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Internal strain assessment using FBGs in a thermoplastic composite subjected to quasi-static indentation and low-velocity impact

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Abstract

We present, for the first time, an experimental investigation of internal strain monitoring in thermoplastic composites subjected to quasi-static indentation and low-velocity impact using embedded fiber Bragg gratings (FBGs). The goal is to highlight the interest and limitations of the in-core instrumentation of glass fiber-reinforced polypropylene laminates subjected to these two classical loading conditions. We propose an instrumentation strategy utilizing FBGs that is expected to provide a reliable set of internal strain values and strain rates, which can be used for the analysis of the damage behavior and the validation of a numerical mesoscale model of laminates. Based on a specific sensor insertion procedure, monitoring techniques and optical observations, we show how the applied methodology alleviates major issues, such as determining the in-plane and through-thickness position of the embedded FBGs, their influence on the structural integrity or the interpretation of the reflected optical signal.

Keywords:

Thermoplastic composite; Quasi-static indentation; Low-velocity impact; Fiber Bragg grating; Strain monitoring.

1. INTRODUCTION

Glass fiber reinforced polypropylene (GFPP) is one of the most widely-explored thermoplastic composites for automotive structural components because of economic and environmental considerations [1] besides having an excellent impact resistance. However, the internal damage state of such components under dynamic loading is still largely unknown, and the models that can precisely predict the damage behavior of GFPP, in particular, are minimal [2]. The numerical tools developed for thermoset-based materials mainly account for the behavior of composites which are orthotropic elastic and characterized by brittle fracture [3] but are not adequate to model the rate- and pressure-dependent damage behavior of the thermoplastic composites. The strong viscoelastic and viscoplastic behavior of the material must also be taken into account [4, 5, 6, 7]. In developing such a rate-dependent model, one of the essential data is the strain rate experienced by the material.

The strain rate is usually measured using strain gages or digital image correlation (DIC). These techniques can only measure the strain field on the surface of a specimen, which can be considered as a quick indicator. However, identifying the strain fields in the upper and lower faces is not sufficient to reveal the through-thickness strain distribution as well as the strain rate. As the outer surfaces of a specimen are gripped during dynamic loading, it is likely that there are significant sub-surface inter-ply shear strains, inducing a nonlinear through-thickness strain distribution. Thus, for a thorough description of the strain distribution and related strain rates, internal measurements are highly desirable [8].

Fiber Bragg gratings (FBGs) are good candidates to measure strain within loaded laminates [9,10, 11,12]. Their silica nature allows them to withstand the high temperatures involved in composite manufacturing, and they are small enough to be embedded between the plies of a composite laminate without significantly affecting the mechanical properties of the host material. As regards the study of impact loading using embedded FBGs, a vast majority of papers present rather efficient methodologies for the in-plane detection and localization of the impact [13,14,15,16]. Characterizing damage using embedded FBGs or, to be more precise, estimating delamination size and growth is another explored theme. Until today no methodology has shown significant efficacy and reliability. Most attempts highlighted limits for

further application. Takeda et al. [17] proposed an approach based on the analysis of the reflected wavelength spectrum where the distortion and intensity changes are related to the impact-induced delamination. The major limitation of this approach is the need to precisely position the FBG in the expected location of damage, in-plane and through the thickness of the laminate. In this condition, it is difficult to estimate the influence of the sensor and how the signal intensity is disturbed along the optical fiber. Frieden et al. [18] used an inverse numerical-experimental optimization procedure based on eigenfrequency measurements obtained with embedded FBGs. Although this method was efficient to determine the impact position, it was unable to identify the aspect ratio and damage size. Chambers et al. [19] investigated the strain response after impact to evaluate how it could be used to infer the damaged area. The authors considered that such a method would be efficient if a closely-spaced network of embedded FBGs was used and if the strain response of the composite specimen subjected to impact had been calibrated (experimentally or numerically). In any case, to detect an impact, the FBG should not be placed too far from the damaged area. Embedding of sensors between the plies also raises the question of the structural integrity of the composite. What is the effect of the sensor concerning the mesoscopic and macroscopic responses of composites when they are subjected to impact? May the sensor affect the mechanical properties or could it be the source of crack initiation? These questions were partially addressed by Salvetti et al. [20] who studied the mechanical response of instrumented carbon fiber reinforced plastic (CFRP) composites subjected to low-velocity impact (LVI). They concluded that an embedded network of FBGs in the mid-plane of a laminate would lower its stiffness, but that there was no clear evidence of how the optical fiber influences the damage formation that causes the stiffness degradation. Webb et al. [21] oriented their research on the uncertainty induced on the strain readings delivered by an FBG embedded in a twill weave CFRP laminate. The woven texture of twill weave CFRP promoted non-uniform strain fields over the FBG sensor during impact loading, inducing a distortion of the reflected spectrum and the generation of multiple peaks. In such condition, the Bragg peak interrogator revealed wavelength hopping that could lead to unreliable readings. Although Webb et al. were able to track the Bragg peak using a very high-frequency spectrum analyzer, their study highlighted

a source of uncertainty that ought to be considered when performing dynamic measurements using embedded FBGs. Antonucci et al. [22] were concerned with the knowledge of the sensor' location and orientation. The authors underlined that embedding FBGs in a laminate does not allow for effective control over their placement and that the sensors would most probably move from their original position during manufacturing. To overcome this issue, they developed a methodology based on the comparison of FBG internal strain measurements in glass-reinforced polyester composite under quasi-static indentation (QSI) and numerical simulation. The position and the orientation of the sensor were tuned in the simulation until a match was found with the experimental behavior.

