SENSING WITH EMBEDDED FIBER BRAGG GRATINGS IN EXTREME MECHANICAL CONDITIONS

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Abstract

Fiber Bragg gratings (FBGs) are increasingly being used as strain sensors in aerospace structures testing due to their inherent advantages over conventional electric strain gauges. However, although the early identification of the capability of FBGs to be embedded in composite laminates opened the possibility to count on a integrated load monitoring system, practical reasons has delayed the implementation of such systems.

One of these reasons is the fact that FBGs are not intrinsically averager as electrical strain gauges: fiber Bragg gratings are sensitive to longitudinal strain gradients and transverse stresses, phenomena both that affects the spectral behaviour of the sensor.

Embedding conditions have to be then carefully considered in the preliminary design of an embedded sensing network layout if consistent strain results have to be obtained. Results presented on this paper reflect the effect of extreme embedding conditions in the strain measurements of FBGs.

1 Introduction

Fiber Bragg gratings (FBGs) are increasingly being used as strain sensors in aerospace structures testing due to their inherent advantages over conventional electric strain gauges. However, although the early identification of the capability of FBGs to be embedded in composite laminates opened the possibility to count on a integrated load monitoring system, practical reasons has delayed the implementation of such systems. Some of these reasons are:

- To carry on board a fiber optic sensing network is not free, and there must be a reason to do it: design optimization or reduction of maintenance time/cost. A Structural Health Monitoring (SHM) system has to prove the value of each dollar of cost (installation and maintenance) and each gram of weight to justify its presence on an aircraft, and a load monitoring system may be useful installed on a military aircraft, but not on an airliner, with a well-known flight envelope.
- To integrate a fiber optic sensors network on a structure is not easy, nor cheap: although many techniques and devices has been developed and patented to solve the problem of ingress/egress fiber optic on composite laminates, the procedures are tricky, expensive on time and cost, and with a high rate of "dead sensors". Intrusivity of the embedded optical fiber, resultant in a degradation of the mechanical properties of the host laminate, is still a matter of research. Besides, reparability of damaged laminates with embedded fibers, or reparability of an embedded fiber optic is also an unsolved issue.
- When these and other problems (sensors zeroing and calibration, temperature compensation, etc.) have been solved, to count on a multi-channel, high-speed, anti-aliasing FBG demodulator certified for flight will be only a matter of time.

2 Problem description

However, another important issue has to be in mind when operating with a network of embedded FBGs. These sensors are not intrinsically averager as electrical strain gauges: fiber Bragg gratings are sensitive to longitudinal strain gradients and transverse stresses, phenomena both that affect the spectral behaviour of the sensors (promoting distortions that affect the strain measurement) depending on many variables such as: type of fiber optic used (single mode, polarization maintaining…), refractive index profile, length of the grating, type of coating used in the fiber (acrylate, polyimide…), thickness of the laminate, directionality of the strains and stresses fields, position and orientation of the fiber in the laminate, etc. [1],[3],[4].

Embedding conditions have to be then carefully considered in the preliminary design of the sensing network layout if consistent strain results have to be obtained. Results presented on this paper reflect the effects of extreme embedding conditions (transversally to the reinforcement and the direction of the load) on the spectral behaviour of fiber Bragg gratings and the measurement of strains.

3 Test description

To reveal these problems, four composite specimens made of intermediate modulus graphite/epoxy prepreg (HEXPLY M21/34%/194/ T800S-24k-WIDTH, Hexcel Composites, S.L.) with 5-6 fiber Bragg gratings each integrated in different conditions have been manufactured and tested in order to monitor the influence of extreme mechanical conditions (strong transverse strains and stresses) on the spectral behaviour of fiber Bragg gratings and the measurement of strains.

