EMBEDDING FIBER OPTICAL SENSORS IN FRP-HYBRID MATERIALS

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ABSTRACT

The presented work includes development and verification of techniques for embedding fiber-optical sensors in Fiber Reinforced Polymers (FRP) and Aluminum hybrid materials for Structural Health Monitoring (SHM) purposes. The fiber-optical sensors both survive the manufacturing process of the FRP-Hybrid material and achieve sufficiently strong bonding to the material matrix.

Mechanical tests have been performed to characterize the performance of embedded fiber-optical sensors for obtaining strain data under both static- and cyclic loading. Further, the fiber-optically read strain data is comparable with the strain readings from surface-mounted extensometers and strain gauges.

Embedded fiber-optical sensors could monitor up to 1,5 – 2% strain in quasi-static tensile tests. During cyclic tests at low load, within the linear elastic region, the embedded sensors provided strain data for the entire testing cycle (18 000 cycles). At high cyclic loading, above the linear elastic region (300 MPa, 5 Hz), the embedded sensors provided strain data for 5000 cycles.

This work has shown that embedded fiber-optical sensors can be used for Structural Health Monitoring of mechanical components.

1 INTRODUCTION

Structural health monitoring (SHM) of constructions and mechanical parts is growing in importance as their level of complexity increases due to demands of lower weight and higher performances e.g. Hence, integrated sensors in mechanical components can possibly be used to surveil the status of the component during use.

In this study fiber-optical sensors are embedded in a Fiber Reinforced Polymers (FRP) and Aluminum hybrid material to detect strain. The application is for light-weight automotive chassis parts subjected to cyclic loading. Embedding fiber-optical sensors into FRP materials causes a minimum of negative effects on the composite properties due to its small size and that the shape of the fiber is similar to the reinforcement. Challenges are to secure that the sensors both survive the manufacturing process of the FRP-Hybrid material, and that they have sufficiently strong bonding to the material matrix to be able to detect strain in the material.

First, the embedding process of the fiber-optical sensors into the material is presented, followed by mechanical tests, both static- and fatigue testing, where the performance of the embedded fiber-optic sensors strain-reading of the FRP-hybrid material is presented. Comparisons are made both to surface mounted fiber-optic sensors, and to conventional strain measuring techniques i.e., strain gauges and extensometer.

2 EMBEDDED SENSORS IN FRP MATERIALS

The work in this section focuses on the technique for embedding fiber-optical sensors in the FRP and Aluminum hybrid materials. For verification of compatibility of chosen materials Microbond testing is utilized. Also, the strain state in the FRP-hybrid material during the manufacturing process is recorded by using an embedded fiber-optical sensor.

2.1 Selection of fiber-optic sensor type and fiber coating

In this work the Fiber Bragg Grating (FBG) [1] sensors have been chosen to detect strain in the FRP-Hybrid material. The sensing technique works as follows. The reading equipment, the interrogator, launches a broad band pulse into the optical fiber and the FBG reflects the light of a certain wavelength λ_{Bragg} (Fig. 1).

