Adhesive Disbond Monitoring with Microstructured Optical Fiber Bragg Grating Sensors

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ABSTRACT

We present a sensing system that is based on a combination of 3 optical fiber sensors which are non-intrusively integrated in an adhesive layer, and that allows detecting the initiation and monitoring the growth of disbonds. The fiber sensors consist of fiber Bragg gratings fabricated in a dedicated microstructured optical fiber and feature an enhanced response to shear stress. The change in response of the sensors to tensile loading of the joint is used as a measure for the shear stress redistribution in the bond layer caused by disbonding. With our technique we can detect the initiation of disbonds as short as 100 μm, which corresponds to 0.4% of the overlap length. This is the first time, to the best of our knowledge, that an adhesive disbond on-line monitoring system is presented that can quantitatively evaluate even very short disbonds.

KEYWORDS : *optical fiber sensor, fiber Bragg grating, microstructured optical fiber, adhesive bond, structural health monitoring, disbond monitoring.*

INTRODUCTION

Adhesive bonding is becoming an increasingly popular mechanical fastening technique for many applications [1]-[3]. More conventional techniques such as riveting, bolting or welding can weaken the structure locally. Furthermore, adhesive joints are lightweight, they allow for a more uniform stress transfer between different components, they can be used to join dissimilar materials, they do not affect the corrosion resistance of the material, and they have a smoother appearance. However, industry remains hesitant to rely entirely on adhesive bonds, and at present adhesive bonding is still mostly combined with another type of mechanical fastening. One reason is that no adequate technique is currently available to evaluate the manufacturing quality of an adhesive bond or to monitor its reliability during the lifetime of the structure. Results obtained with non-destructive evaluation techniques using acoustic emission, ultrasonic detection or even classical electrical strain gauges have been published, but none of these techniques allows reliable and accurate in–situ disbond monitoring [4]-[6].

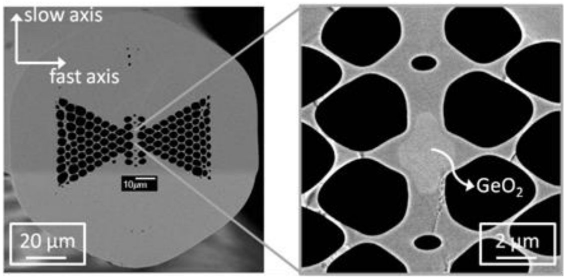
Optical fiber sensors, and in particular fiber Bragg grating sensors, have already been proposed several times for adhesive bond monitoring purposes. Optical fiber Bragg grating (FBG) sensors are light and flexible, they can be embedded non-intrusively in adhesive layers and multiple FBGs can be multiplexed into a chain of FBG sensors [7]. So far most fiber optic based bond evaluation techniques either require complex read-out systems, feature a significant cross-sensitivity to temperature, or call for extensive calibration procedures [8]-[12]. Disbonding of the adhesive/adherend interface or cracks in the bond leads to a redistribution of the shear stress profile in the bond layer. Therefore, a method that allows continuously assessing the shear stress distribution in the adhesive bond will also return information about the bond quality. Our work relies on that principle and we propose a configuration of multiple dedicated Bragg grating based shear stress sensors that can measure the shear stress at different locations in the bond line, and that is able to monitor the initiation and growth of disbonds and to determine their length.

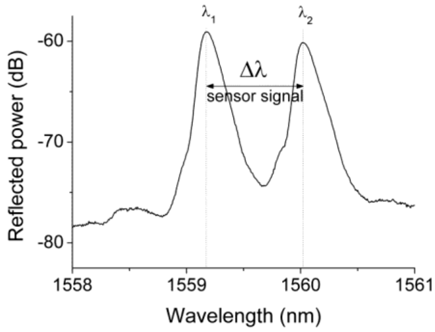
Our FBG sensors are fabricated in highly birefringent microstructured optical fibers (MOF). MOFs have been proposed to overcome issues specifically related to conventional polarization maintaining fibers, such as for example their significant thermal cross sensitivity and rather low transverse strain sensitivity [13]. High birefringence in MOFs is induced by an asymmetric air hole geometry and only a small and low GeO2-doped region is needed to allow for Bragg grating inscription using conventional UV inscription techniques. Moreover, their transverse strain sensitivity can be enhanced by properly tuning the air hole geometry, i.e. by altering the number of air holes, their sizes and/or their positions in the cross-section of the fiber. Results of the 'butterfly' microstructured optical fiber Bragg grating (MOFBG) sensor demonstrate that by designing dedicated MOFs one can improve the transverse strain sensitivity by an order of magnitude compared to conventional polarization maintaining fibers [14]. We have shown recently that the butterfly MOFBG sensor can also be used for shear stress sensing [15]. By aligning the optical axes parallel with the directions of principal stress in a shear loaded material, the butterfly MOFBG sensor will detect the shear load induced transverse stress.