Specimen's configuration and manufacturing conditions were:

- Stacking sequence: $[0]_{11}$ (11 unidirectional layers in the direction of the load.
- Curing cycle: heating from room temperature to 185C at 1C/min, 2 hours of stabilization, autoclave pressure of 7 bars, 450 mmHg of vacuum maintained.
- Optical fiber: SMF-28 type Nufern photosensitive optical fiber, diameter 0.125 mm without coating, 245±15mm with coating.
- Fiber Bragg Gratings:
  - Lengths: 2 and 10 mm.
  - Coating: acrylate annealed at 200C during 2 hours, bare fiber.
  - Orientation with respect the laminate: transverse to the direction of the load, except a FBG per specimen, superficially bonded with cyanoacrylate adhesive and used as strain gauge to measure the longitudinal strain.
  - Position in the laminate: the FBGs were integrated at different positions through the thickness in the laminate: the centre of the laminate, under the first layer, embedded at the surface and bonded after the curing process.

Influence of several variables on the measurements will be considered, as follows:

- Length of the FBGs: 2 and 10 mm
- Position of the FBGs in the laminate of the specimen and integration conditions: embedded in the neutral line, under the fist ply, embedded in the surface, bonded
- Coating of the FBGs: acrylate, annealed acrylate, bare fiber.

In two of the specimens, identical, 2 and 10 mm long FBGs were integrated at the middle of the laminate to test the influence of the length of the grating and the presence of coating in the spectral behaviour of the grating after the manufacturing process (due to the effect of the thermal residual strains and stresses) and during the load application.

<u>Details of specimens 1 and 2:</u>

S01(2).1: 2mm long, bare, embedded transversally at the middle of the laminate.

S01(2).2: 10mm long, bare, embedded transversally at the middle of the laminate.

S01(2).3: 10 mm long, coating without annealing, embedded transversally at the middle of the laminate.

S01(2).4: 10mm long, coating with annealing, embedded transversally at the middle of the laminate.

S01(2).5:10mm long, bare, bonded longitudinally.

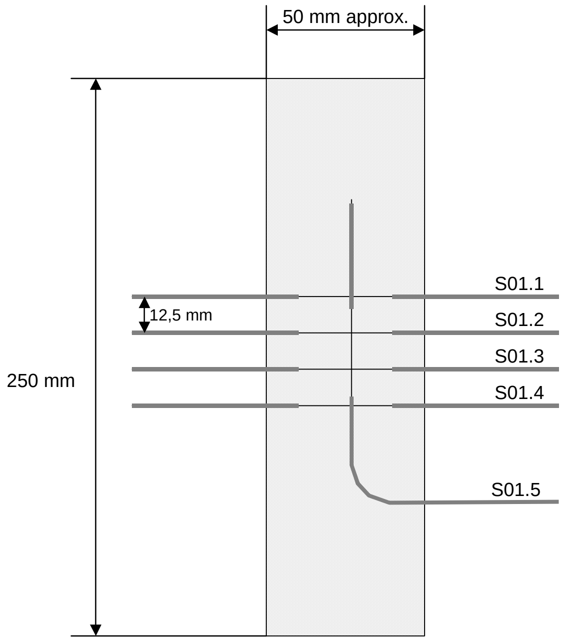

Fig.1. Schematic of the specimens 1 and 2, with the position of the integrated sensors.

In the other two specimens, 2 and 10 mm long FBGs were integrated without coating at different positions through the thickness in the laminate to test the influence of the length of the grating and their position though the thickness of the laminate in the spectral behaviour of the grating after the manufacturing process (due to the effect of the thermal residual strains and stresses) and during the load application.

<u>Details of specimens 3 and 4:</u>
S03(4).1: 10mm long, bare, embedded transversally at the surface of the laminate.
S03(4).2: 10mm long, bare, bonded transversally at the surface of the laminate.
S03(4).3: 10 mm long, bare, embedded transversally below the first layer of the laminate.
S03(4).4: 10mm long, bare, embedded transversally at the middle of the laminate.
S03(4).5: 2mm long, bare, embedded transversally at the middle of the laminate.
S03(4).5:10mm long, bare, bonded longitudinally at the surface of the laminate.