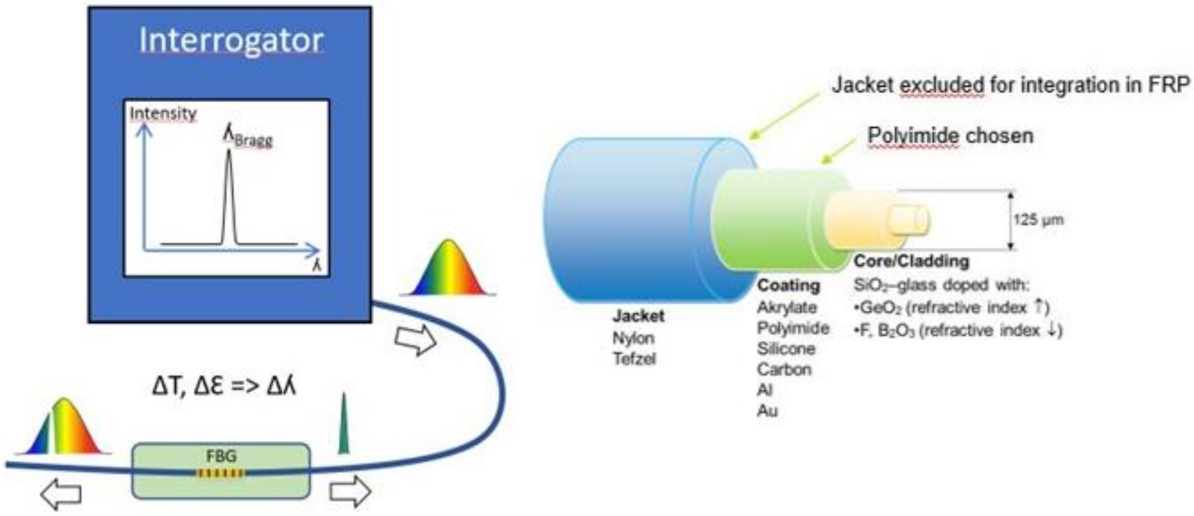


Figure 1: FBG sensing principle and optical fiber.

The reflected wavelength shifts to longer wavelengths when the temperature or strain increases; one degree change in temperature corresponds to 10 pm shift in wavelength, and one µstrain corresponds to 1.2 pm change in wavelength. As the wavelength shift depends both on temperature and strain, the shift corresponding to temperature changes needs to be subtracted from the detected wavelength shift to get the strain. The temperature is detected by another FBG loosely attached on top of the test specimen.

The 125 µm thick optical fiber has an outer diameter of 150 µm with its Polyimide coating. Polyimide was chosen before acrylate and silicon as fiber coating due to its good adhesion to the silica glass fiber surface, and its small thickness. The FBGs used in this work were the T20 product from Technica (www.technicasa.com) with a strain range of +/-1.5% (15 000 µstrain).

2.2 Microbond testing

For quantitative comparison of interfacial shear strength (IFSS) between fibers and resin, Microbond testing has been performed (Fig. 2).

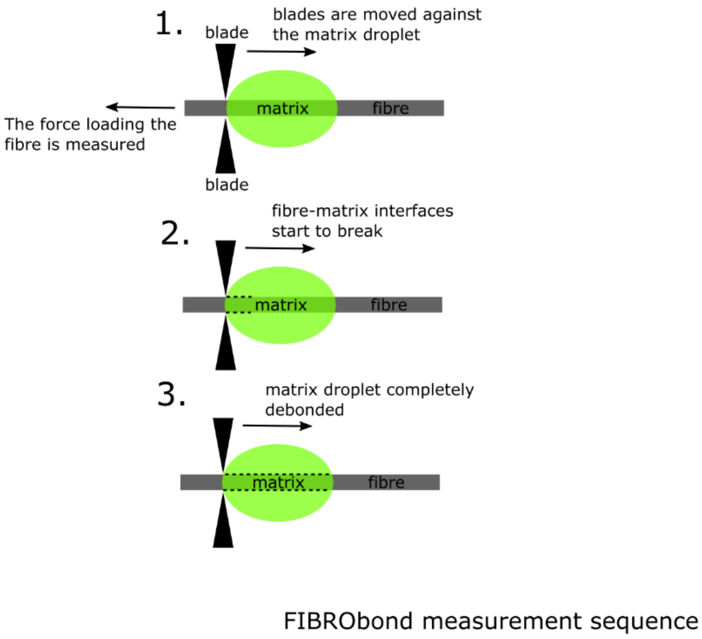


Figure 2: Microbond testing principle to quantify adhesion.

The measurements were done with a high-throughput FIBRObond (Fibrobotics Oy, Tampere, Finland) [2] device. Polyimide coated and uncoated optical fibers have been compared to the structural E-glass fibers. The epoxy resin used for testing is identical to the one in the FRP-hybrid material. The results indicate that the adhesion is sufficiently good for both uncoated fibers and the chosen Polyimide coating. For surface mounting of the optical fiber sensors an adhesive has been verified and compared to E-glass. The IFSS results for both the adhesive and resin are shown in (Fig. 3).

