Barely visible impact damage detection and location on composite materials by surface-mounted and embedded aerospace-compatible optical fibre Bragg grating sensors

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Barely visible impact damage detection and location on composite materials by surface mounted and embedded aerospace-compatible optical fibre Bragg grating sensors

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ABSTRACT

Composite materials are finding their way into aerospace applications thanks to their high stiffness-to-mass ratio. Nevertheless, composite components require frequent inspections because of their sensitivity to critical damage. Damage as small as barely visible impact damage (BVID) can grow as result of structural loading, with component failure as possible outcome. Optical fibre sensors (OFS) are considered excellent candidates for permanently installed structural health monitoring (SHM) systems, owing to their many advantages over electrical sensors. Current state-of-the-art BVID detection with OFS has so far however been limited to proof-of-concept demonstrations at low technology readiness levels. In this work, we equipped a total of 16 coupons, made of 5 different state-of-the-art composite materials, with aerospace compatible embedded or surface mounted optical fibre Bragg gratings (FBGs). We impacted each coupon at two locations and acquired the FBG reflection spectra before and after each impact. We first demonstrate how changes in the Bragg wavelength and in the Bragg peak shape can be quantified when the FBGs are exposed to the (non-uniform) strain field of BVIDs. Second, we show that this method was able to successfully detect the BVID in all considered scenarios and that in most cases, it was able to also locate the damage within an uncertainty of ±1 FBG location. Finally, we show the reliability of this method in terms of repeatability and considering the effects of temperature changes and on-ground airplane vibration. To the best of our knowledge, we are the first to use in-flight-compatible embedded and surface mounted FBG-sensors for the detection and location of BVIDs on aerospace-grade composite materials. These results motivate the use of FBG sensors as a permanent sensor network for cost-efficient damage detection in composite aerospace components for locally monitoring damage-prone locations.

Keywords: fibre Bragg gratings (FBG), composite, structural health monitoring (SHM), barely visible impact damage (BVID).

1. INTRODUCTION

Composite materials are increasingly used in aerospace applications because of their increased stiffness to mass ratio compared to their metallic counterparts. Composite components are typically manufactured through ply stacking, where the reinforcement fibres are oriented in the stacking plane, and therefore show excellent mechanical characteristics in the in-plane directions but are inherently prone to damage in the out of plane direction.¹

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An impact in this direction can generate damage that is not immediately visible to the naked eye, called Barely Visible Impact Damage (BVID). BVID is typically defined as damage with an indentation of about 0.3 mm and a delaminated area smaller than 350 mm², and although initially harmless, this damage can grow by structural loading of the components with possible component failure as a result. Therefore, measures are being taken to limit the effect of these BVIDs. Aerospace components are manufactured with increased thickness to be more resistant against impacts and are inspected frequently during operation for the presence of BVIDs. These measures lead to increased mass, and thus increased fuel consumption and CO₂ emission and to longer inspection times, thus increased downtimes and operation cost.

A sensor network integrated onto or into the composite structure could overcome these drawbacks by being able to serve as a fast inspection tool for investigating the health of the host structure. Optical fibre sensors (OFS) are often considered as ideal candidates for structural health monitoring (SHM) in aerospace applications. Indeed, because of their small diameter, light weight, multiplexing capabilities and immunity to electromagnetic interference they have previously demonstrated their compatibility with composite materials. Optical fibre sensors are widely used for cure or load monitoring scenarios of composite materials, but for damage detection, they often lack a high enough technology readiness level (TRL) for implementation in real aerospace environments.

Their small diameter allows OFS to be embedded within the layers of composite components. This is usually done parallel with the composite reinforcement fibres between two unidirectional plies with identical orientation, to avoid that the optical fibre would cross the reinforcement fibres. Takeda et al. and Okabe at al. showed that it is possible to use embedded FBGs to detect the presence of BVID by comparing the shapes of the Bragg peaks before and after application of the damage. They applied an impact right next to the location of the FBG such that the BVID delamination applied a non-uniform strain redistribution over the length of the FBG. Correlating the shape of the Bragg peak before the impact with the same Bragg peak after can be used as an indicator for the presence of damage. Recently Choi et al. also showed that it is possible to obtain the strain redistribution due to the presence of a BVID by means of distributed OFS. They compared the strain levels of an embedded optical fibre obtained through a Brillouin optical correlation-domain analysis (BOCDA) before and after impact and were able to identify and locate the strain redistribution due to the impact.

