Experimentální Analýza Napětí 2010
Experimental Stress Analysis

Use of Fibre Bragg Grating Sensors for Structural Health Monitoring of Structures

Milan Růžička,[1] Milan Dvořák,[2] Viktor Kulíšek[3]

Abstract: Structural Health Monitoring (SHM) consist a system of active and passive sensors and data management, which are able to detect type, position and range of damage, initiated and propagated in the structure. Presented paper described SHM monitoring with using of fibre Bragg grating (FBG) sensors, which were applied for a crack growth and disbonding detection of bonded composite repairs on Al-alloy structures. The results have shown good accordance of SHM detection with real observations during experiments. It demonstrates applicability of the FBG in SHM system for detection of damages by application of composite repairs.

Keywords: Structural Health Monitoring, Fibre Bragg grating sensor, Composite repair

1. Introduction

Structural Health Monitoring (SHM) is a process of implementing a damage detection methods and strategy of evaluation for engineering structures [1]. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors. It includes also the extraction of damage-sensitive features from measurement history, and the statistical analysis of these features to determine the current state of system health.

Damage is defined for this purpose as changes of material, geometry, boundary conditions and system connectivity of a structural system, which adversely affect on performance of the structure.

Outputs of long term monitoring process are periodically updated to provide information about ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments. After extreme events, such as cyclic or blast loading, SHM is used for rapid condition screening and aims to provide, in near real time, reliable information regarding the integrity of the structure.

[1] *Prof. Ing. Milan Růžička, CSc; Czech Technical University in Prague; Technická 4, 166 07 Praha 6, Czech Republic; milan.ruzicka@fs.cvut.cz*
[2] *Ing. Milan Dvořák; Czech Technical University in Prague; Technická 4, 166 07 Praha 6, Czech Republic; milan.dvorak@fs.cvut.cz*
[3] *Ing. Viktor Kulíšek; Czech Technical University in Prague; Technická 4, 166 07 Praha 6, Czech Republic; v.kulisek@rcmt.cvut.cz*

The SHM problem can be addressed in the context of a statistical pattern recognition paradigm [2]. This paradigm can be broken down into four parts:

a) Operational Evaluation,
b) Data Acquisition and Cleansing,
c) Feature Extraction and Data Compression,
d) Statistical Model Development for Feature Discrimination.

When one attempts to apply this paradigm to data from real world structures, it quickly becomes apparent that the ability to cleanse, compress, normalize and fuse data to account for operational and environmental variability is a key implementation issue when addressing Parts b)-d) of this paradigm. These processes can be implemented through hardware or software and, in general, some combination of these two approaches will be used.

2. Repairs of fatigue cracks and their monitoring

2.1. Brief historical review

In the SHM Workshops [3] and [4], the project of development, examination and certification of composite bonded repairs of the critical places of the Czech light combat jet L-159A (Aero Vodochody) was described in detail. A full scale fatigue test of the airframe was conducted during the development and certification process of this aircraft (1995). A successful application of fatigue crack repair to the auxiliary stringer using the technology of bonded composite patches was verified during this test. However, the repair was designed and performed with technologies available at that time. The pre-cured carbon/epoxy (C/E) patches and adhesive SW 9323 was used. No sensors were applied for fatigue damage monitoring in this test.

It has shown on the test results that the technology used had a significant effect on a decreasing of crack growth rate in critical areas of the structures and thereby increased the airframe durability. The fatigue test did not show growth of the crack with the applied repair until 4.2 lifetimes.

The project continued with comparison of fatigue behaviour of two composite patch types including environmental effects. Different types of dog-bone specimens with the repaired crack were tested. First the (C/E) patch and then the unidirectional boron-epoxy (B/E) prepregs for the pre-cured composite patches was used. Both SW 9323 adhesive as well as foil adhesives (FM 73, SW 9323) were tested. The stiffness of boron fibres is much higher than carbon fibres. This fact enables the design of very thin patches. The value of the B/E prepreg coefficient of thermal expansion approaches that of aluminum alloys and it decreases the additional loading due to high curing temperatures and residual stresses.

There was also focused on the health monitoring of patches during its lifetime by operational loading. Fibre Bragg gratings (FBG) sensors were tested in addition to other methods to detect debonding process or crack growth under the patches.