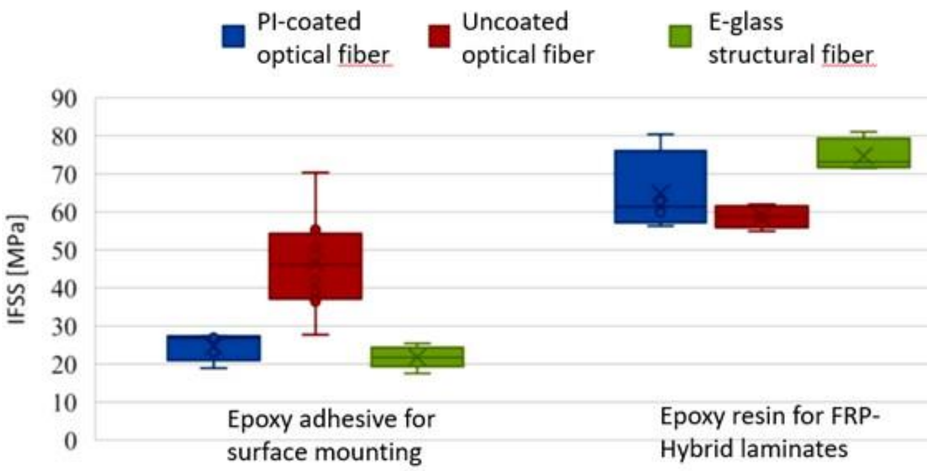


Figure 3: IFSS results for Microbond testing indicate good adhesion to both optical fibers and structural E-glass fibers for the chosen epoxy resin.

2.3 Embedding optical sensors into FRP-hybrid material

The manufacturing process for the FRP-hybrid material specimens consists of hot pressing of an E-glass/epoxy pre-preg between two sheets of 0.8 mm aluminum skin plates. The temperature of the tool is 120°C. The optical fiber is embedded with the sensor section centered and aligned in the 0° layer in the pre-preg prior to hot-pressing. Each end of the optical fiber, with optical connectors, is led out on the side of the specimen. To protect the protruding optical fibers during the hot press cycle, it is necessary to use spacers in the tool. A test specimen with embedded fiber-optic sensor is shown in Figure 4.

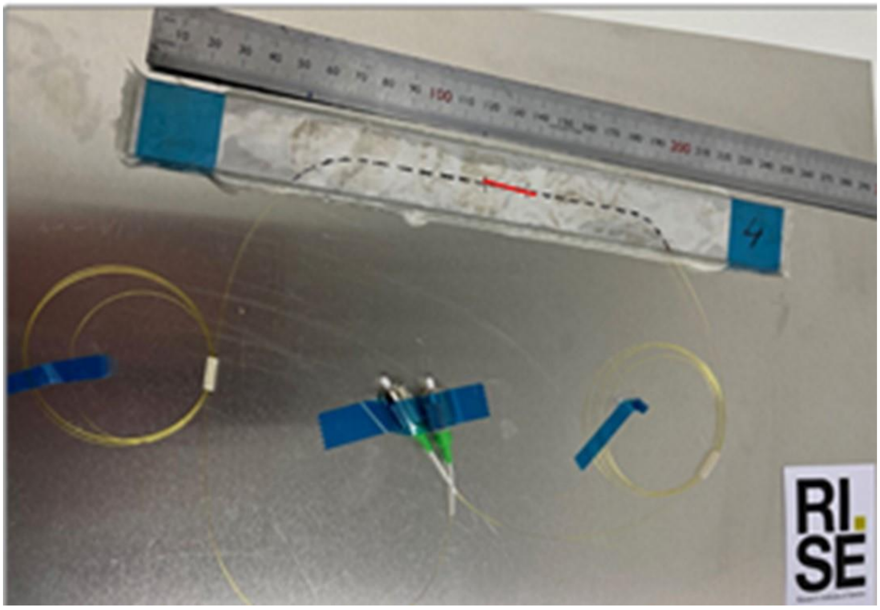


Figure 4: FRP-hybrid material specimen with embedded optical fiber positioned as the dotted line indicates. The FBG sensor section of the fiber is highlighted in red.