1 SHEAR STRESS SENSING WITH A BUTTERFLY MOFBG SENSOR

The sensing principle of the butterfly MOFBG sensor relies on the change of modal birefringence B_{mod} caused by a mechanical load that is applied to the cladding of the fiber, or to the host material in which the sensor is embedded [13]. Because of the asymmetric microstructure (Figure 1a), a radial load will induce an asymmetric mechanical stress distribution in the core of the fiber. The refractive indices n_x and n_y of the modes polarized along the x- and y-direction are therefore affected in a different manner. This is translated into a change of the separation $\Delta\lambda$ between the individual Bragg peak wavelengths λ_i for each linearly polarized mode, which is directly linked to B_{mod} as given by $\Delta\lambda = 2 \cdot B_{mod} \cdot \Lambda$, with Λ the period of the FBG. We consider $\Delta\lambda$ as the sensor signal (Figure 1b), and the sensitivity of the butterfly MOFBG sensor corresponds to the rate of change of $\Delta\lambda$ when submitted to a specific mechanical or thermal load.

The butterfly MOFBG sensor has a sine-like dependence of the transverse strain sensitivity to the angular orientation of the microstructure with respect to the direction of the applied load [14]. It is most sensitive when the load is applied along α= 90°, which is indicated by the slow-axis or y'-axis in Figure 1. However, when the sensor is embedded in a shear loaded material at an angular orientation α= +45° or α= -45°, it will detect the transverse strain that is induced by the shear load. By orienting the sensor at +45° or -45°, the fundamental optical axes are aligned parallel to the directions of principal strain in the material. We previously demonstrated that the shear stress sensitivity of a butterfly MOFBG sensor is 59.8 pm/MPa when embedded at α=-45° in a single lap adhesive joint that is tension loaded [15].





a. b.

Figure 1: a. Cross sectional view of the 'butterfly' microstructured optical fiber Bragg grating (MOFBG) sensor. The specific asymmetric air hole topology results in a MOFBG sensor with unprecedented shear stress sensitivity. b. Optical reflection spectrum of a butterfly MOFBG sensor. The peak separation $\Delta\lambda$ is used as sensor signal to measure shear loading.

2 SHEAR STRESS SENSING IN AN ADHESIVE BOND LINE

To embed one or multiple optical fibers in the adhesive bond line of a single lap adhesive joint (SLJ), no modifications of the fabrication process are required. The overlap regions of the adherends are polished and degreased. The adhesive is applied to the lower adherend, and immediately afterwards the optical fiber sensors are placed in the adhesive line. The angular orientation α of the optical fibers, and their position x along the overlap length is controlled during integration. Finally, the top adherend is added and the sample is cured at room temperature for at least 24h. The instrumented joints are subjected to a static tensile load by gripping them at both ends in a hydraulic servo-controlled tensile test machine with a load capacity of max. 100 kN. During loading, the FBG sensor response is recorded using an FBG interrogator (FBG-scan 608 [16]). Linear regression analyses of the responses of the MOFBG sensors to tensile loading F result in sensor sensitivities expressed in pm/kN. The theoretical model of Goland-Reissner [17] is used to relate the applied load to the shear stress at the position of the sensor, while the low amount of peel stress present at the sensor location is neglected. This allows calculating the shear stress sensitivity, expressed in pm/MPa. After testing the samples up to failure, their sides are polished in order to determine the exact angular orientation of the embedded optical fibers with a microscope.

We first demonstrate experimentally that the shear stress sensitivity of the butterfly MOFBG sensor is comparable when embedded in various adhesive bond configurations. Three sensors have been embedded in SLJs, bonded by different types of adhesive; two types of epoxy-based adhesives (Araldite 420 A/B and Araldite 2015) and one methyl methacrylate adhesive (Supergrip MMA 8105). This resulted in shear stress sensitivities of respectively 59.7 pm/MPa, 63.3 pm/MPa and 59.8 pm/MPa. These values demonstrate that the sensor response does not depend on the type of adhesive in which it is integrated. Since many different joint configurations are used in practical applications, we also test the shear stress sensitivity of the butterfly MOFBG sensor when integrated in a double lap joint (DLJ). Because of its symmetric configuration, the peel stress level in this bond type is much lower than that in a single lap joint. We obtain that a sensor sensitivity of 59.7 pm/MPa when embedded in a SLJ and a sensitivity of 52.9 pm/MPa when embedded in a DLJ. The small differences in shear stress sensitivity of the different configurations can be attributed to the uncertainties on the joint dimensions, on the material properties and on the location and angular orientation of the optical fiber sensors.