This literature review reveals that using embedded FBGs to characterize damage remains very challenging. Knowing the precise distance of the FBG from the damage, its exact through thickness position and orientation when it is embedded, or its influence on the damage behavior are some of the hurdles to overcome before considering impact- and indentation-induced internal strain measurements. This review also highlighted that only thermoset composites had been investigated using FBGs, and in particular CFRP composites.

In this paper, we present, for the first time, an experimental investigation of internal strain monitoring in unidirectional continuous fiber thermoplastic composites (i.e., GFPP) with cross-ply configuration subjected to quasi-static indentation and low-velocity impact, representing two different loading speeds, using embedded FBGs. The idea here is not to compare the results of the loading speed but to see the interest and limitations of the in-core instrumentation of a GFPP laminate subjected to two different loading conditions. We propose an instrumentation strategy that is expected to provide a reliable set of internal strain values and strain rates, which can be used for the analysis of the damage behavior and feeding and validating a numerical model. Based on a specific sensor insertion procedure, on monitoring techniques and optical observations, we show how the applied methodology alleviates the abovementioned difficulties, such as determining the in-plane and through-thickness position of the embedded FBGs, their influence on the structural integrity or the interpretation of the reflected optical signal.

2. EXPERIMENTAL

2.1. Material, specimens, and FBGs.

Prepregs of unidirectional continuous glass fiber-reinforced polypropylene (GFPP) were used to manufacture the specimens. The matrix is a copolymer polypropylene (PP) where rubber particles were added to the homopolymer PP. This copolymer provides enhanced properties under impact loadings as compared to the homopolymer PP. A stacking sequence of $[0_2/90_2]_s$ was chosen to ensure that the delamination mainly took place at the 0/90 interfaces near impacted and distal faces, guiding our instrumentation strategy. The laminates were made using a hot-press molding process. A steel mold was designed and manufactured with specific features for instrumenting the laminates (Fig. 1a). Four grooves on a side and four others on the adjacent side are provided to allow instrumenting the laminates in the 0° and 90° orientations, respectively. A laminate can thus be instrumented with eight optical fibers.

However, we would see in the next section that for practical reasons this is not advisable. The mold type and hot-press cycle description were the same as that described in [23]. The laminates were approximately 2 mm thick, 110 mm wide and 275 mm long (the width and length were made according to dimensions of the tape and the mold, respectively). The laminates were cut to provide one “instrumented specimen” (specimen with embedded FBGs) and one “bare specimen” (a sister specimen without embedded FBGs); each one has a dimension of 110 x 110 mm (Fig. 1b). This approach enabled us to compare two specimens made by the same manufacturing conditions.

The FBG working principle has already been described in various papers in the last decades [9, 10, 11,12]. We remind the reader that a Bragg grating is a periodical modulation of the refractive index, inscribed by UV interferometry in the core of an optical fiber (generally single mode), along a few millimeters. When a broadband light source is coupled to the optical fiber containing an FBG, the grating diffractive properties promote that only a very narrow wavelength band is back reflected. This band presents a singular peak which corresponds to the Bragg wavelength λ_B , and is expressed by the Bragg condition:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda_B$$

where n_{eff} is the effective refractive index and Λ_B is the period of the grating.

When the FBG is subjected to an axial strain (ε_{xx}) or to temperature changes ΔT , the peak shifts proportionally with these solicitations. Under constant temperature ($\Delta T = 0$), the axial strain is expressed as follows:

$$\varepsilon_{xx} = \frac{\Delta \lambda_B}{\lambda_B \cdot K_\varepsilon}$$

where λ_B is the Bragg wavelength and K_ε ($0.78 \cdot 10^{-6}$) is the strain-optic coefficient of the optical fiber. The FBGs employed here are written in standard SMF28e single mode optical fiber. The diameter of the fiber is 250 μm . For an effective load transfer from the matrix to the sensor, the acrylate coating of the SMF28 fiber is removed along the FBGs. The diameter of the bare fiber is 125 μm .

Figure 1. a) GFPP laminate with embedded FBGs within a steel mold, b) bare and instrumented specimens used for QSI testing; another set of specimens was made and used for impact testing.