2.4 Monitoring of strain during manufacturing of FRP-hybrid test specimens

Since the pressing cycle for the FRP-hybrid material includes heating to 120°C during compaction, followed by holding at elevated temperature during curing of the FRP core before cooling down to room temperature, it was expected that the embedded fiber-optical sensor would show some remaining strain caused by the pressing cycle. By arranging the pressing of a test specimen so that the sensor could be plugged in to the interrogator and monitored during the pressing-, curing- and cooling cycle, the resulting change in strain could be determined. As expected, a final remaining compaction of the sensor was detected. The reason for this can be explained by the combination of thermal- and chemical shrinkage caused by the curing occurring at the elevated temperature in the pressing cycle. This effect is not considered to be negative for the performance of the fiber-optical sensor since the remaining compaction measured to be about 1800 micro strain is in the working range for the sensor. It is considered as a positive effect for strain measurements since starting at a compacted stage will increase the measurement range in tension.

In Figure 5 the length contraction of the fiber-optical sensor during hot pressing, curing, and cooling is shown. The strain has been determined after compensating for the wavelength shift due to temperature change. The measured remaining contraction at room temperature was determined to be about 1800 micro strain.

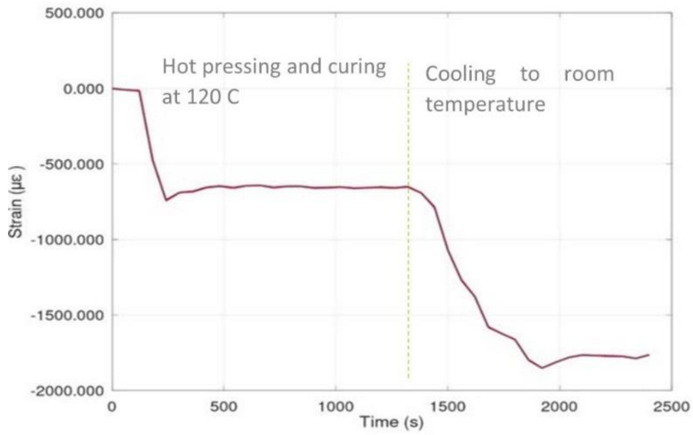


Figure 5: Diagram showing the length contraction of the fiber-optic sensor during hot pressing, curing, and cooling. After cooling the remaining length contraction is about 1800 micro strain.

3 MECHANICAL TESTING OF FRP-HYBRID MATERIALS

The work in this section includes mechanical tests, both static- and fatigue testing, to characterize the performance of embedded fiber-optical sensors for obtaining strain data for the FRP-hybrid material under both static- and cyclic loading. Comparisons are made both to surface mounted fiber-optical sensors, and to conventional strain measuring techniques i.e., strain gauges and extensometer.

3.1 Manufacturing and instrumentation of FRP-hybrid test specimens

All test specimens with embedded fiber-optical sensors were manufactured according to the developed method described in Section 2.3. In addition to embedding sensors centered along the length inside the specimens, there were also specimens made with an additional sensor positioned across the test specimen on the opposite side of the FRP-core inside the specimens. The reason for including these sensors was to be able to detect contraction of the width while the specimen is extended in the length direction. In Figure 6a, a fully equipped test specimen is shown. It has a surface mounted strain gauge and embedded fiber-optical sensors both in vertical and horizontal direction. A variant of test specimens was made with surface mounted fiber-optical sensors in addition to the embedded to investigate if they performed equally as the embedded. Test specimen with surface mounted fiber-optical sensor is shown in Figure 6b.