The FE model of the whole aircraft – a global analysis model – was used for the definition of technical specification of the full scale fatigue test. The global model does not describe the damage area in sufficient details. Its purpose is to provide a correct layout of stiffness and deformation at the whole airframe and define boundary conditions for analysis of detailed parts. The group of solvers at the Czech Technical University in Prague created detailed local FE model (in ABAQUS software) of the damaged area without and with applied repair. This FEM analysis results had supported transfer of real loading conditions to simple coupon specimens, on which static, fatigue and SHM monitoring experiments were consequently realized.

2.2. Theoretical background of fibre Bragg gratings sensors

An optical FBG sensor consists of a photosensitive single-mode fibre in which a segment of core exhibits a periodic modulation of refractive index following exposure to an ultra-violet laser beam at 248 nm [5]. A phase-mask is commonly employed to generate the spatial pattern required to form the grating. The resulting Bragg wavelength associated with the grating is given by Bragg s law as follows

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

where λ_B kBG is the Bragg wavelength, n_{eff} is the effective refractive index of the grating, Λ is the period of the grating. When the FBG is illuminated by a broadband light source, the partially reflective grating planes reflect a narrow band optical spectrum having a peak reflection intensity corresponding to the Bragg wavelength λ_B . An FBG sensor monitors external perturbations, such as temperature and strain through a series of shifts in the Bragg wavelength. Externally-applied strain will cause the effective refractive index to vary, increasing the periodic spacing of the grating resulting in a corresponding shift in the Bragg wavelength. The sensitivity of the wavelength shift to pressure variations is generally negligible since the pitch-pressure and pressure-optic coefficients are generally insignificant. The theoretical wavelength shift of an FBG sensor subjected to mechanical strain and temperature variations is commonly given by

$$\Delta\lambda_B = \lambda_B(1-\rho)\Delta\varepsilon + \lambda_B(\alpha+\zeta)\Delta T , \tag{2}$$

where $\Delta\varepsilon$ and ΔT are strain and temperature variation and ρ , α and ζ are the photoelastic coefficient, thermal expansion coefficient and thermo-optic coefficient. The shift in central wavelength results from changes in the optical and physical properties of the grating via strain-optic and thermo-optic effects as well as changes in the periodic spacing of the grating due to mechanical strain. Strain-optic and thermo-optic effects relate to changes in the grating s effective refractive index as a result of mechanical and thermal loading, respectively.

3. SHM monitoring on model specimens using of FBG sensors

The experimental program was aimed at the possibilities of monitoring a crack initiation, a crack growth in an Al-specimen with a fatigue crack and an applied patch repair with the focus on the usage of embedded FBG.

Disbonding an adhesive between a composite patch and an Al-sheet were then tested on other form of specimens - skin doubler specimens (SDS). FBG sensors were implemented in this instance directly in the foil adhesive layer.

3.1. Fatigue cracks grow monitoring

For the starting experiments, flat dog-bone type specimens (of the width 56 mm and 2 mm in thickness) were selected. These specimens had premade central cracks, 30 mm in the length, ending in bored holes (it simulated a treatment of the real fatigue crack). Over the cracks on one side of the specimen were bonded carbon/epoxy patch repair with embedded FBG sensors. The patch repair was composed from 7 layers of unidirectional C/E high strength lamina; all layers were oriented with 0 degree angle. An MS-01 sensor from the FOS&S Company was embedded between the 6th and 7th layer of the patch repair. Length of the grating was 10 mm. Total thickness of the patch was approximately 0.9 mm. Nominal thickness of the adhesive joint was approximately 0.35 mm. A width of the patch was only 20 mm, so that it over-bridged both cracks surfaces.