2.2. Instrumentation strategy

Prior to proposing the FBG instrumentation strategy, we performed various preliminary studies related to the laminate processing as well as out-of-plane mechanical tests (indentation). Basic issues were revealed regarding the optical fiber protection at laminate ingress, sensor quantity and its distribution, FBG length, marking and sensing efficiency. These preliminary studies are not reported here but, in addition to the literature review, the outcome has provided a guideline in defining the workable instrumentation strategy. This approach relies on five major points which are described below and illustrated in Fig. 2.

Figure 2. Illustration of the five major points of the instrumentation strategy.

- 1) FBGs are placed above and below the expected delamination interface. As one of the major damage processes in impact and indentation is delamination, FBGs are placed adjacent to the delamination plans which are in the case of a $[0_2/90_2]_s$ laminate at the 0/90 interfaces. The objective is to sense the influence of delamination on the neighboring strain fields. The FBGs are not placed in the delamination plane because the 0/90 interface is subjected to strong shear strain that could be detrimental to FBG response. A conventional FBG is designed to measure axial strain, and this is reliable when the sensor is not subjected to large transverse effects (Fig. 2-1).
- 2) FBGs are marked at each extremity. The optical fiber is marked with permanent ink to allow for determining the precise position and orientation of the sensor after embedment and manufacturing. Thanks to the translucency of polypropylene laminate, the ink marks can be detected with bare eyes. This detection is made clearer if some light illuminates the opposite side of the observed face (Fig. 2-2). The same methodology could be extended to not translucent polymers by marking the FBGs with special inks detectable for example by X-ray inspection or other non-destructive techniques.
- 3) FBGs are embedded in the same direction as the reinforcement fibers to ensure a high-quality signal. When the FBGs are positioned transverse to the adjacent reinforcement fibers, they may experience micro-bending, which is detrimental. In addition, FBGs are inserted within the ply. In doing so, the plies are cut longitudinally, and the optical fiber is inserted between two parts of the ply. This technique has several advantages. First, the optical fiber can be held in the same position during the stacking operation. Then, the optical fiber and its FBG can be fully embedded parallel with the reinforcing fibers. Finally, it offers a better control of the through-depth position, minimizing a possible migration during the manufacturing process (Fig. 2-3).
- 4) Three in-plane locations are investigated. These locations were considered knowing that the objective is to obtain a relevant strain field using a minimum number of FBGs. Our preliminary indentation test revealed the shape and area of the delamination. Accordingly, we decided to investigate a position on the axis that is parallel to the 0° direction and passing through the indentation center point (position A), one on the axis that is parallel to the 90° direction and passing

through the center of indentation (position C) and one on a bisecting axis (position B). Moreover, to make sure we obtain reliable information from the FBG, with a spectral response that is not distorted by the delamination, the sensors are positioned reasonably away from the delamination but near enough to measure its influence on the strain field. We also do not want the strain measurement to be mostly affected by the clamping (Fig. 2-4); thus, the sensor was also positioned away from the clamping edge.

- 5) The sensors are distributed over several laminates. If we consider four FBGs placed through the depth at each of the three in-plane positions, there should be 12 FBGs in one specimen. Embedding all these sensors in a single specimen is problematic for various technical reasons related to the fragility and the concentration of the FBGs. In order to avoid various risks of optical fiber and FBG rupture, high concentration of FBGs that may influence the damage mechanism, and unclear observation of each embedded sensors, the 12 FBGs are (1) distributed on three identical specimens and (2) distributed to a symmetrical position in each specimen (Fig. 2-5). Schematic drawings showing the in-plane and through-thickness positions of the embedded FBGs for the three specimens are presented in Fig 3.

Figure 3. Schematics showing in-plane and through-thickness positions of the embedded FBGs in three identical specimens according to different distributions: (a) instrumentation #1, (b) instrumentation #2, (c) instrumentation #3.

2.3. Experimental setups and procedures

The complete set-up of QSI test with FBG measurement instruments and damage monitoring system (digital camera) is given in Fig. 4a. The QSI test was performed using an in-house fixture fitted in the Instron 5882 (100 kN load cell). As mentioned above, three instrumented and three bare specimens were tested. After clamping the specimen by a torque of 5 kg.m (for each screw), the indentation load was

applied on the specimen at 1.25 mm/min loading speed, following ASTM D6264 Standard. The indenter displayed in Fig. 4b has a hemispherical tip (diameter of 16 mm). The loading/unloading test was performed up to a displacement limit of 6 mm and back to the initial point (0 mm). Under the specimen and the clamping fixture, a digital camera was positioned to capture the damage progression (Fig. 4b). This was possible due to the translucency of the PP matrix and a ring light illuminating the indented face. Sequential pictures containing the shadow of damage were taken every 1-mm displacement and recorded in the computer. A Micron Optic sm125 was used to interrogate the signal (reflected power and wavelength) from the FBGs. The shift of Bragg peaks was continuously recorded with a 2 Hz acquisition rate, while a full spectrum response was acquired every 1-mm displacement, same with the picture taking process.