The sensor configuration of the different specimens used in the mechanical tests are presented in Table 1.

a) b)

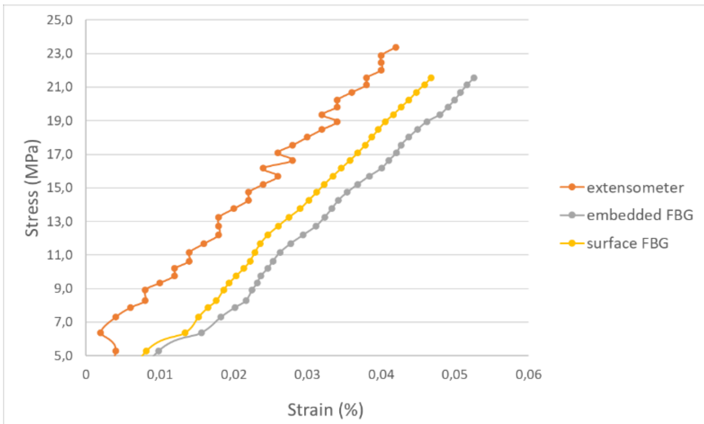
Figure 6: a) Test specimen with a surface mounted strain gauge and embedded fiber-optical sensors both in vertical and horizontal directions marked in figure with dotted lines. b) Test specimen with both embedded and surface mounted fiber-optical sensors. The surface mounted sensor is aligned with the embedded sensor and centered between the grips of the extensometer.

Sensors	Quasi-static test		Fatigue test	
	Low load	High load	Low load	High load
Embedded Longitudinal FBG	X	X	X	X
Embedded transverse FBG			X	X
Surface mounted longitudinal FBG	X	X		
Extensometer	X			
Strain gauge		X	X	X

Table 1: Configuration of sensors in experiments.

3.2 Comparison of embedded fiber-optical sensors to extensometer and surface mounted fiber-optical sensor in quasi-static testing

A test set-up was made in a MTS model 20 testing machine with a 100 kN load-cell to verify that strain readings from embedded fiber-optical sensors could be logged and be compared to a known reference strain measurement system, i.e. the MTS extensometer. An additional surface mounted fiber was utilized to compare the performance to the embedded sensor. The testing load was limited to be safely within the linear elastic region for the sample. Tests were performed with several repetitions. The test set-up is shown in Figure 7a. The result was that both the embedded and surface-mounted optical sensors were detecting the strain similar to the extensometer in the linear elastic region (Fig. 7b).



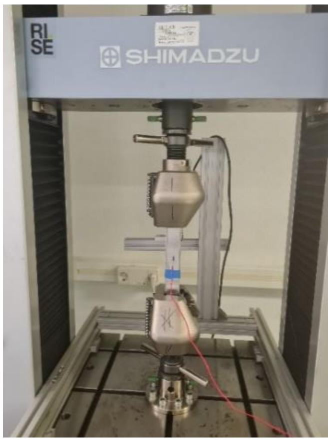
a) b)

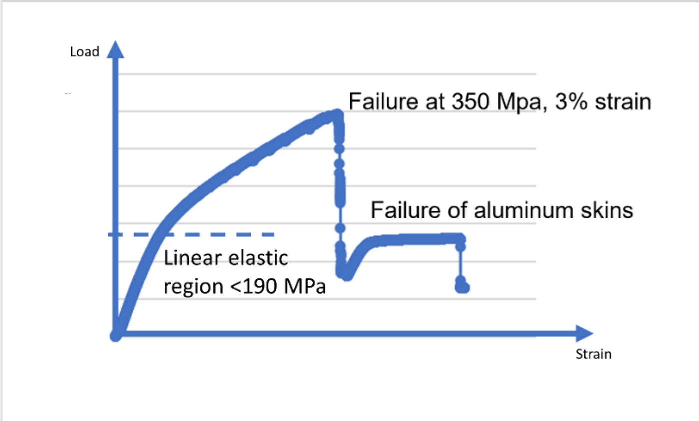
Figure 7: a) Test machine MTS during static testing. b) T Strain measurements at high resolution up to 0,05% strain indicating that there is some difference in the synchronization to the testing machine but the incline, representing the E-modulus are matching well between the extensometer and the two fiber-optical sensors.

At low strains up to 0.05% there were some differences noted. One reason can be that the recording of data from the optical sensors are made separately from the testing machine and need to be synchronized in time to match the extensometer connected to the testing machine. This can be an explanation for the horizontal deviation that seems to be in the range of 0.015% between the extensometer and embedded fiber-optic sensor. Most important is that the incline of the curves representing the E-modulus of the test specimen are consistent for the three sensors. In Figure 7b strain measurements are shown up to 0.05% strain.