The goal of the experiments was to use FBG sensors to detect stress redistribution in the composite repair due to the initiation of fatigue cracking or disbonding of the repair's edge. Two types of experimental measurements were used for the health monitoring of the structure:

- real-time monitoring during fatigue loading
- static loading during regular breaks of cyclic loading

Experiments were made at the Department of Aerospace Engineering at Ryerson University in Toronto, Canada. All tests were run on an MTS 322 test frame with MTS 647 hydraulic wedge grips. Two configurations were used for the experiments with FBGs. The first configuration used the Micron Optics Si425 Optical Interrogator. This configuration was capable of capturing the Bragg wavelength value with a maximal sampling frequency of 250 Hz. For the current experiment, a sampling frequency of 50 Hz was used. In the second configuration, the optical interrogator was replaced by the Ando Aq6331 Optical Spectrum Analyzer (OSA) with JDS Uniphase Broadband Light Source and an optical coupler. This configuration was used for capturing the distribution of the reflected spectrum of the signal. Due to the slow speed of scanning, it was possible to use this configuration only for measurements during the dwell on a static load.

Three specimens were tested at the same loading conditions. The specimens' geometry did not differ with the exception of the positioning of the FBG sensors and thickness of the third specimen. In the first two specimens, grating of 10 mm length was placed somewhere in the ideal distance from the central crack as was show in the FE analysis chapter. In the third specimen, grating was placed closer to the central crack area. During cycling, a fatigue crack occurred on one of the bored holes and then started to grow, see Fig. 1. Due to the imperfections of the specimen, the crack from the second bored hole initiated and started to grow with some delay. After both cracks reached the specimen edges, a quick failure of the adhesive joint happened. All FBG sensors survived until the end of experiments.

In Fig. 2 the behaviour of the Bragg wavelength amplitude during the life of specimen No 1 is shown. The increase in the amplitude value due to the crack initiation is visible after 30,000 cycles. From visual checks by optical camera the crack was detected at 34,500 cycles (scanning every 1,500 cycles). Two major jumps in the stiffness behaviour were captured in moments when one of the fatigue cracks reached the specimen edge. These global stiffness changes were verified from the behaviour of displacement amplitude that was captured by LVDT. Therefore it can be said that the methodology used was successful in the detection of crack initiation and growth.

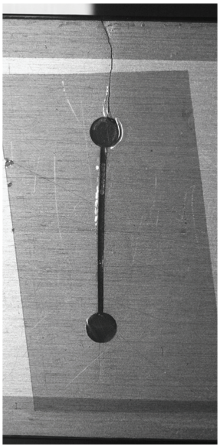

Fig. 1. Figure Crack growth during testing.

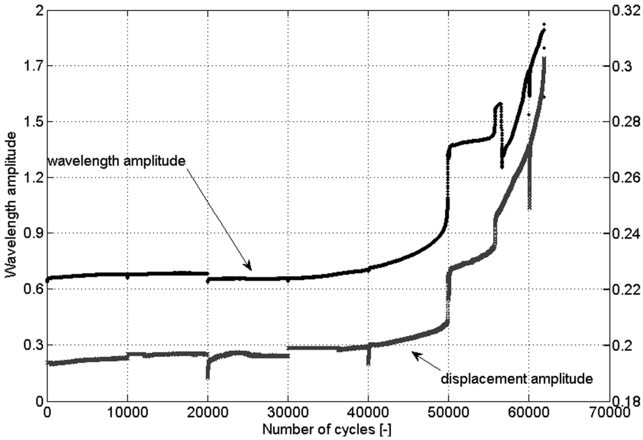

Fig. 2. Wavelength and displacement amplitude during the lifetime of the specimen No 1.

3.2. Monitoring of disbonding

Skin Doubler Specimens (SDS) (see Fig. 3a) were used to model end of the repair patch. It consists of aluminum body and two boron/epoxy patches, which were bonded with FM 73 film adhesive. Patches were pre-cured in autoclave and were composed from three boron/epoxy prepregs. Cyclic loading methodology, how to initiate disbonding, was taken over from [7]. Specimens were periodically loaded on increasing load levels. Decrease of the strain amplitude was detected by strain gauges, installed on the edges of patches (see Fig. 3b). In this case, strain amplitude was measured also by FBG sensor, which was integrated directly into the film adhesive layer. Optic fibre was placed with grating located near the edge of patch (below a surface strain-gauge). Ingress point of fibre is protected by combination of adhesive tape and silicone putty. Protective liners from glass/epoxy laminate were bonded with SW 9323 adhesive.