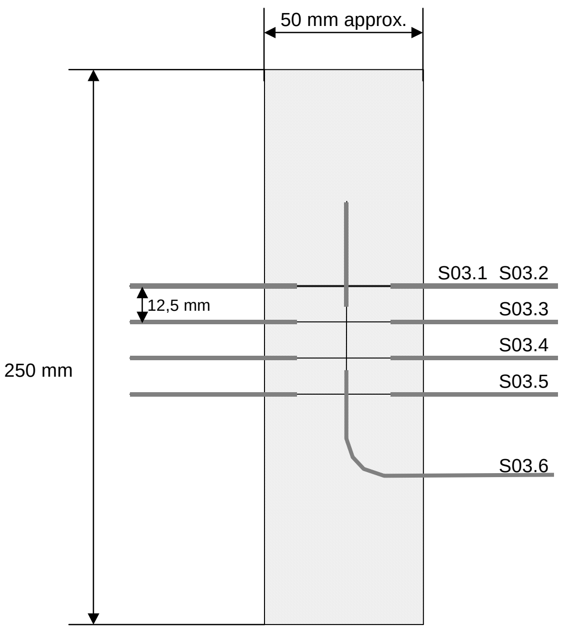

Fig.2. Schematic of the specimens 3 and 4, with the position of the integrated sensors.

The configuration of the specimens and the characteristics of the tests aim to increase the knowledge in the spectral behaviour of fiber Bragg gratings used as embedded sensors into composite laminates. In summary, the objective of the tests was then to analyze the influence of variables as the length of the gratings, their position through the thickness of the laminates and the presence of a soft coating in the spectral behaviour of fiber Bragg gratings under unfavourable conditions: embedded transversally to the reinforcement fibers, and submitted to transverse loads.

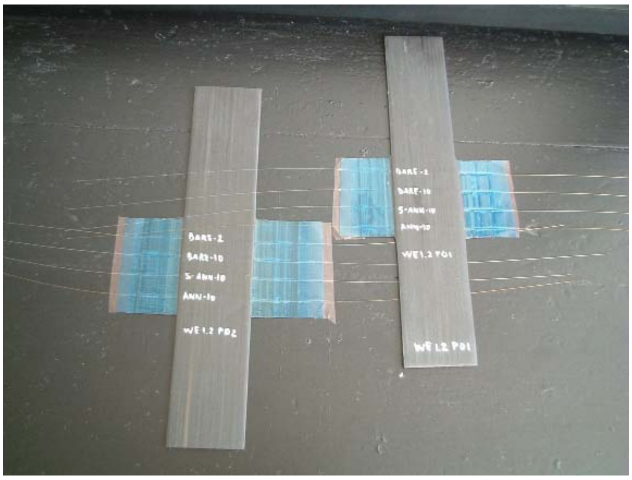

Fig. 3. Two of the specimens already manufactured after protecting the fiber ingress points.

The embedding process and the manufacturing of the part was successful, with the survival of all the embedded sensors. After the demoulding of the parts, the specimens were hand trimmed and the optical fiber ingress points were protected in order to avoid their breakage during the rest of the test.

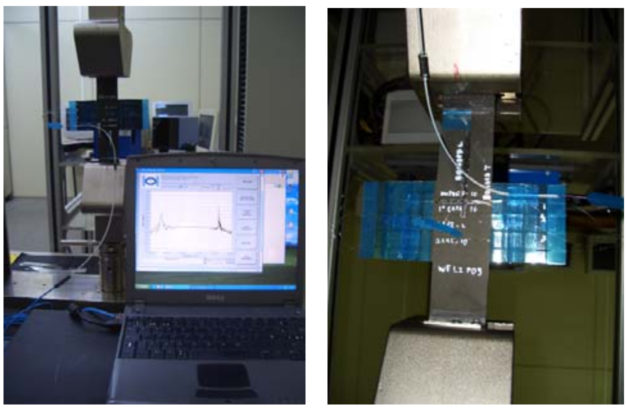

Fig. 4. Test setup showing the acquisition of the spectra, and a detail of the specimen on claps

The specimens were submitted to a tensile test from zero load to 30 KN, measuring the longitudinal sensors around 3000 $\mu\varepsilon$ in the main direction of the coupons.

4 Results

Even before the test was performed, most of the results related to the spectral behaviour of the integrated gratings could be easily predicted:

The configuration considered would force intense residual transverse stresses and strains so, with different intensities, the typical peak splitting phenomenon would affects the spectra of most of the integrated gratings after the curing of the specimens.

