Composite Structures 130 (2015) 75–84

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Response of fiber Bragg gratings bonded on a glass/epoxy laminate subjected to static loadings

Matthieu Mulle [a,*], Ali Moussawi [a], Gilles Lubineau [a,*], Samuel Durand [b], Didier Falandry [c], Philippe Olivier [d]

[a] King Abdullah University of Science and Technology (KAUST), Physical Science and Engineering Division, COHMAS Laboratory, Thuwal 23955-6900, Saudi Arabia
[b] MECA Design Office, Nantes, France
[c] CRITT Mechanical Engineering and Composites, Toulouse, France
[d] Clement Ader Institut (ICA), Paul Sabatier University, Toulouse, France

ARTICLE INFO

Article history:
Available online 22 April 2015

Keywords:
Structural health monitoring (SHM)
Composite
Laminate
Sandwich
Fiber Bragg grating (FBG)
Digital image correlation (DIC)

ABSTRACT

Fiber Bragg gratings (FBG) may be used to monitor strain over the surface of a structure as an alternative technology to conventional strain gauges. However, FBG bonding techniques have still not been established to yield satisfactory surface measurements. Here, two adhesives were investigated, one with low viscosity and the other with high viscosity for bonding FBGs on glass/epoxy sandwich skins. First, instrumented elementary specimens were tested under tension. FBG strain results were analyzed together with digital image correlation (DIC) measurements. The influence of the bonding layer on the measured strain and on the integrity of the sensor was investigated by considering different regions of interest. Next, an instrumented structural sandwich beam was tested under four-point bending. FBG rosettes were compared to conventional strain gauge rosettes. The high viscosity adhesive demonstrated behaviors that affected FBG accuracy. Brittleness of the bonding layer and poor interface adhesion were observed using DIC and X-ray tomography. By contrast, the low viscosity adhesive demonstrated satisfactory results. The FBG strain measurements appeared to be consistent with those of DIC. The accuracy is also adequate as the FBGs and the conventional strain gauges had similar results in three directions, under tension and under compression.

1. Introduction

Optical fiber Bragg gratings (FBG) are widely used in mechanical sensing of composite materials [1–3], mainly because of their resistance to high temperatures, allowing them to withstand the temperatures required in composite curing processes [4,5] and of their small size, allowing them to be embedded between laminate plies without significantly altering the structural integrity of the host material [6,7]. FBGs offer other advantages that make them ideal candidates rather than conventional strain gauges for structural sensing: they are immune to electromagnetic fields, they have the ability to be multiplexed, meaning that several sensors can be distributed on a single optical fiber, they provide an absolute wavelength reference making them immune to interruption and they may be used as very reliable temperature sensors [8,9]. These advantages suggest that FBGs can be used in long-term structural health monitoring (SHM) applications [10].

Composite materials are increasingly used in civil engineering. Among these materials, sandwich panels provide a promising self-standing structure for the roofs of large buildings. In some regions these structures are subjected to harsh environmental conditions (high heat combined with high relative humidity and strong winds). This calls for a reliable in-situ strain monitoring. Conventional electrical strain gauges could be used for such program but it appears that it would imply an important number of cables, complex compensation procedures and the eventual influence of electromagnetic fields. The use of FBGs in this setting mitigated the likelihood of encountering these problems. In this case a major question relates to whether or not to embed the optical fibers. The large dimensions of such structures, the usual open mold contact lay-up environment and the frequent intense manufacturing flow process involved do not allow for precise integration of sensor arrays in sandwich laminated skins. Consequently it is reasonable to adopt a surface bonding technique to install the FBGs.

Surface bonding of FBGs leads to questions about strain transfer. To analyze the strain transfer mechanism from a loaded substrate to the optical sensor, theoretical approaches have been

* Corresponding authors.
E-mail addresses: matthieu.mulle@kaust.edu.sa (M. Mulle), gilles.lubineau@kaust.edu.sa (G. Lubineau).

http://dx.doi.org/10.1016/j.compstruct.2015.04.015
0263-8223/

developed to provide prediction tools [11–17]. Numerical analyses using finite element modeling (FEM) are then proposed to validate the analytical models [11–14]. Only a few authors have validated their analytical approaches experimentally [13,15,16]. Ansari and Yuan [15] tested bonded coated fibers as well as bare fibers on an aluminum beam subjected to bending. They used a Michelson interferometry sensing technique was used. In this case, the sensor gauge length is much larger than the length of FBGs. They concluded that when optical fibers are used without any coating (bare fiber) a total strain transfer from substrate to sensor is obtained. Zhang et al. [16] compared two adhesive processes, epoxy resin and sprayed metal. FBGs were bonded on a galvanized steel wire. They reported that the geometry of the bonding layers, as well as their properties, have an impact on the measurement accuracy. Betz et al. [10] tested the viability of a surface-bonded FBG for a major aircraft company. The sensor was covered by a varnish build up. The results were validated by FEM and compared to conventional strain gauge measurements. The high potential of this installation technique was revealed due to its processing ease and practical advantages in comparison to embedding techniques.