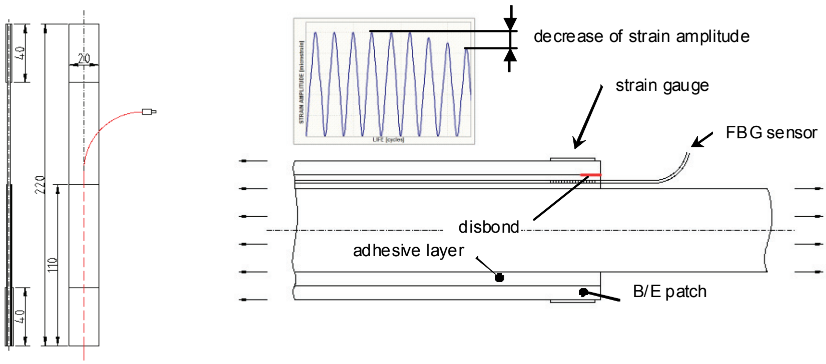

Fig. 3. (a) Skin Doubler Specimen (FBG sensor is marked by red line). (b) Principle of detection of disbonding during tensile fatigue loading of Skin Double Specimen.

Fatigue experiments were carried out in Aeronautical Research and Test Institute in Prague. Five specimens were tested, each with the same dimensions and location of sensors. Optical interrogator Safibra FBGuard was used to capture signal from the FBG sensors (length of grating 5 mm, central wavelength about 836 nm). Sampling frequency of 70 Hz was used (32-35 samples per period). Data were processed using Matlab software. Maximum value of strain amplitude from each cycle was recorded.

Specimens were loaded by force controlled tensile transient load (R=0), at load levels (4.4, 4.9, 5.5, 6.3, 7.0, 7.7, 8.3, 9.0) kN. Each load level lasted 50,000 cycles and specimens were loaded to the final fracture. Loading frequency was about 2 Hz. Time of the disbonding initiation was determined during offline data analysis. It was defined as life cycle count, at which strain amplitude decreased by more than 10%.

Five SDSs were tested in total. Typical example of fatigue life of one of the specimens is shown in Fig. 4. Disbonding of patch, which started during load level of 7.0 kN, was detected by increase of strain amplitude measured by the FBG sensor and by decrease of strain amlitude measured by the colocated strain gauge. This could be caused by disbonding of patch-glue interface. FBG sensor remains attached to the aluminum body of specimen, thus its deformation is higher. Strain gauge indicates lower deformation, because it is attached to disbonded patch.

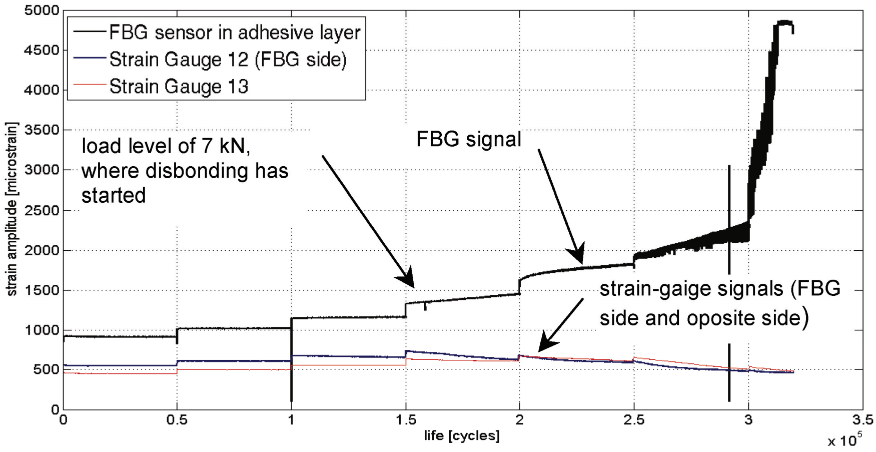

Fig. 4. (a) Example of fatigue life (Specimen SS-03).

Good coincidence between changing of signals of strain-gauges and FBGs was evident in all measured specimens, although in three cases disbonding has progressed on the side of the specimen opposite to one included FBG sensor. All FBG sensors remained functional even after the specimen fracture.