The peak splitting will increase with the tensile loading applied in the longitudinal direction of the specimen due to the orientation of the FBGs and the increase of the resultant transverse stresses applied to them.

4.1 Influence of FBG length

The length of the gratings has influence on the shape of their spectrum and their sensitivity to the surrounding stresses and strains fields. The spectra of the 10 mm long FBGs are intrinsically 5 times thinner than the spectra of the 2 mm long FBGs, allowing more accurate strain measurements embedded in uniform strain fields. However, they are also more sensitive to transverse stresses and strain fields and perturbations in the longitudinal strain fields.

This effect is experimentally observed in the Bragg gratings embedded into the specimens considered. Figures 5 and 6 show respectively the spectra of two gratings 2 and 10 mm long, without coating, embedded in the middle of specimen 1, unloaded (in blue) but with the peak splitting promoted by the thermal residual transverse stresses, and submitted to transverse tensile load (in red).

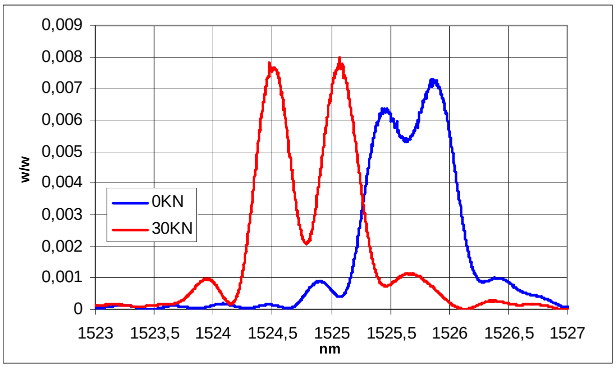

Fig. 5. Reflective spectra of a 2 mm long FBG, without coating, embedded in the middle of the laminate of specimen 1, unloaded (in blue) and with the splitting promoted by the thermal residual transverse stresses, and submitted to transverse tensile load (in red).

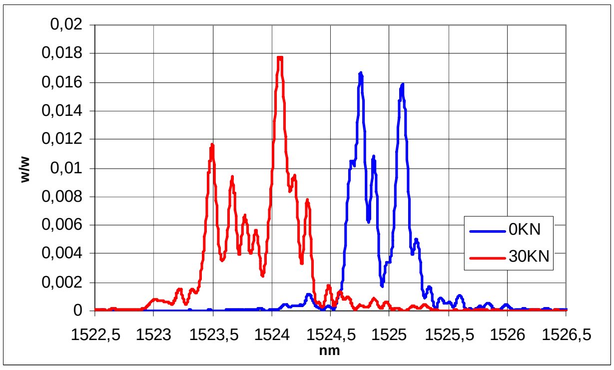

Fig. 6. Reflective spectra of a 10 mm long FBG, without coating, embedded in the middle of the laminate of specimen 1, unloaded (in blue) but with the splitting promoted by the thermal residual transverse stresses, and submitted to mechanical transverse tensile load (in red).

The spectrum of the 10 mm long grating not only shows with better resolution the two splitted peaks effect of the transverse stresses over the grating, but reveals a high distortion in the strain profile parallel to the optical fiber, that the spectrum of the 2 mm long FBG do not shows.

In both cases, the spectral demodulation and signal interpretation of both kinds of gratings is a complex issue, and the use of such gratings for strain measurement, at least with conventional optoelectronic equipments, is obviously not recommendable.

4.2 Influence of the coating

The presence of acrylate coating will have also a smoothing effect on the influence of residual stresses promoted during the curing process, and the mechanical transverse stresses promoted by the mechanical loading, reducing the expectable strong spectral distortion of embedded bare FBGs to a simple peak widening. However, at high load levels, the presence of complex biaxial strains and stresses fields are revealed with considerable spectral distortion.

This effect can be also experimentally observed in the specimens tested. Figure 7 shows the spectrum of a fiber Bragg grating 10 mm long, with acrylate coating, embedded in the middle of the laminate of specimen 1, unloaded (on the right, in blue) and without splitting, and submitted to increasing levels of mechanical transverse tensile load. The comparison of this behaviour with the spectrum of a grating with identical characteristics, embedded in the same specimen and in analogous conditions, but without coating (as the FBG of fig.6) is significant.