In this work we aim to increase the technology readiness level of optical fibre sensors for damage detection by detecting and locating calibrated BVIDs in aerospace-grade CFRP materials with in-flight compatible optical fibre sensors. Most of the work in literature for BVID detection on composite material is achieved with embedded optical fibres. Although it offers the optical fibres an inherent protection from the harsh aerospace environments, demonstrations with embedded optical fibres seldom reach the TRL required for real aerospace components because concerns remain in whether or not they influence the mechanical properties of the host material. Additionally, the egress of the fibres (i.e. where the fibres exit the structure) remains a troublesome challenge when manufacturing and using the component. Indeed, since most components are trimmed to their final dimensions, it is far from straightforward to make a robust optical connection with optical fibre sensors exiting the side of the structure. Also repairing defected embedded sensors is practically impossible. When it comes to damage detection, we show here that they are still prone to several drawbacks, hindering them from being used at higher TRL.

We therefore focus on surface mounted optical fibres, which can overcome these drawbacks. However, most reports use standard unpackaged telecom fibre in combination with standard cyanacrylate or UV curable adhesives that are not tested for compatibility with aerospace conditions. Because the strain transfer from the BVID to the core of the optical fibre is much lower for surface mounted OFS than for embedded OFS, the BVID is usually detected indirectly by measuring the acoustic signal generated by the impact or the change in vibrational behaviour of the component. Here we demonstrate the repeatability and reliability of BVID detection with optical fibre sensors in terms of on-ground aircraft conditions. We aim with this demonstration to increase the TRL of this methodology.

This manuscript is structured as follows: in section 2 we explain the materials and methods. More specifically section 2.1 explains the composite materials that we used, in section 2.2 we detail the in-flight compatible optical fibre sensor and the damage indicators for the detection and location of the BVIDs and in section 2.3 we elaborate on the impact application of the BVID. Section 3 shows the results and discussion and is split in section 3.1, covering the surface mounted optical fibres, section 3.2, elaborating on the reliability and repeatability of this method and section 3.3, covering the results of the embedded optical fibres. The conclusion is presented in section 4.
2. MATERIALS AND METHODS

2.1 Composite coupons

We used common state-of-the-art aerospace CFRP materials for fabricating the coupons. The material types and their stacking sequence are summarized in Table 1 and will from now on be referred to as M1 to M5. The materials were selected to represent a variety of typical composite manufacturing methods: thermoset (M1), thermoplastic (M3) and liquid resin infusion (M2). The materials M4 and M5 are a variation of the thermoset material M1. M4 is infused with carbon nanotubes (CNTs) for better EMI shielding and M5 is provided of a viscoelastic damping veil layer to increase vibration and impact resistance. All coupons were trimmed for obtaining the final dimensions of 225 × 300 mm, as illustrated in Figure 1. The surface of an M1 and an M3 coupon can be observed in Figure 3 (a) and (b) respectively.

Table 1: overview of the composite materials

<table>
<thead>
<tr>
<th>Ref.</th>
<th>CFRP type</th>
<th>Material</th>
<th>Stacking sequence</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>UD thermoset prepreg</td>
<td>M21/194/34%/T800S</td>
<td>[+45/-45/02/90/0]s</td>
<td>20</td>
</tr>
<tr>
<td>M2</td>
<td>Dry fibre (NCF) + resin</td>
<td>U-C-PB-209g/m²-1220mm and PRISM EP2400 resin</td>
<td>[+45/90/-45/0/45/0/-45]s</td>
<td>21,22</td>
</tr>
<tr>
<td>M3</td>
<td>UD thermoplastic prepreg</td>
<td>Tenax®-E TPCL PEEK-HTA40</td>
<td>[0/90/+45/-45/0/90/+45/-45/0]</td>
<td>23</td>
</tr>
<tr>
<td>M4</td>
<td>M1 + CNTs</td>
<td>M21/194/34%/T800S + CNTs</td>
<td>[+45/-45/02/90/0]s</td>
<td>20</td>
</tr>
<tr>
<td>M5</td>
<td>M1 + VEIL</td>
<td>M21/194/34%/T800S + VEIL</td>
<td>[+45/-45/02/90/0]s</td>
<td>20,24</td>
</tr>
</tbody>
</table>

Figure 1: Layout of the coupons with (a) surface mounted optical fibre sensors and (b) embedded optical fibre sensors. The optical fibres are drawn in blue, with the FBG locations marked with numbered blue crosses. The two impact locations I1 and I2 are indicated with red crosses.

