approach for setting the sensing silica fiber directly on the reinforcing fiber material with an adapted embroidery technique. An embroidery machine using computerized support was modified in order to align and fix the optical fiber accurately to the reinforcement carbon and/or glass fiber matrix. By using programmable 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. Our results clearly pave the way for a reliable and efficient industrial fabrication of smart FRP sensing structures for structural health monitoring.

Keywords: CFRP, GFRP, Fiber Bragg Grating, Embroidery, Health Monitoring.

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 (Lau et

* Corresponding author: Email: klaus.holschemacher@fb.htwk-leipzig.de

† Presenter: Email: stefan.kaeseberg@fb.htwk-leipzig.de

al. 2001). 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. A clear distinction between temporary and permanent measurements should be made in this context. 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.

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 (Lu and Xie 2007). 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. 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. Besides the composite material's failure types, the bond behavior between FRP and concrete surface is a very crucial parameter (Bastianini et al., 2005). This contact layer is particularly critical for the design of CFRP strengthened concrete structures. The small tensile strength of concrete is the most critical parameter for the bond bearing strength in structures that have a bending moment being applied to.

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

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. As commonly known, safe and reliable predictions of a building's structural integrity are the essence in civil engineering. The mentioned failure types tend to happen very abruptly and often without any prior announcement so that a reliable ductile behavior of the strengthened structural element cannot be safely predicted. 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 (Lu and Xie 2007) 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 operation, thus reporting their current mechanical state and integrity data without any user interaction (Mehrani et al. 2009). 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.

2. PROPERTIES OF FIBER BRAGG GRATING

2.1. Configuration and Assembly

Fiber Bragg Gratings are formed by a periodic sequence of refractive index changes in the core of an optical fiber. FBG’s are usually created by exposing an optical single-mode fiber to a periodic interference pattern of high-power ultraviolet light. This periodic variation in the refraction index along the fiber’s core results in a disturbed light propagation inside the optical fiber. (Note: In standard operation, the optical fiber guides all inserted light without any disturbance.) Light is normally composed by a number of different colors where the distinct length of the light’s wave λ represents a particular color. In an optical fiber’s regular operation, nearly all wavelengths λ are traveling through without any major interception.

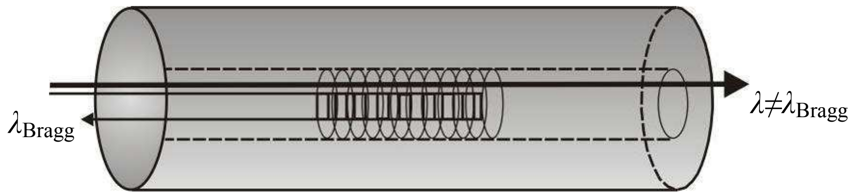

Figure 2: Optical silica fiber with Bragg grating.

With an FBG inside, the propagating light is partially reflected at the transition points of areas having different refraction indices (Kurtaran and Kiliçkaya 2007). For the majority of wavelengths, the reflected light parts are generally out of phase and extinguish without any measurable effect. However, for one certain wavelength - named Bragg wavelength λ_{Bragg} - the light portions reflected by the consecutive index changes are in an equal phase and hence constructively added up, leading to a significant amount of light being returned. Due to the sensitivity of the fiber’s refractive index n_{eff} to strain and temperature changes, such variations will lead to a defined shift in Bragg wavelength (i.e. light color). So, if one can detect the exact Bragg wavelength value then a definite statement about the fiber’s strain state and temperature can be made. Concerning the optical power spectrum, this results in a characteristic notch in the transmitted spectrum and in a peak in the reflected spectrum that travels back to the light source. Applications that want to access the reflected signal must couple the signal out of the fiber by an appropriate means, e.g. a splitter or a circulator.

2.2. Arrangement of several Fiber Bragg Grating at one Optical Fiber

One important reason for a continue promotion of fiber Bragg gratings is the ability of multiplexing, i.e. the distribution of multiple FBG's along one optical fiber. The geometrical arrangement along the length of the fiber can vary. Figure 3 shows an example.

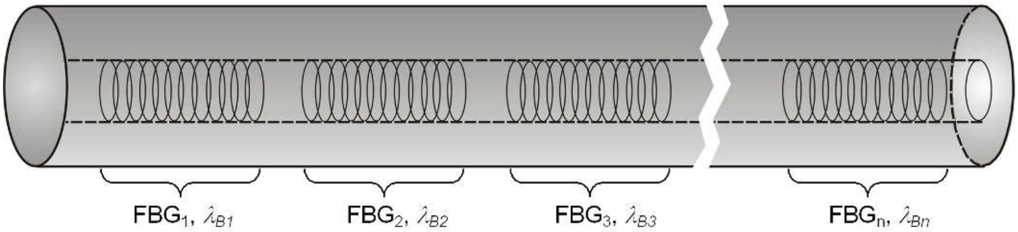

Figure 3: Optical fiber with several Bragg gratings.