Figure 4. a) Complete experimental setup of the quasi-static indentation test. b) Detailed view of the indenter and the sample fixture.

The measurement conditions of internal strain in the specimen under LVI testing are very different from QSI, precisely because of the speed of the process. In these conditions, are we able to use the same instrumentation strategy to obtain reliable and useful results? To answer this question, we decided to perform the LVI test in a way that the degrading conditions are as close as possible to the QSI. For this, we tuned the parameters of the LVI setup so that comparable damage area was obtained. The choice of energy level was made on this basis (parameters are given below). Several preliminary tests on non-instrumented specimens were performed to reach this damage criterion.

The low-velocity impact test was performed using an Instron CEAST 9350. The complete set-up during impact is shown in Fig. 5a. The impactor displayed in Fig. 5b has a hemispherical tip (diameter of 16 mm, identical to that of the indenter), and a total mass of approximately 5.4 kg. The test system was equipped with a velocity sensor and an anti-rebound system to avoid repeated impact on the plate. The specimen

was compressed at 5.5 bar using a pneumatic clamping system that has a circular cut-out (diameter = 76 mm, identical to that of the indentation fixture) at the upper and lower clamps. The impactor was then placed at a prescribed falling height to achieve a velocity of 2.6 m/s that corresponds to an impact energy range of 18 J. A Micron Optic si255 was used to interrogate the FBGs. The shift of Bragg peaks was continuously recorded with a 5 kHz acquisition rate. Unlike during the QSI test, the lap of time during impact, which was around ten milliseconds, did not allow for spectral response recording when the impact load was being applied. The optical interrogation process of the spectral response is a swept analysis over 16000 points that is technologically very challenging to complete in such a short period. Nevertheless, we managed to record the full spectrum response before and after the impact test. Although the impact chamber of the Instron CEAST 9350 had to be closed for safety reason, the optical fibers could be inserted through the chamber without being damaged or even detrimentally squeezed thanks to the softness of the door's silicon sealant.

Figure 5. a) Complete experimental setup of the low-velocity impact test. b) Detailed view of the sample support and fixture.

3. RESULTS AND ANALYSIS

3.1. In-plane visualization and identification of FBG positions

After being cut to the required dimensions, the instrumented sample was placed on the indentation fixture and illuminated with the ring light. The indenter is positioned close to the top surface (to be indented). Using the remotely controlled camera placed underneath the specimen, we observed its distal face. Fig. 6a-c shows three photographs of specimens with instrumentation #1, #2 and #3, respectively. We could clearly see the shadow of the indenter that precisely defines the center of the specimen. A set of longitudinal and transverse axis could then also be defined. The more important outcome was the possibility to detect the markers at the FBGs extremity that appeared through the translucent PP matrix.

This observation is obviously clearer for the FBGs positioned in the lower plies of the specimen (plies 2 and 3). To detect the position of the FBGs in the upper plies, we flipped the specimen, making sure the references are identical, and proceeded with back light observation. By referring to Fig. 3, we now see that some FBGs have slightly migrated from the designed position to a different coordinate.

In Fig. 6b we can see that the FBG at point A' is not only shifted from the longitudinal axis but also not quite perpendicular to it. These shifts and misalignments are induced during the manufacturing phase when a rearrangement of the plies and matrix flow take place. They are not critical if they can be determined accurately, allowing a reliable interpretation of the strain behavior and comparison with numerical simulation. As for impact specimens, we also identified the position of FBG before and after the impact test, using the same QSI fixture and photographic setup.

Figure 6. Backlighted instrumented specimens showing FBG positions for (a) instrumentation #1, (b) instrumentation #2, (c) instrumentation #3 (Note that the pictures are showing the distal face of the specimen, which is the opposite view of the schematics in Fig. 3).

3.2. QSI

3.2.1. Influence on the macroscopic behavior

The force-displacement curves of bare and instrumented specimens under quasi-static indentation are shown in Fig. 7. We observe similar behavior for all laminates although discontinuities in the progressions of the curves may take place in both types of laminates. From those results, it is difficult to establish that the four embedded FBGs have an influence or not on the macroscopic response of the GFPP laminate under QSI.

Figure 7. Load versus displacement plots of 3 pairs of specimens (bare and instrumented) subjected to QSI tests.

3.2.2. Influence on the damage

To assess the influence of the embedded instrumentation on the damage behavior we compared the damage progression during the QSI test for all instrumented and bare specimens. Fig. 8 shows pictures of the damage (mainly delamination) at various displacement levels (0, 2, 4, 6 mm), using the backlighting method. A typical peanut shape of the damage is observed. For a precise evaluation and comparison of the damage and its progression, we calculate the ratio between the projected area of the damage (A) and the total exposed circular area of the specimen ($A_0 = 4536.46 \text{ mm}^2$). Average results are shown in table 1 of instrumented (#1, #2 and #3) and bare specimens. The difference of projected damage area between instrumented and bare specimens is relatively small. Moreover, we see that the damage progresses non-symmetrically, but it does not grow favorably towards the FBGs in the instrumented specimen. We observed similar behavior in the other series of samples (instrumentation #2 and #3 and related bare samples). Hence, there is no evidence of the influence of the optical sensors on the delamination process in the GFPP laminate under QSI.