2.2 Optical fibre sensors

The optical fibre sensors used in this work are draw-tower-gratings (DTGs®). These are FBGs inscribed during drawing the fibre, but before applying any coatings, resulting in excellent strength and fatigue characteristics. The DTGs® used here had a length of 8 mm and a reflectivity of about 30 % and were coated with a layer of Ormocer®. They were purchased from FBGS International.

2.2.1 Surface mounted optical fibre sensors

To ensure protection of the surface mounted optical fibres from harsh aerospace environments, we used optical fibre sensors that were additionally packaged with glass fibre reinforced polymer (GFRP) and an 0.2 mm outer jacket of high-density polyethylene (HDPE) to create a robust wire-like profile with a total outer diameter of 1.0 mm, these types of fibres are called strain measurements wires (SMW) and can be seen in Figure 2 (a).
After sanding and degreasing the surface of the coupon, the fibres were bonded to the CFRP by prestraining them and encapsulating them over the whole length with a layer of HBM X120 two-component epoxy adhesive designed for optical fibres, as can be seen in Figure 3. The complete installation process has previously been reported in.

The fibres were mounted in a cross formation onto the CFRP, with a vertical and horizontal fibre, as illustrated in Figure 1 (a). This allows for using the FBGs as 2-dimensional axes system for BVID locating. Each fibre direction holds a set of 6 wavelength multiplexed DTGs® with a centre to centre distance of 26 mm. Figure 3 shows the centre of an M1 coupon (a) and M3 coupon (b) where the horizontal and vertical fibres meet. The impact locations noted with I1 and I2 and BVIDs can also be seen in both images. An example of a spectrum of one of the fibres before and after installation on an M2 coupon can be seen in Figure 2 (b), where a prestrain of $681 \pm 5 \mu \varepsilon$ was applied on the fibre.

Both the sensor as well as the installation method have been previously tested to survive standardized in-flight conditions for temperature, pressure, humidity, fluid susceptibility, vibrations and tensile fatigue. The sensor and bonding method furthermore offer the possibility of being automated because of the wire-like nature of the sensors.

2.2.2 Embedded optical fibre sensors

The embedded optical fibre sensors were not packaged to ensure minimal distortion of the composite material, and because embedded fibres are inherently protected by the host material for harsh aerospace environments. At the egress the fibres were however protected by a Teflon tubing that was co-embedded over 10 mm into the composite coupon. The tubing was sealed with UV-curable adhesive to ensure no capillary resin flow. The fibres were routed as depicted in Figure 1 during the stacking of the composite plies and were temporarily kept in place by an adhesive tacky spray. The fibres were
embedded in between the two layers with 0° angles at a depth of 1/4th of the coupon thickness: [+45/-45/02/90/0]s. They were embedded in such a way that the optical fibre sections with FBGs were parallel to the reinforcement fibres.

2.2.3 Damage indicators

To quantify the strain redistribution acting on the FBG due to the presence of a BVID, we use two damage indicators. The first indicator is the wavelength shift, $\Delta \lambda_B$, for quantifying any change in uniform strain acting over the length of the FBG, as schematically shown in Figure 4 (a). The second is the Pearson correlation coefficient $\rho$ for quantifying the change in the shape of the Bragg peak due to any non-uniform or non-axial strain over the length of the FBG$^{19}$, as shown in exaggeration in Figure 4 (b). If the spectra before and after impact show $\Delta \lambda_B = 0$ and $\rho = 100\%$, no strain change is observed, if they however show a $\Delta \lambda_B \neq 0$ and/or $\rho < 100\%$, a uniform strain and/or non-uniform strain is respectively acting on the FBG$^{19}$. Changes of these damage indicators by ambient conditions must be adequately considered.