3 SHEAR STRESS MAPPING ALONG A BOND OVERLAP

We embed 3 shear stress sensors in a SLJ at the specific locations *x* where the magnitude of the peel stress is minimal (Figure 2). The SLJs are made of two aluminum laps bonded by a two-component epoxy adhesive (Huntsman Araldite® 2015, E = 1850 MPa, G = 650 MPa and ν= 0.42). We subject the sample to a cyclic tensile loading test to evaluate the shear stress sensitivity and the response of the sensors and their ability to detect disbond initiation and propagation by monitoring their response throughout the fatigue test. At regular intervals the loading frequency – following a haversine trend and using a displacement controlled tensile load – is decreased from 2Hz to 0.01 Hz. During these intervals, we record the Bragg peak wavelengths to determine the sensor sensitivity.

The cyclic test starts at a low frequency of 0.01 Hz and the responses of the 3 sensors are recorded. Linear regression analyses of the results show that sensor 2, which is located in the center of the overlap, has a sensor response of 51.1 pm/kN, while sensor 1 and sensor 3, both located towards opposite edges of the overlap, yield a sensor response of respectively 109.9 pm/kN and 141.5 pm/kN. Since shear stress increases towards the edges of the overlap, these sensors will experience more shear loading, resulting in a higher sensor response. When taking into account the lap joint dimensions, material properties, and fiber locations, we can use Goland-Reissner theory to calculate the shear stress at the particular location of the fibers [17]. When neglecting the much lower peel stress, the 'shear stress sensitivity' of the sensors can be derived. This results in 51.3 pm/MPa, 63.3 pm/MPa, and 60.5 pm/MPa for respectively sensor 1, sensor 2, and sensor 3. These values correspond well to values reported earlier, which also demonstrates that we can evaluate the shear stress at different positions along the length of the bond overlap.

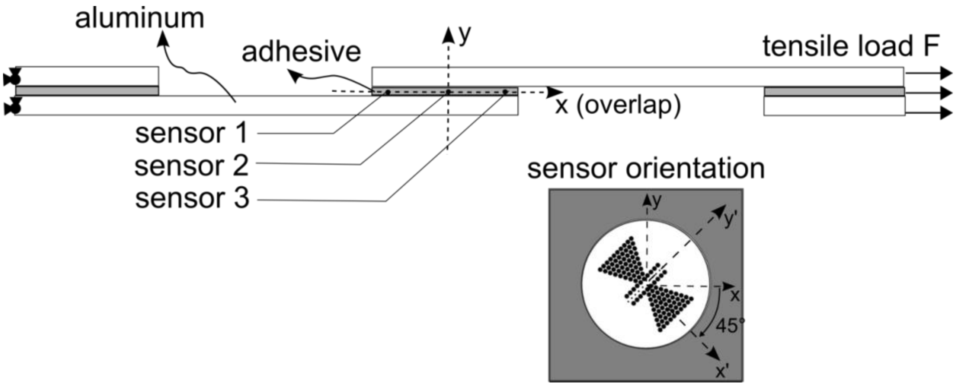


Figure 2: Configuration of the sensing system, consisting of 3 FBG sensors fabricated in a butterfly MOF, with a microstructure oriented with an angle of 45° and embedded at different locations along the overlap length.

4 DETECTION OF DISBOND INITIATION AND PROPAGATION

When the SLJ is submitted to a cyclic fatigue loading test, disbonds and cracks will be initiated and will propagate until failure of the sample. Due to these cracks, the shear stress distribution in the joint will change throughout the test. This continuous stress redistribution will result in changes of the sensor responses. These responses can therefore be used as a basis for detecting the occurrence of disbonding and for quantifying the disbonding length.

During the cyclic test, at regular intervals, we reduce the loading frequency of 2 Hz to 0.01 Hz. During these intervals, we determine the sensor response in a similar manner as discussed in section 3 for the first loading cycle. The evolution of the sensor response throughout the complete cyclic test is a measure of the redistribution of shear stress in the bond layer, which provides information on the initiation and propagation of cracks or disbonds.