Figure 8. Pictures of the distal side of specimens (cut out from the same laminate) during the QSI test at various loading conditions for the sample with instrumentation #1 (top) and, bare specimen (bottom).

Table 1. Average damage area and ratios at various displacements for instrumented (#1, 2 and 3) and bare specimens

Displacement (mm)	Instrumented specimens		Bare specimens	
	Damage area $A \text{ (mm}^2\text{)}$	Damage ratio $A/A_0 \text{ (%)}$	Damage area $A \text{ (mm}^2\text{)}$	Damage ratio $A/A_0 \text{ (%)}$
0	0	0	0	0
2	76 ± 17	1.7	68 ± 4	1.5

4	260 ± 37	5.7	288 ± 64	6.4
6	506 ± 8	11.2	541 ± 46	11.9

3.2.3. Spectral response

With our interrogation unit, recording a spectral response involves scanning the intensity of the reflected signal over an 80 nm bandwidth with an interval of 5 pm. This gives some information on the reflected power distribution along the FBGs. We use this information to check whether we have a uniform or distorted strain distribution along the grating length of the FBG. A uniformly distributed strain will be represented by a clear spectrum peak and is considered to be reliable data regarding average axial strain along the length of the FBG. During the QSI, spectral responses have been recorded at different load levels.

The results reported in Fig. 9 show spectrum responses every 2 mm displacement for FBGs of the specimen with instrumentation #1. The arrows on top of the spectra indicate the loading progression from 0 to 6 mm displacement. The left graph shows the spectra in the longitudinal direction (0°). The solid red lines represent the spectra of the FBG placed in ply 2 (point B). With increasing loading, the spectra shift to the right. This is because the FBG placed below the mid-plane of the laminate is under tension. The related spectrum shapes are progressing with a well-defined peak. The spectra of the FBG placed in ply 7 (point B') are progressing in the opposite direction. The FBG placed in the upper plies is under compression. The related spectrum shapes (in dotted red lines) are also progressing with clear peaks, but we observe a growing broadening at the base of each spectrum. However, the peak itself is not distorted, and a Bragg peak wavelength value can be determined at each displacement level. In such a condition, we can reliably associate this information to strain measurements. The right graph shows the spectra in the transverse direction (90°). The FBG positioned in ply 3 (point C') is under tension and presents spectra (in solid green lines) with well-defined peaks at each displacement level. The interpretation of the response of the FBG placed in ply 6 (point A) is more problematic (green dotted lines). We see that the

spectra are clearly progressing to the left, logically indicating that the sensor is under tension, but there is a drastic loss of signal at the 6 mm displacement response. This may be due to various factors, but as no distortion was observed on the preceding spectra, we assume that severe micro-bending along the optical fiber was promoted by the bending of the laminate under loading, altering the light guide and consequently reducing the light signal intensity. The spectrum analysis upon unloading, not presented here, showed the full recovery of the signal. Except for this last incident, the spectral responses that were recorded for specimens with instrumentation #2 and #3, exhibited similar trends and are not presented here. Hence, according to this spectrum analysis, we can say that the internal strain measurements are obtained in reliable conditions.

Figure 9. Wavelength spectral response every 2 mm displacement during the loading phase, for FBGs in the longitudinal direction (0°) (left) and FBGs in the transverse direction (90°) (right).

3.2.4. Internal Strain monitoring

The results of strain changes during the QSI test of the specimen with instrumentation #1 are presented in Fig. 10. The left graph shows the change of strain according to time during the loading and the unloading phases. The solid lines represent the strain changes, in tension, taking place in FBGs positioned below the mid-plane in longitudinal (red) and transverse (green) directions at point B and C', respectively. In both cases, the associated strain changes reveal a non-linear behavior. It is interesting to see that various strain rates can be determined with respect to time (or displacement). The dotted lines represent the strain changes, in compression, taking place in the FBGs positioned above mid-plane. The green dotted line corresponds to the FBG signal, at point A, whose spectral response was severely affected after 4mm displacement, as mentioned in the previous section. The drastic reduction of reflected power has a detrimental effect on the strain measurement. Indeed, the strain plot obtained from this FBG shows an unexpected maximum point according to time and a disruption around the maximum loading. The

spectral analysis allows us to interpret and invalidate the FBG information. This shows the importance of monitoring the spectral response. The red dotted line corresponds to the strain changes detected by the FBG positioned at point B'. The strain rates upon loading and unloading appear to be linear.