Figure 4: (a) damage indicator 1, a uniform strain will result in a wavelength shift, and (b) damage indicator 2, a non-uniform strain will result in a change in Bragg peaks shape.

In this work the spectra were acquired with a Micron Optics SM125-500 interrogator with a wavelength range of 1510-1590 nm, a resolution of 5 pm, an accuracy and stability of 1 pm and dynamic range of 50 dB$^{29}$. All measurements occurred at controlled temperature ($\pm 0.5\, ^\circ$C). The Bragg wavelength was calculated by performing a weighted means calculation in a 200 pm window centring the maximum of the peak and the correlation coefficient was obtained in a 200 pm window centring the Bragg wavelength of both Bragg peaks.

2.3 BVID application

The coupons were clamped in a frame as shown in Figure 5 and then impacted by an INSTRON CEAST 9350 Drop Tower Impact System$^{30}$. The BVID impact energies were experimentally calibrated for each material type beforehand. Table 2 shows an overview of all impact scenarios. For each of those scenarios two coupons were impacted at locations I1 and I2 as noted in Figure 1, yielding a total of 4 BVIDs per scenario. Note that for M3 4 impacts next to each other were required.

Table 2: overview of impact scenarios

<table>
<thead>
<tr>
<th>scenario</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
</tr>
</thead>
<tbody>
<tr>
<td>material</td>
<td>M1</td>
<td>M1</td>
<td>M2</td>
<td>M3</td>
<td>M3</td>
<td>M4</td>
<td>M5</td>
</tr>
<tr>
<td>energy</td>
<td>16 J</td>
<td>20 J</td>
<td>16 J</td>
<td>4x 14 J</td>
<td>4x 16 J</td>
<td>20 J</td>
<td>20 J</td>
</tr>
</tbody>
</table>

The size of the delamination of each BVID was determined via analysis of the impact location with a DolphiCam CF08 handheld C-scan$^{31}$ and were between 90 and 348 mm$^2$. Figure 6 shows an example of such a C-scan reconstruction in 2D of a 16 J impact on M1 creating a ~111 mm$^2$ BVID.
3. RESULTS AND DISCUSSION

3.1 Surface mounted optical fibres

The first step in damage detection is measuring the presence of the BVID by comparing the spectra before and after impact. Figure 7 shows an example of the spectrum of a vertical fibre on an M4 coupon before and after impact at location I2. The impact occurred between FBG 2 and 3 (in Figure 7 the 2nd and 3rd peak from the right). It can indeed be observed that, although small, the changes in this spectrum occur at the 2nd and 3rd FBG from the right. To quantify the change in residual strain applied by the presence of the BVID, the damage indicators at each individual Bragg peak are calculated.

Figure 8 shows the same 6 peaks before and after impact, but for more clarity each in a 400 nm window. The difference between the two spectra is indeed most noticeable at the second and third Bragg peak, peak 1 and 4 show a smaller difference, and for peak 5 and 6 the difference can hardly be noticed with the naked eye. This is confirmed by the damage indicators, which are quantified above every Bragg peak. This example shows that the presence of a BVID indeed induces a strain redistribution, which can be detected by the FBG sensors. Moreover, this redistribution is sensed most by the closest FBGs: as shown in Figure 2 this impact occurred between FBG 2 and 3 of the vertical fibre.
Figure 7: example of an FBG chain before and after application of BVID: the spectrum of a vertical fibre is affected most at FBG 2 and FBG 3 (from the right) due to a BVID applied at location II2 on an M4 coupon.

Figure 8: example of the difference between the six FBG peaks of the vertical fibre on an M4 coupon before and after impact 2. The BVID creates a strain redistribution that is sensed most by the FBGs close to it.

Figure 7 and Figure 8 show the results for the vertical fibre as in Figure 1 (a), but the same analysis is performed on the FBGs of the horizontal fibre. This results in 12 wavelength shift-based and 12 correlation-based damage indicators per coupon. For the purpose of detecting the presence of the BVID, the maximum value of each of those 12 values is compared to a threshold value.
All maximum wavelength shifts were found to be above 10 pm and all correlation coefficients are under 99.94 % (1 - ρ ≥ 0.6 ‰). The BVID thus creates a (non-)uniform strain redistribution that is measurable by the two damage indicators of surface mounted FBG sensors. These results therefore motivate the use of optical strain sensors for structural health monitoring of damage-prone locations.