3.3 Comparison of embedded fiber-optical sensors to strain gauges in quasi-static testing to failure

Tensile testing to failure was performed on a Shimadzu model AG-X plus with a 50 kN load cell (Fig. 8a). The test specimens were equipped with an embedded fiber-optical sensor in the center and a surface mounted at same location along the specimen. On the opposite side there is a surface mounted strain gauge as reference. The full deformation and damage behavior of a test specimen is described in Figure 8b. There is a knee ending the linear elastic region at about 190 MPa and failure is in the range of 350 MPa. At this stage the composite core in the hybrid material breaks. This is followed by a failure in the aluminum skins at higher strain but lower stress.





a) b)

Figure 8: a) Shimadzu, model AG-X plus with a 50 kN load cell during test. b) Schematic deformation and damage behavior of a FRP hybrid test specimen is divided in a first failure at about 350 MPa, followed by later failure of the aluminum skins at higher strain. The dotted line represents the linear elastic region at about 190 MPa.

3.3.1 Strain to failure data comparing fiber-optical sensors to strain gauges

The results of the strain measurements made both with embedded and surface-mounted fiber-optical sensors are compared to strain data from the surface-mounted strain gauges in Figure 9 below where two tests are presented. Overall, it can be concluded that the strain measurements from the optical sensors and strain gauges are matching. The strain gauge survives all the way through the full failure of the Aluminum skin plates which is beyond 4% strain. The embedded fiber-optical sensors are in both cases surviving up to between 1,5 - 2% strain, which is in the region of the maximum strain that can be measured according to specifications in the data sheets for the fiber-optical sensors. For the surface-mounted optical sensors, the detection works up to about 1% strain in both cases. The fact that the surface mounted optical sensors fail before the embedded sensors is corresponding to the Microbond testing presented above in Section 2.2. Here it is shown that the interfacial shear strength (IFSS) is significantly lower for the epoxy adhesive used for surface mounting than for the epoxy resin used in the FRP hybrid laminate.

In Figure 9 strain data for both sample 1 and 2 during tensile tests are shown. They both indicate similar performance for the two sensors in comparison the fiber-optical sensor. The fluctuating response of the surface mounted optical fiber sensor (green) is due to distortions of the wavelength peak that the interrogator uses to calculate the strain. The distortion of the peak comes from a change in strain along the sensor that is assumed originating from changes in the material and/or in the bonding of the sensor to the material.

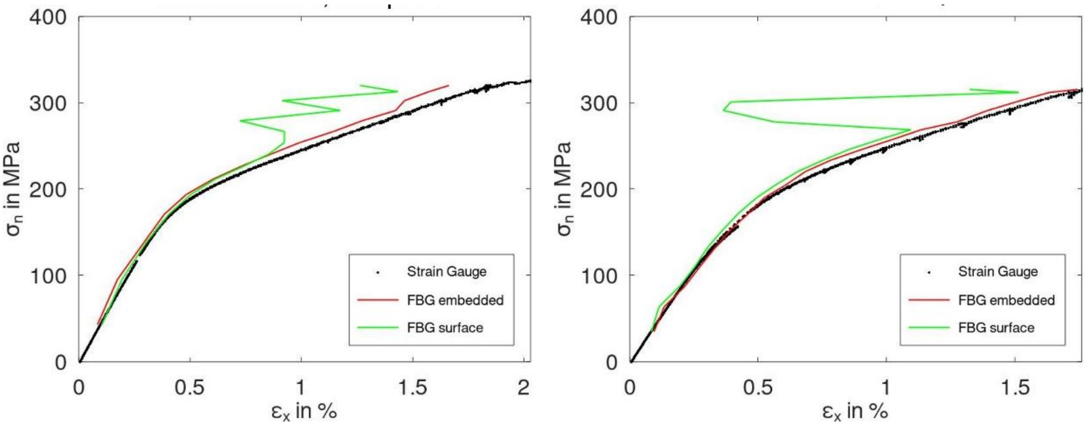


Figure 9: Strain data for sample 1 and 2. They both indicate that the strain gauges were reading all the way to failure beyond 2% strain. The embedded fiber-optical sensors lasted to 1,5 - 2% and the surface mounted sensors to about 1% strain.