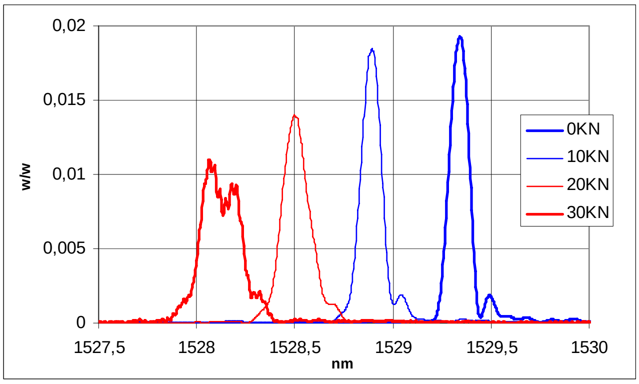

Fig. 7. Spectrum of a FBG 10 mm long, with acrylate coating, embedded in the middle of specimen 1, unloaded (on the right, in blue) and without splitting, and submitted to increasing levels of transverse tensile load.

The comparison of this behaviour with the spectrum of a grating with identical characteristics, embedded in the same specimen and in analogous conditions, but without coating (as the FBG of figure 6) is significant. The use of a soft coating is mandatory for embedded gratings that are going to be used for measuring strains, specially if the conditions of embedding allow the occurrence of high levels of transverse stresses, because the conventional optoelectronic demodulators are generally simple peak locators that can give wrong information, detecting inexistent sensors when peak splitting occurs.

However, the extra information given by the distorted spectrum of bare embedded FBG can be useful if the gratings are going to be used as damage detection sensor [2],[5]. In those cases, the use of fiber Bragg gratings without coating will be preferable. Of course, in these cases, the use of optoelectronic demodulators with full spectrum analyzing capability will be mandatory.

4.3 Influence of depth of embedding

There are important differences in the spectral behaviour of gratings embedded at different depths into the laminates. Figures 8, 9, 10 and 11 shows the spectra of fiber Bragg gratings integrated into the specimen 3 at different depths: embedded into the middle of the laminate, below the first layer, embedded in the surface and cold bonded after the curing process.

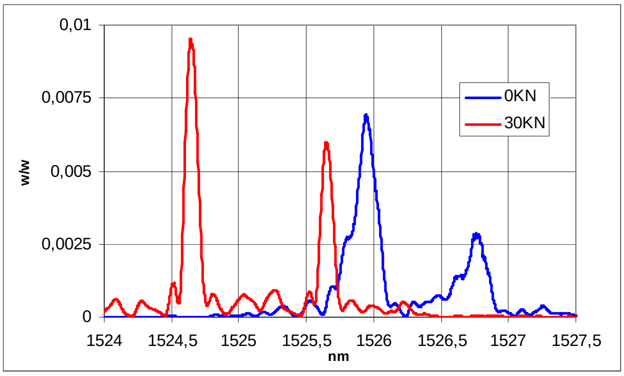

Fig. 8. Spectrum of a FBG 10 mm long, bare, embedded in the middle of the laminate of specimen 3, unloaded (in blue) but with the splitting promoted by the thermal residual transverse stresses, and submitted to transverse tensile load (in red).

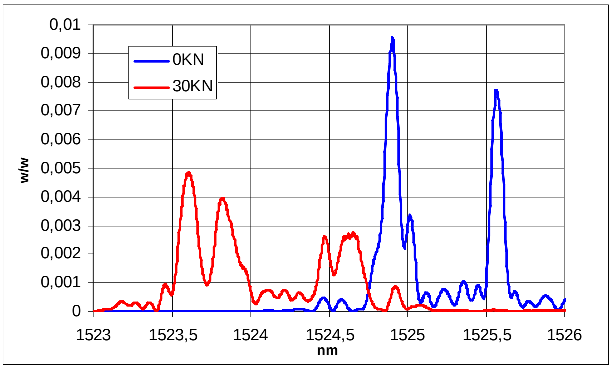

Fig. 9. Spectrum of a FBG 10 mm long, bare, embedded below the first layer of specimen 3, unloaded (in blue) but with the splitting promoted by the thermal residual transverse stresses, and submitted to transverse tensile load (in red).