4. Summary/Conclusions

Real-time health monitoring of cracked dog-bone specimens, over-bridged by bonded C/E patch, was successfully verified on three aluminum specimens with and embedded FBG. From the determined behaviour of the amplitude values of Bragg wavelength during the specimen lifetime, fatigue cracks initiation and growth were successfully detected. These results were verified from the global stiffness changes captured by load cell and also from images of the gage area that were captured during cycling. Other verification was done from static experiments in tension that were made in given time intervals. The crack initiations and growth were detected from the comparison of the change of the slope of Bragg wavelength-tensile force dependency during lifetime.

Detection methods used during experiment on SDS specimens showed good agreement also in the determination of the beginning of the patch disbonding. In comparison to strain gauges, integrated FBG sensors give better response to strain. They provide possibility of monitoring of growing disbonding by means of the spectrum splitting. Disbonding of patches occurred at the lower load levels, comparing to the case of specimens without optical fibre in the adhesive layer. In three cases out of five, disbonding was detected on the side of specimen without FBG sensor. Both disbonding on specimen side with FBG in the adhesive layer and virtually simultaneous disbonding on both sides of specimen were detected in one case. This allows to assume that the lower load levels during disbonding are not primarily caused due to damage of the adhesive joint by the integrated FBG sensor.

However, more experiments need to be done to examine the influence of optical fibre to the adhesive layer behaviour.

The capability of monitoring of composite repair patches by FBG sensor and its using for crack growth and disbonding monitoring has been successfully demonstrated. SHM system of composite parts utilizing of FBGs is nowadays built up by cooperation with Aero Vodochody Ltd.

Acknowledgements

The presented results were supported by the Ministry of Industry and Trade of the Czech Republic by project FR-TI1/290. The authors would like to thank Dr. X. Gu from the Department of Electrical Engineering at Ryerson University in Toronto, Canada for his support with manufacturing of FBGs.

References

[1] Farrar Ch.R. and Worden K., "An introduction to structural health monitoring," *Philosophical Transactions of The Royal Society A*, **365**(1851), pp. 303-315 (2007). ISSN 1364–503X.

[2] Farrar Ch.R. and Worden K., "Vibration-based structural damage identification," *Philosophical Transactions of The Royal Society A*, **359**(1778), pp. 131-149 (2001). ISSN 1364–503X.

[3] Růžička M., Kribalis P., Henzl P. et al., "Design and application of composite repairs of fatigue cracks," in *Proceedings of the 6th International Workshop on Structural Health Monitoring*, Chang F-K., ed., Stanford University, September 2007 (DEStech Publications, Inc., Lancaster, Pennsylvania, 2007), Vol. 1, pp. 391-398. ISBN 978-1-932078-71-8.

[4] Kulíšek V., Poon C., Růžička M. et al., "Health monitoring of structures with fatigue damage and applied composite repair," in *Proceedings of the 7th International Workshop on Structural Health Monitoring*, Chang F-K., ed., Stanford University, September 2009 (DEStech Publications, Inc., Lancaster, Pennsylvania, 2009), Vol. 1, pp. 167-174. ISBN 978-1-60595-007-5.

[5] Kuang K.S.C., Zhang L., Cantwell W.J. and Bennion I., "Process monitoring of aluminum-foam sandwich structures based on thermoplastic fibre–metal laminates using fibre Bragg gratings," *Composites Science and Technology,* **65**(3-4), pp. 669–676 (2005). ISSN 0266-3538.

[6] Worden K, Farrar C.R., Manson G. and Park G., "The fundamental axioms of structural health monitoring," *Philosophical Transactions of The Royal Society A*, **463**(1834), pp. 1639-1664 (2007). ISSN. 1364–503X.

[7] Giurgiutiu V., "Structural Health Monitoring and NDE - an Air Force," in *Proceedings of the Fourth European Workshop Structural Health Monitoring 2008*, Uhl T., ed., Krakow, July 2008 (DEStech Publications, Inc., Lancaster, Pennsylvania, 2008), pp. 91-98. ISBN 978-1-932078-94-7.

[8] Baker A., Rose F. and Jones R., eds., *Advances in the Bonded Composite Repair of Metallic Aircraft Structure* (Elsevier Science Ltd., Oxford, 2002). ISBN 978-0-08-042699-0.