The horizontal and vertical orientation of the fibres, as shown in Figure 1 (a), allows for creating an axis system in 2 dimensions for detecting the location of the BVID. This could already be observed in Figure 8, where the largest difference in the spectrum for impact 2 occurs between FBG 2 and FBG 3 on the vertical fibre. In order to obtain a coordinate for the BVID location, the wavelength and correlation information were studied separately per method and per orientation (vertically (V) and horizontally (H)).

In order to quantify this location, a Gaussian fit was performed through the Δλ data and the 1-ρ data versus the FBG location. The Gaussian fit allows for locating the largest changes in Δλ and/or 1-ρ while not being too sensitive for outliers. The location of the BVID was determined by the expectance value of the fit, with the confidence bounds on the expectance value as indication for the accuracy of the detection. We set the threshold for detection at ±1 FBG location (26 mm).

![Graph showing BVID location determination](image)

Figure 9 shows the detection algorithm applied to an M3 coupon for the impact at location I1 and for the damage indicators obtained for the horizontal fibre. The expectance values of the normal distributions for both indicators are within ±1 FBG location from the actual BVID location (black dashed line). With each fit the confidence bound on the expectance value was also determined. We required this confidence bound to be less than 2 FBG locations, to have a precision of ±1 FBG location or higher.

Table 3 summarizes the results per indicator (Δλ and ρ) and per fibre direction (V(ertical) and H(orizontal)) for all coupons. If the location was accurately obtained within the pre-established precision window, the detection is indicated with a checkmark. If the location could not be detected, it is noted with a zero, and if the location was wrongly detected, it is marked with a cross. The last two rows summarize the overall detection for both methods: e.g. not located with ρ (0), but accurately located with Δλ (√), is considered as located (√).

Only for one impact (M1-1, 16 J, I1) the location of the BVID was wrongly detected, yielding a false negative rate of 4 %. In total we were able to accurately locate 21 out of 24 BVIDs vertically and 20 out of 24 impacts horizontally within the confidence bounds of ±1 FBG position.
Table 3: impact location based on wavelength shift, Pearson correlation, and both. A check means located, a zero not enough statistics to locate and a cross wrongly located.

<table>
<thead>
<tr>
<th>Comp.</th>
<th>M1-1</th>
<th>M1-2</th>
<th>M1-3</th>
<th>M1-4</th>
<th>M1-2</th>
<th>M1-2</th>
<th>M3-1</th>
<th>M3-2</th>
<th>M3-3</th>
<th>M3-4</th>
<th>M4-1</th>
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<tbody>
<tr>
<td>Δλ_B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>V</td>
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<td>✓</td>
<td>✓</td>
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<tr>
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<td>×</td>
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<tr>
<td>H</td>
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<tr>
<td>Δλ_B &amp; ρ</td>
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</table>

These results thus show that after 100 % detection success rate most of the BVIDs can also be accurately located with surface mounted optical fibre sensors. This information can thus be used as input for a more detailed analysis of the composite component (e.g. a C-scan), at the predicted location of the damage. As such a scan of the entire component is no longer necessary, saving on inspection time.

The accuracy of detection was chosen to be no more than ± 1 FBG location, which was in this case ± 26 mm, but can be tailored depending on the application.

### 3.2 Reliability and repeatability

To illustrate the statistical relevance of the results in view of the robustness of the damage detection for on-ground measurements in between flights, selected measurements (on M2 and M4 coupons) were acquired 60 times repeatedly before and after impact and the damage indicators for damage were determined for every corresponding measurement. The variance on those damage indicators was obtained for those 60 measurements by determining the normal distribution for the Bragg wavelength, and the Gamma distribution (as 1-ρ<0) for the Pearson correlation coefficient. The aforementioned thresholds of 10 pm for Δλ_B and 0.6 % for ρ were more than 2 standard deviations on the spread of the damage indicators, which indicates a probability of more than 95 %. The same conclusion can be made for all the selected measurements.