Figure 3a shows the percentage of change in response of each of the 3 sensors with respect to their initial response. The evolution of the sensor responses throughout cyclic testing of the single lap joint displays distinct features which can be attributed to the initiation and growth of disbonds and that can help to predict the onset of lap failure. The trend of the sensor response is reconstructed by 2D FE analyses (Simulia Abaqus FEA [18]) of the sensor responses when static disbonds are present. A disbond is modeled by omitting a narrow row of mesh elements in the adhesive layer. In Figure 3a we show the very good agreement between results from experiments (solid scattered point) and modeling (empty scattered points). Figure 3b shows the disbond lengths or positions of the crack tip that lead to sensor responses that correspond best to those experimentally achieved and displayed in Figure 3a. The modeling results show that after 3 000 cycles, a disbond of 0.25mm is located at the left side of the overlap, resulting in an increase of the response of sensor 1 of 10%. At the right side a disbond of 0.75mm is present, leading to an increase of the sensor response of 25%. Once the disbond has propagated that far that sensor 1 is no longer located in a high region with a high level of shear stress, its sensor response will decrease. This is characterized by the change in trend around 10 000 cycles for sensor 1. After 10 000 cycles, the responses of sensor 1 and sensor 3 decrease, while the response of sensor 2 increases steeply after 16 000 cycles. This increase can be attributed to the shorter overall overlap length of the bond, which generates a larger shear stress along the bond line.

Our results demonstrate that by monitoring the response of shear stress fiber optic sensors integrated in a SLJ, we can continuously assess the shear stress distribution and hence detect the initiation and propagation of disbonds. Moreover, we find that when a disbond is present with a length of 1% of the initial overlap length, the sensor response can already change by 10%. Additional FE modeling has demonstrated that the shortest disbond length that can be detected by our sensing system – considering a Bragg peak separation detection accuracy of 2 pm [16] – is 100 µm, which corresponds to 0.4% of the initial bond overlap length.

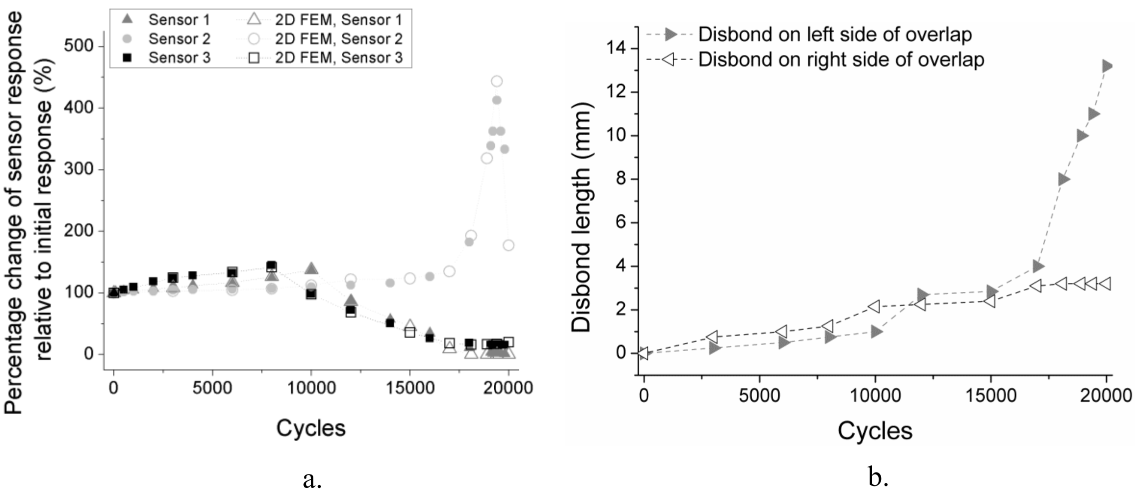


Figure 3: a. Evolution of the procentual change with respect to the initial sensor response recorded during the low frequency cycles in the fatigue test. b. The disbond lengths or positions of the crack tip that lead to sensor responses that correspond best to those experimentally achieved and displayed in Figure 3a. The sensing system allows detecting disbonds at both sides of the overlap, when the single lap joint is subjected to a cyclic fatigue test. The shortest disbond that can be detected with our system using commercially available FBG sensor interrogators is 100 µm.

CONCLUSION

We have proposed to use uniform FBG sensors fabricated in highly birefringent microstructured optical fibers (MOF) to measure shear stress in adhesive bonds. .

We embedded 3 sensors at different locations along the length of the overlap of a single lap adhesive joint. We managed to map the shear stress distribution in the adhesive by following the response of these sensors when the joint is tensile loaded. Whenever disbonds occur, the resulting redistribution of the shear stress modifies the sensor response. Using the ratio of the 3 sensor responses we determined the shear stress redistribution and we linked this to a specific disbond length. Considering the Bragg peak wavelength detection resolution of commercially available interrogators, we showed that we can detect disbonds of 100 µm, or 0.4% of the overlap length. Our experimental results have been verified using two dimensional finite element modeling.

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