3.4 Comparison of embedded fiber-optical sensors to strain gauges in fatigue testing

The fatigue testing was performed in a hydraulic testing machine, Instron 8516, with a 25 kN load cell (Fig.10). The specimens had a surface-mounted strain gauge and embedded fiber-optical sensors both in vertical and horizontal directions, corresponding to earlier shown in Figure 6a.

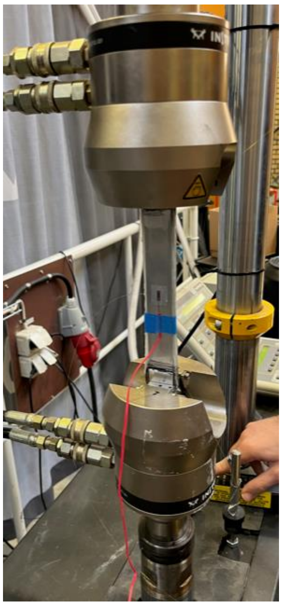


Figure 10: The test set-up for fatigue testing in a hydraulic Instron 8516 testing machine with a 25 kN load cell. The test specimen has embedded sensors both in vertical and horizontal direction and a surface mounted strain gauge as reference.

Two levels of force were chosen for the fatigue test. The chosen setting in each test is described in Table 2. The low level is within the linear elastic region, whereas the high level is above. Fatigue data for the FRP hybrid material (shown in Figure 8b) was providing the input for setting the levels of force. The “high” load represents testing above the linear elastic region whereas the “low” load is within the linear elastic region with a margin.

Test name	Maximum stress (MPa)	Frequency (Hz)
Fatigue 1, high	300	5
Fatigue 2, low	150	5

Table 2: Load settings in fatigue tests.

During the fatigue test, data from both the fiber-optical sensors and the strain gauge were logged separately. The signals from the sensors were also monitored during the test. In Figure 11 it is shown the type of data that could be followed during the test to secure that the sensors were still functioning and reading strain data properly. The strain gauge data is shown on the left in Figure 11, and the wavelength reading of the optical fibers to the right. While the strain gauge signal is an amplitude to be monitored, the optical fiber signal is a wavelength indicated by a peak cycling its position back and forth horizontally along the wavelength axis due to the alternating load. The indication that the test specimen is increasing in length during the test, is illustrated by the strain gauge by the slow inclination of the curve pattern, where the strain values are increasing over time. For the fiber-optical sensor, the fatigue behavior is instead illustrated by the positions of the min and max values of the wavelength. The cycling interval shown is slowly moving to higher wave lengths (to the right) as the strain levels are increasing during the fatigue testing.

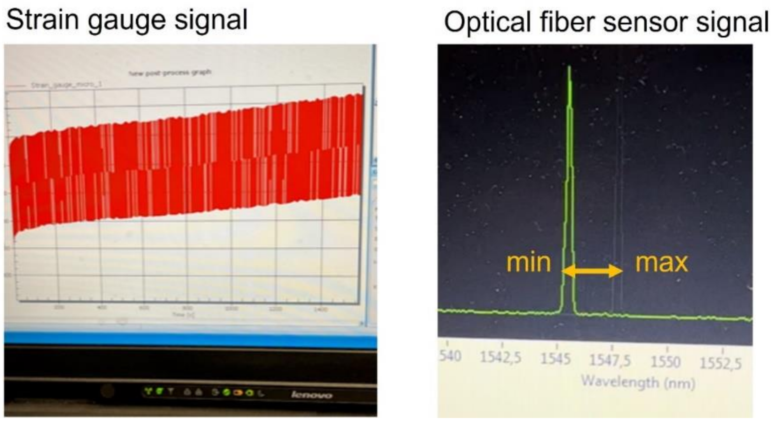


Figure 11: In-situ monitoring of the sensors during the fatigue testing. The increasing length of the test specimen is generating a slow inclination of the curve for the strain gauges, and a slow increase of min and max values for the wavelength of the fiber-optical sensors.