For practical reasons, every single Bragg grating measuring point is defined by a distinct Bragg wavelength, which allows the user to assign an event locally to the particular FBG. This creates a wavelength-coded, distributed optical sensor. Using FBG's as sensors, the reflected peak at the distinct wavelength λ_{Bragg} has to be detected by an appropriate monitoring unit. Today, those units are available from a couple of suppliers worldwide. The analysis of the reflected light spectrums can be done with different methods. Techniques based on active and passive optical filters as well as interferometric and spectral measurement systems are possible. We have done the spectral analysis with a spectrometer that allows the direct measurement of the Bragg wavelength.

3. OPTICAL FIBER ALIGNMENT

3.1. Sensor fiber and textile matrix for FRP

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 4). 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. 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 accurately on the carbon fiber material.

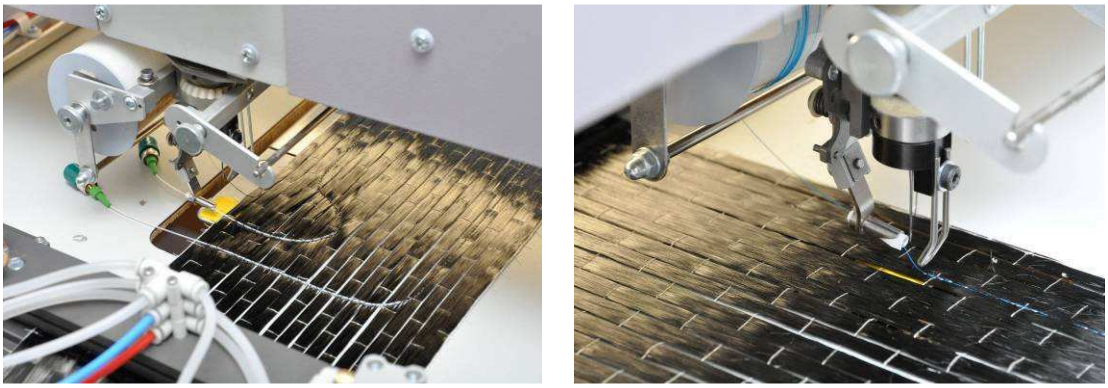

Figure 4: Embroidery of optical fiber on technical textile (carbon fiber clutch).

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. As described earlier, FBG sensors are discrete in-fiber elements that are detecting changes in the strain state only at their local position within the optical fiber. 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 (see Figure 5).

Figure 5: Handling at building site.

While primarily applied to carbon fiber clutches and/or meshes, the technology was transferred to other technical textiles based on glass or aramid fibers in a second step. Compared with carbon fibers, the glass-based samples provide a smaller modulus of elasticity and they are cheaper, too. In case the health monitoring has priority over the structure's strengthening being a secondary objective then using glass fiber clutches in GFRP's might be an interesting alternative to CFRP's. We have investigated both ways during our project.

3.2. Impact on optical fibers and FBG during processing

Embroidery of CFRP or GFRP clutches is a non-regular processing for that type of textile. Therefore, our investigations were mainly focused on a possible impact on the structural integrity of both the optical sensor fiber and the glass/carbon matrix during the whole fabrication process. Subsequent tension tests on CFRP sheets with and without FBG's resulted in only marginal losses of bearing strength and stiffness. The use of computer-controlled machines seems to effectively prevent all types of fiber and/or FBG from being damaged. That can effectively be checked with an online spectral measurement during and/or after the embroidering process, which will detect the FBG's spectral shift induced by mechanical stresses. Figure 6 shows a marginal strain increase (at the FBG's position) during the embroidery process that is far beneath the fiber's damage threshold of >10.000 microstrain. Thus we may subsume that our embroidery process does neither affect the optical or reinforcement fiber's structural integrity nor the FBG's functionality. The same conclusion can be made for the epoxy laminating process as well as for the FRP's application to concrete structures like shown in Figure 5.