Figure 10. Graph of strain vs. times (left) and force vs. strain (right) during the QSI test of the specimen with instrumentation #1.

The force vs. strain graph (Fig. 10 right) shows that the strain response upon unloading did not follow the same path as that upon loading. This is due to the indentation induced damage that affected the mechanical properties of the laminate. Residual strains are observed at the end of the test, in particular with the FBGs placed at point B' and C'. Depending on the proximity of the FBG and the size of the damage, various residual strain levels are measured.

3.2.5. Cross-section observation of the FBG

To evaluate the potential disturbance caused by FBGs on the damage mechanism, we performed microscopic observations of the specimen at the sensors location. Cross-section micro-graphs obtained at three magnification scales of the four FBGs embedded in the specimens with instrumentation #1 are shown in Fig. 11. The first row of micro-graphs shows cross sections of FBGs in the full laminate (laminate thickness $\approx 2\text{mm}$). The second-row shows cross sections of FBGs at the scale of the plies (ply thickness $\approx 250\ \mu\text{m}$). The last row shows a close view of cross sections of FBGs (diameter without coating $= 125\ \mu\text{m}$).

Figure 11. Cross-section micro-graphs at three magnification scales of the 4 FBGs embedded in the specimens with instrumentation #1 after the QSI tests.

The observations reveal several relevant points. First, we note that the cuts in the longitudinal direction of the plies made to insert the FO are completely sealed after manufacturing. There is thus no mechanical incidence due to the cutting of the prepreg plies. Second, all FBGs have migrated vertically up the top of the ply in which they are inserted but not farther up. The actual vertical position after processing must be taken into account for model validation/comparison. Third, we see that the matrix is closely bonded to the FBG. A good cohesion/adhesion between the matrix and the FBG ensures a good load transfer and thus reliable measurements. Finally, we do not observe any cracks or delamination around the fiber. This means that when the FBGs are positioned according to our instrumentation strategy they cannot be considered as being damage initiators.

3.3. Low-velocity impact

3.3.1. Influence on the macroscopic behavior

Similar to QSI, we investigate the macroscopic response of the specimens. The force-displacement curves of bare and instrumented specimens under 18 J impact are shown in Fig. 12. Looking at each graph individually, we may see some small difference of behavior from one specimen to the other, but in general, no trend can be extracted from these results. Again, there is no evidence of the influence of the embedded FBGs on the macroscopic behavior of GFPP laminate subjected to LVI.

Figure 12. Load vs. displacement plots of 3 pairs of specimens (bare and instrumented) subjected to LVI tests.

3.3.2. Influence of FBGs on damage

From the observation of the specimens after the LVI test (Fig. 13), two remarks related to the influence of the FBG on the damage growth can be made. First, the comparison of the shape and size of the damage in the instrumented and the bare specimen reveals a close similitude. Second, the damage does not show any specific growth in the direction of the embedded FBGs. For this level of impact energy, the FBGs are

not promoting delamination or nucleating cracks. Hence, their presence is not influencing the damage behavior of the GFPP laminate when subjected to LVI.

Figure 13. Pictures of both sides of instrumented (#1) and bare specimens (cut from the same laminate) after low-velocity impact test.

3.3.3. Spectral response

Scanning the power level every 5 pm over an 80 nm bandwidth represents a set of 16000 pts. From an optical and technological aspect, it is very challenging to obtain such data in a few milliseconds. To the knowledge of the authors, there is no commercial optical interrogator allowing this performance. The interrogator we are using for this test has already a high capacity to detect at 5 kHz the peak shift of the Bragg spectrum for four channels (4 FBGs). It would be very demanding to have both this capacity and the ability to scan the spectrum response of 4 FBGs at the same time. However, as wavelength spectra may be investigated at a very high rate over a narrow bandwidth with a reasonable resolution [24], we expect that the combined performance will be reached shortly with commercial FBG interrogators. With this technological limitation, we only recorded the spectral response just before the test and right after. Figure 14 shows the responses of all FBGs of specimen #1. We see in all cases that, except for a shift of the spectra, their shape remained similar to the initial one after the test. No detrimental distortion is detected. Thus, we can be confident with the strain measurement. However, due to the acquisition rate limitation of the instrument, the spectra representing the maximum deformation are not shown. These graphs tell us that the FBGs were not damaged during the impact and that there are residual strains after impact.

Figure 14. Wavelength spectral response before and after the low-velocity impact test of the specimen with instrumentation #1.