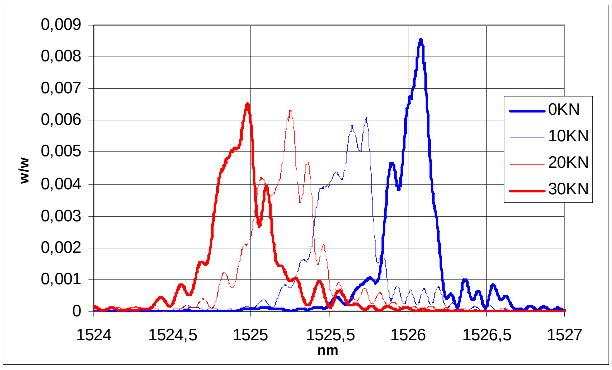

Fig. 10. Spectrum of a FBG 10 mm long, bare, embedded at the surface of specimen 3, unloaded (in blue) but with the splitting and distortion promoted by the thermal residual strains and stresses, and submitted to increasing transverse tensile load.

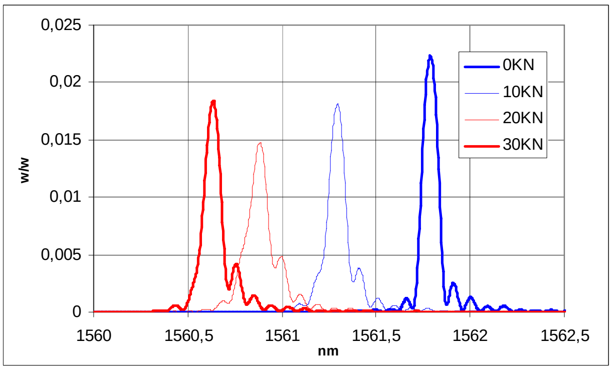

Fig. 11. Spectrum of a FBG 10 mm long, bare, cold bonded at the surface of specimen 3, unloaded (in blue) and without splitting, and submitted to increasing transverse tensile load.

There are only slight differences between the residual transverse stresses detected by the FBGs embedded in the middle and below the first layer of the laminate, and both present identical response to the tensile load applied to specimen. However, the grating embedded at the surface of the laminate presents a very distorted spectrum, without a clear peak splitting, and their sensitivity to the transverse stresses promoted by the tensile load is very low.

The grating bonded at the surface of the laminate presents only a very light sensitivity to the applied transverse load that hardly widens its spectrum.

All these results reveal that embedded FBGs can not be indiscriminately used for strain monitoring of composite laminates. Even in the case of coated gratings, a careful analysis of the loading conditions of the monitored part have to be previously done and, in case of doubt, the use of complete spectral analyzers instead of basic peak locators is recommended.

4 Conclusions

The dimension of the fibre Bragg gratings has important influence on the shape of the spectrum and their sensitivity to the surrounding stresses and strains fields when using embedded into composite laminates.

Longer gratings allow intrinsically more accurate strain measurements when embedded in uniform strain fields. However, they are also more sensitive to transverse stresses and strain fields and perturbations in the longitudinal strain fields, and consequently noisier.

Independently of their length, the spectral demodulation and signal interpretation of bare FBGs embedded into composite laminates under complex stresses and strains fields is a complex issue, and the use of such gratings for strain measurements, at least with conventional optoelectronic equipment, is obviously not recommendable.

The use a soft coating covering the gratings is mandatory for strain measurement due to its smoothing effect on the influence of residual stresses promoted during the curing process, and the mechanical transverse stresses promoted by the mechanical loading, reducing the expectable strong spectral distortion of embedded bare FBGs to a simple peak widening.

The position of the gratings through the thickness of the laminate has also important influence in their spectral response.

Embedded FBGs cannot then be indiscriminately used for strain monitoring of composite laminates, and a good knowledge of the load conditions of the part is highly recommended before the integration of the sensing network.

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