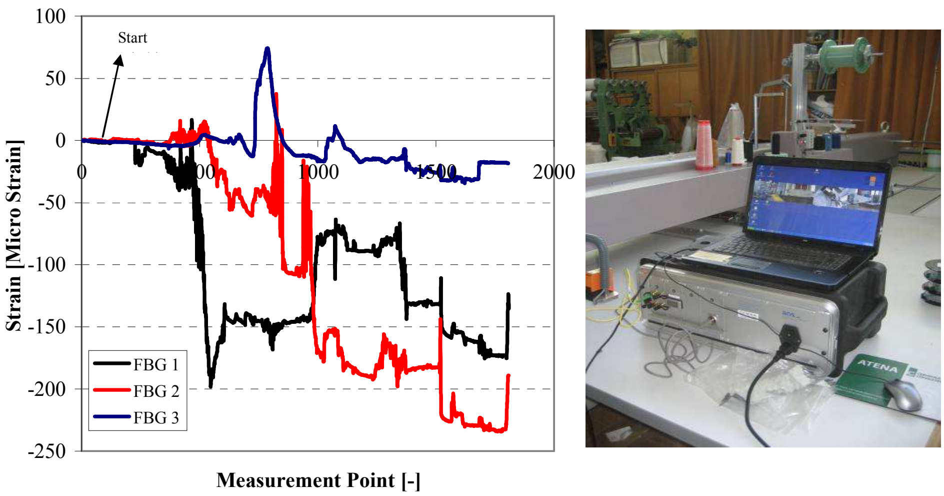

Figure 6: Strain vs. time (FBG measurement) during the embroidery process.

4. EXPERIMENTS ON SMART FRP SHEETS

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. All subsequent experiments underlined a good correlation between common measurement techniques like strain gauges and the FBG integrated in the smart FRP. In our projects later stage, our research group particularly focused to "smart" GFRP. 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. 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 (based on our stitched FBG’s), 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 our newly developed “smart” FRP sensor. In Figure 7 the installation of the monitoring systems at the roof element (trapezoidal sheet) can be seen. Furthermore an installed smart FRP beside one of the common strain gauges is presented.

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

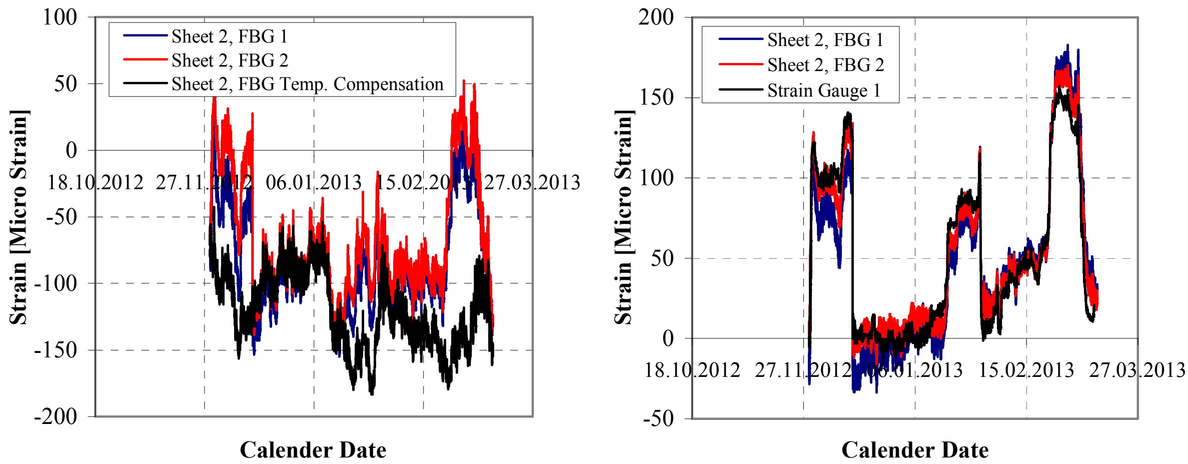

Figure 8: Strain development in FBG of GFRP Sheet #2 over a period of 3 month.

The GFRP sensor pads each containing two FBG used for strain measurement and one for temperature compensation were placed with a different distance to the support of the trapezoidal sheets. After a critical weigth test we initialized the long-term online in order to aquire the strain gradients of the common strain and the FBG-GFRPs. For storage of data we used a sophisticated, server based online monitoring software (GKSpro) developed by our partner GGB. This software environment is able to aquire, process, and display the huge amount of measurement data received from both the electrical and optical sensors. For example, in Figure 8 the strain development of all FBG of the smart FRP Sheet #2 (during the winter 2012/2013) are shown. The FBG's temperature dependence can be recognized. In Figure 8 (right side) our intrinsic temperature compensation was used to mathematically off-set the thermal effects, which results in justified strain values that now can easily compared to the electrical strain gauge's output. The almost perfect agreement between the different measurement systems in both qualitative and quantitative aspects is stunning and to our knowledge, an unprecedented case of validation. The GFRP sensor has clearly indicated three times incidents of heavy snowfall. Up to today, FBG based GFRP sensors, monitoring system, and the server based data acquisition are working absolutely reliable.

5. 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.

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