3.3.4. Internal strain monitoring

The shifts of Bragg peaks are detected and transformed into strain changes. According to the high performance of the interrogation unit, the full impact event, lasting approximately 10 ms is covered with a set of 50 data points for each FBG. Results are shown for the specimen with instrumentation #1 in Fig. 15. The strain changes according to time are shown in the left graph of Fig. 15. Clear responses in tension are provided with both FBGs placed in the lower plies of the specimen (at positions C' and B). The maximum values of strain seem to be slightly shifted in time from one FBG to the other. It is difficult to tell if this is due to the mechanical behavior or an acquisition speed limitation of the interrogator. However, these profiles allow the evaluation of a strain rate as a good part of the rise is linear. From the FBGs placed in the upper plies, only one clear response may be considered useful for evaluating a strain rate (at position A). The other FBG (at position B') delivers an unexpected response. First, the maximum strain is measured with a big delay compared to the three others. Second, we see that during the loading part of the impact event, the strain change take two different paths. In the collected experiment data, two Bragg peak values were given for the same FBG. It is clear that this is due to a non-uniform distribution of strain along the FBG that is generating a spectrum division. Such an effect is similar to that revealed in [21] and referred as a wavelength hopping effect in their spectrum analysis, as mentioned in the introduction. Although both peaks are detected, the strain values are not reliable, and this may explain why the maximum compression is not reached at the same time as with the other FBGs. Residual strains are again revealed after the impact, confirming the same observation made in the spectral analysis. In the force vs. strain graph of Fig. 15 (right) the FBGs in tension show rather irregular progression during loading. This is probably due to sudden ruptures of fibers or delamination between plies during loading. Hysteresis is observed during unloading, indicating that the loss of structural integrity due to damage in the neighborhood of the sensor is detected. In contrast, almost no hysteresis is observed for the FBG in tension at position A. It seems that the area where this FBG is positioned is not affected by the impact damage. The visible tip of the delamination is, however, only a few millimeters away from the FBG, as shown in the upper left picture of Fig. 13.

Figure 15. Graph of strain vs. times (left) and force vs. strain (right) during the LVI test of the specimen with instrumentation #1.

4. CONCLUSION

We investigated the use of embedded FBGs to determine internal strains in unidirectional thermoplastic composites (glass fiber reinforced polypropylene) subjected to quasi-static indentation and low-velocity impact. We performed measurements according to a specific instrumentation strategy and demonstrated that in most cases we obtained an effective and reliable set of strains and strain rates. More specifically, we conclude with the following remarks:

- Embedded FBGs provide an efficient tool for internal strain measurements, but the insertion process, ensuring the integrity of the optical fiber during the ply stacking, hot-press manufacturing and part releasing steps, remains a technological challenge.
- Marking FBGs allows a precise determination of their in-plane position and orientation after processing which is critical if theoretical validation is envisaged.
- Microscope observation of laminate cross-section around the FBG after test demonstrated excellent cohesion and absence of crack initiation.
- The presence of FBGs in the laminates does not affect the macroscopic behavior in both QSI and LVI conditions.
- The QSI process is slow enough to allow monitoring of the spectral response throughout the test whereas the LVI process is too fast for a similar monitoring procedure, even using commercial equipment with the best performance. Moreover, the analysis of the Bragg peak shift during impact revealed wavelength hopping occurrences which, in this case, invalidated the FBG information. This highlights the need for spectral response monitoring to ensure the reliability of the strain measurement.

The internal strain evolution results obtained from consistent and well-identified FBG measurements will provide a reference for the calibration and validation of a finite element simulation of GFPP laminates subjected to QSI and LVI. It is under development and will be documented in a separate publication. Also, we expect that this predictive model will help to clarify and strengthen our explanation on the FBG readings.

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References

1. Osborne J. Automotive Composites – in Touch with Lighter and More Flexible Solutions. *Met Finish* 2013;111:26–30.
2. Pulungan D, Lubineau G, Yudhanto A, Yaldiz R, Schijve W. Identifying design parameters controlling damage behaviors of continuous fiber-reinforced thermoplastic composites using micromechanics as a virtual testing tool. *Int J Solids Struct* 2017; 117:177–190.
3. Hongkarnjanakul N, Bouvet C, Rivallant S. Validation of low-velocity impact modelling on different stacking sequences of CFRP laminates and influence of fibre failure. *Compos Struct*, 2013; 106:549-559.
4. Yudhanto A, Lubineau G, Wafai H, Mulle M, Pulungan D, Yaldiz R, Verghese N. Monotonic and cyclic responses of impact polypropylene and continuous glass fiber-reinforced impact polypropylene composites at different strain rates. *Polym Test* 2016; 51:93–100.