3.4.1 Comparison of fiber-optical sensors to strain gauges during cyclic loading

The results of data acquisition during cyclic loading from the different sensors are presented below. There are two levels of cycling forces, “Fatigue 1, high” and “Fatigue 2, low” as described in Table 2. Since the test specimens are equipped with fiber-optical sensors, both in vertical and horizontal direction, it is possible to follow changes in strains also across the test specimens. The high load setting in “Fatigue 1” was recorded all the way to failure which occurred after 26 minutes (7800 cycles). The low load setting in “Fatigue 2” was recorded for 1 hour (18 000 cycles) and then terminated without failure.

The peak readings from the vertical fiber-optical sensor and the strain gauge for “Fatigue 1, high” is shown in Figure 12a. As can be seen, the optical fiber signal started to become distorted after about 5000 cycles. It was checked afterwards that the sensor itself was still intact with the same reference readings as before the test. The distortion is then suggested coming from uneven stress distribution along the length of the sensor due to some possible changes in the material surrounding the embedded sensor. In Figure 12b the reading from the transverse fiber-optical sensor is shown. The observation that the strain readings are increasing over time in the vertical direction while they are decreasing in the transverse direction could possibly indicate that the test specimen is increasing in length and narrows in width during the test.

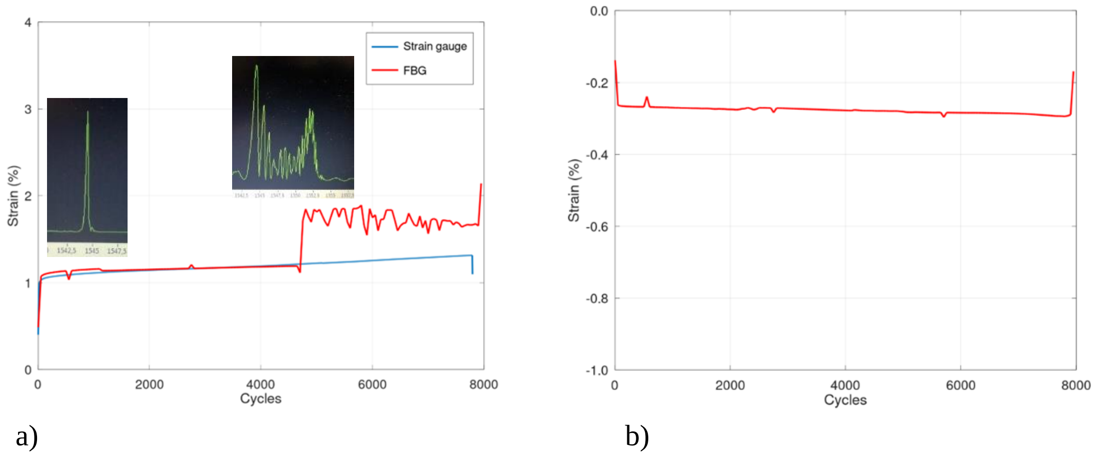


Figure 12: a) The peak readings from the vertical optical fiber and the strain gauge for “Fatigue 1, high”. The optical fiber signal started to become distorted after about 5000 cycles. The inserts show the peak before and after 5000 cycles. b) The peak readings from the horizontal optical fiber for “Fatigue 1, high”.

9 CONCLUSIONS

The presented work includes development and verification of techniques for embedding of fiber-optical sensors in Fiber Reinforced Polymers (FRP) and Aluminum hybrid materials.

Mechanical tests have concluded that the embedded fiber-optical sensors can detect strain data under both static- and cyclic loading. Further, the fiber-optically read strain data is comparable with the strain readings from surface-mounted extensometers and strain gauges.

Hence, embedded fiber-optical sensors can be used for Structural Health Monitoring of mechanical components.

ACKNOWLEDGEMENTS

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