In summary several studies suggest that the thickness between the sensor and the substrate should be as small as possible [12,16,17] and that the polymeric coating should be removed [15]. These studies also suggest that the bonded length should be longer than the sensor gauge length [12,16] to avoid misleading longitudinal strain gradients and that the overall bonding layer thickness must be reasonable to prevent distortion of the FBG's reflected spectrum [12,16,17]. Similar distortions may take place if the adhesive is too stiff and bulky [16]. If the stiffness of the substrate is low compared to that of the optical fiber strain transmission loss is possible [13].

Adhesion between the bare fiber and the protective material or the adhesive has not been the focus of much research. The theoretical developments cited above are generally based on the assumption that all interfaces are perfectly bonded so that displacement is consistent along the interfaces. Yet, a previous experimental study [18] clearly revealed that the protective coating was poorly bonded to the FBG, inducing important measurement inaccuracies.

There is limited research using experimental approaches that seeks to understand and validate the response of bonded FBGs. Motivated by the above considerations, an experimental investigation on the response of bonded FBGs on glass/epoxy composites was undertaken and presented in this paper. The adhesive systems chosen for the test were provided from a major strain gauge manufacturer. These adhesives are commonly used for bonding strain gauges to characterize materials under static and cyclic testing and are made to resist harsh environmental conditions to some extent. Given the installation conditions for sensors on roof sandwich panels, two adhesive solutions are proposed. The first one is a high-viscosity adhesive that is suitable for rough surface bonding and practical implementations. The second one is a low-viscosity adhesive that provides a recommended thin interface layer but that may necessitate polishing the substrate. To analyze the efficiency of both bonding systems two series of static tests were performed. The first consisted of tensile loading tests on two specimens made from the laminated skins of the sandwich. The objective of the tensile test was to compare the FBG results to full-field measurements from digital image correlation (DIC), to analyze the strain fields in the FBG-adhesive area and to evaluate the mechanical impact of the sensing system. Some additional analysis was possible using X-ray micro tomography. The second static test was a four-point bending test on a large instrumented sandwich beam. The goal was to validate the FBG measurements under condition of both adhesive solutions by a comparison with measurements from conventional strain gauges.

2. Material and samples

The reinforcement material and the matrix were chosen accordingly to a civil application of roof paneling of very large dimension. The results of a stress analysis of a sandwich solution provided an optimized design of the composite skins in terms of reinforcement quantities and orientation. Taking into account processing and economical aspects, a tri-axial glass fabric that could be used in both normal and inverted position was found to be the most adequate.

The inner and outer face of the composite sandwich beam used in our test present a reinforcement stack of two layers of the same tri-axial glass fabric (TX 0/+45/90-Saertex-930 g/m^2) to give a [(0/+45/90)/(0/−45/90)] sequence. The matrix was an epoxy resin (Ampreg 21FR – Gurit). The skin's mean thickness was approximately 2 mm and the glass volume fraction was 32% when estimated using an acid digestion technique. The sandwich core was made of 150 mm thick PET foam (PETW/AC8 – Armacell). The manufacturing process consisted of hand lay-up and manual impregnation procedures in an open mold, followed by vacuum bagging and oven curing processes. Elementary specimens were cut from separately made skin laminates using a diamond disk. They were 120 mm long and 16 mm wide. The large structural sandwich beam was 3400 mm long, 450 mm wide and approximately 154 mm thick.

3. Instrumentation

3.1. Optical FBG sensing

An FBG reflects a part of the incident light signal that is represented by a spectrum of wave length [8,9]. It is characterized by a Bragg wavelength, λ_B, that corresponds to the spectrum peak. When the FBG is subjected to axial strain ε_{xx} or temperature changes ΔT, the peak shifts proportionally with these loadings. The Bragg wavelength variation can be expressed as:

$$\Delta\lambda_B/\lambda_B = K_T\Delta T + K_\varepsilon\varepsilon_{xx} \qquad (1)$$

where K_T and K_ε are related to the sensor's sensitivities to temperature and strain, respectively. In this study the temperature component is neglected as tests are carried out at constant temperature. FBGs used here were 5 mm long and written on SMF28e standard fiber. The coating was removed along the FBG. A Micron Optics sm125 unit was used for the acquisition of peak changes and reflected spectrums.

FBGs used here were 5 mm long and written on SMF28e standard fiber. The coating was removed along the FBG. A Micron Optics sm125 unit was used for the acquisition of peak changes and reflected spectrums.

3.2. Adhesives

Two adhesives for extensometry applications were tested. According to the manufacturer, both adhesives were claimed to be are adequate to resist long-term and harsh environmental conditions. That makes them viable candidates for our final structural monitoring. The main difference between the two adhesives is their viscosity. The first solution called system A is HBM X60. It is a pasty cold-curing two-component system made of methyl methacrylate. After rapid mixing of the two components, twenty to thirty seconds are necessary for curing. A typical thumb-pressure procedure is needed to bond the sensor. This system is very attractive for its ease of use even in the upside down position and for its fast curing. The second solution called system B is HBM Z70. It is a liquid cold curing single-component system made of cyanoacrylate. Curing is only possible on very thin