5. Pulungan D, Yudhanto A, Shiva G, Lubineau G, Yaldiz R, Schijve W. Characterizing and modeling the pressure- and rate-dependent elastic-plastic damage behaviors of thermoplastic polypropylene copolymers. *Polym Test* 2017; 68:433-445.
6. Yudhanto A, Wafai H, Lubineau G, Yaldiz R, Verghese N. Characterizing the influence of matrix ductility on damage phenomenology in continuous fiber-reinforced thermoplastic laminates undergoing quasi-static indentation. *Compos Struct* 2018; 186:324-334.
7. Yudhanto A, Wafai H, Lubineau G, Yaldiz R, Goutham S, Verghese N, Mulle M. Revealing the effects of matrix behavior on low-velocity impact response of continuous fiber-reinforced thermoplastic laminates. Accepted for publication in *Composite Structures* (15.11.2018)
8. Alcock B, Cabrera N.O, Barkoula N.-M, Peijs T. Low velocity impact performance of recyclable all-polypropylene composites. *Compos Sci Technol* 2006; 66:1724–1737.
9. Du W, Tao XM, Tam HY, Choy CL. Fundamentals and applications of optical fiber Bragg grating sensors to textile structural composites. *Compos Struct* 1998;42:217–29.
10. Kuang KSC, Kenny R, Whelan MP, Cantwell WJ, Chalker PR. Embedded fibre Bragg grating sensors in advanced composite materials. *Compos Sci Technol* 2001;61:1379–87.
11. Bosia F, Facchini M, Botsis J, Gmür T, De'Sena D. Through the thickness distribution of strains in laminated composite plates subjected to bending. *Compos Sci Technol* 2004;64:71–82.
12. Mulle M, Zitoune R, Collombet F, Robert L, Grunevald YH. Embedded FBGs and 3-D DIC for the stress analysis of a structural specimen subjected to bending. *Compos Struct* 2009; 91:48–55.
13. Zhou G, Sim LM. Damage detection and assessment in fibre-reinforced composite structures with embedded fibre optic sensors - review. *Smart Mater Struct* 2002; 11:925-939.
14. Frieden J, Cugnoni J, Botsis J, Gmur T. Low energy impact damage monitoring of composites using dynamic strain signals from FBG sensors - Part I: Impact detection and localization. *Compos Struct* 2012; 94:438-445.
15. Shrestha P, Kim JH, Park Y, Kim CG. Impact localization on composite structure using FBG sensors and novel impact localization technique based on error outliers. *Compos Struct* 2016; 142:263-271.

16. Lamberti A, Luyckx G, Van Paepegem W, Rezayat A, Vanlanduit S. Detection, Localization and Quantification of Impact Events on a Stiffened Composite Panel with Embedded Fiber Bragg Grating Sensor Networks. *Sensors* 2017; 17:743.
17. Takeda S, Minakuchi S, Okabe Y, Takeda N. Delamination monitoring of laminated composites subjected to low-velocity impact using small-diameter FBG sensors. *Compos Part A* 2005; 36:903-908.
18. Frieden J, Cugnoni J, Botsis J, Gmür T. Low energy impact damage monitoring of composites using dynamic strain signals from FBG sensors – Part II: Damage identification. *Compos Struc* 2012; 94:593–600.
19. Chambers AR, Mowlem MC, Dokos L. Evaluating impact damage in CFRP using fibre optic sensors. *Compos Sci Technol* 2007; 67:1235–1.
20. Salvetti M, Sbarufatti C, Gilioli A, Dziendzikowski M, Dragan K, Manes A, Giglio M. On the mechanical response of CFRP composite with embedded optical fibre when subjected to low velocity impact and CAI tests. *Compos Struct* 2017; 179:21–34.
21. Webb S, Peters K, Zikry M, Vella T, Chadderdon S, Selfridge R, Schultz S. Wavelength hopping due to spectral distortion in dynamic fiber Bragg grating sensor measurements. *Meas Sci Technol* 2011; 22:065301 (11pp).
22. Antonucci V, Esposito M, Ricciardi MR, Giordano M, Zarrelli M. Strain monitoring of composite elements by fibre Bragg grating sensors during a quasi-static indentation. *Compos: Part B* 2014; 56:34–41.
23. Mulle M, Wafai H, Yudhanto A, Lubineau G, Yaldiz R, Schijve W, Verghese N. Process monitoring of glass reinforced polypropylene laminates using fiber Bragg gratings. *Compos Sci Technol* 2016; 123:143-150.
24. Vella T, Chadderdon S, Selfridge R H, Schultz S M, Webb S, Park C, Peters K and Zikry M. A Full-spectrum interrogation of fiber Bragg gratings at 100 kHz for detection of impact loading. *Meas Sci Technol* 2010; 21:094009.

(a)

Steel mold

Laminate before cure

Optical fiber inlets

(b)

Bare specimens

110
mm

0° ↑

SABIC GFPP
copol
[0₂/90₂]_s
QSI A1

SABIC GFPP
copol
[0₂/90₂]_s
QSI A2

SABIC GFPP
copol
[0₂/90₂]_s
QSI A3

Instrumented specimens

(a) Instrumentation #1

(b) Instrumentation #2

(c) Instrumentation #3

(b) Sample support and fixture

Instrumented specimen

Displ. = 0 mm

2 mm

4 mm

6 mm

After unloading

Bare specimen

FBG in ply 2

90°

2mm

250μm

125μm

FBG in ply 3

0°

FBG in ply 6

0°

FBG in ply 7

90°

Instrumented specimen

Back side

Indented side

Bare specimen