FBGs are essentially sensitive to (dynamic) strain and temperature changes. Environmental on-ground influences such as different testing temperatures or noise causing vibration (i.e. dynamic strain) could thus potentially affect the damage detection methodology. We therefore tested the methodology against vibration noise by repeating measurements on an M4 coupon in the presence of typical on-ground vibrations. The corresponding vibration spectrum is defined as to simulate the engine of the airplane running while on-ground\(^3\). The change on the damage indicators due to vibrations was for all tested FBGs again found to be more than 2 standard deviation removed from the thresholds in damage indicators due to the presence of a BVID. We conclude that the damage detection methodology is therefore robust against on-ground vibration noise.

We also tested the methodology against static temperature changes by acquiring and repeating measurement of one M2 coupon while the ambient temperature was fluctuated. The temperatures ranged from room temperature (25 °C) up to about 70 °C. During the experiments, the temperature was acquired with an accuracy of about 0.5 °C. The evolution of the Bragg wavelength for the individual sensors with temperature was fitted accordingly, with R-squared values exceeding 99.9 %. Using the fitted trend, the obtained measurements were analysed and compensated for the temperature difference with room temperature by subtracting the corresponding wavelength difference. The standard deviation on the temperature compensated Bragg wavelength (for the tested temperatures) was found to be below 4.2 pm. A damage detection threshold of 10 pm thus also has a detection probability of > 95 % whilst correcting for temperature differences. This means that all BVID detection results are within this detection probability. It was previously already demonstrated that the Pearson correlation is unaffected by in-flight conditions, including temperature changes within a damage detection threshold of 0.6 %\(^19\). The FBG-based damage detection methodology therefore also proves robust against temperature changes.
This shows the methodology can be used for measuring in between flights and is not affected by the presence of aircraft vibrations and can be adequately compensated for temperature differences between measurements.

### 3.3 Embedded optical fibres

Four coupons manufactured from M5 were provided of embedded optical fibres with a layout as illustrated in Figure 1. Similar to the coupons with surface mounted optical fibres, these coupons were impacted at the locations marked with I1 and I2. The spectrum of the embedded fibres was obtained before and after application of the BVIDs, and for each FBG the two damage indicators were determined. Figure 10 shows the full spectrum of an embedded fibre before and after the application of a BVID at location I2. The impact occurred vertically between FBG 2 and 3 but was closest to the former. Figure 11 shows the same FBGs, but in a 400 nm window centring the Bragg wavelength of the peak before the impact.

![Spectrum before and after application of a BVID at location I2.](image)

**Figure 10:** Spectrum before and after application of a BVID at location I2.

From Figure 11 we can indeed conclude that the presence of the BVID is detected by most FBGs embedded in the coupon. To quantify this, we calculated the two damage indicators per FBG, as noted above each Bragg peak in Figure 11. As an indication for the detection of the presence of the BVID we will again look at the maximum value of each damage indicator for the whole coupon and per impact. For the example of Figure 10 and Figure 11, this would thus be $\Delta \lambda_B^{\text{max}} = 30.5 \text{ pm}$ and $1 - \rho^{\text{max}} = 6.71 \%$, both passing the preestablished thresholds of 10 pm and 0.6 %. This was repeated for all coupons and impacts and resulted in a similar conclusion for all cases. Although it was expected that the sensitivity of embedded FBGs is higher than that of surface mounted FBGs due to better strain transfer, the average $\Delta \lambda_B^{\text{max}}$ for all 8 impacts was $22 \pm 10 \text{ pm}$, while the average $\Delta \lambda_B^{\text{max}}$ measured by the surface mounted fibres on M4, was $63 \pm 21 \text{ pm}$, which is almost 3x higher.

We thus concluded that embedded FBGs indeed experiences a change in (non-)uniform strain due to the presence of a BVID, that surpasses the thresholds established in the previous analysis. It does however seem that embedded fibres are less sensitive than surface mounted ones.

As could already be noticed in Figure 11, the affected FBGs are not necessarily concentrated around the location of the BVID, as was the case for surface mounted FBGs (Figure 8 and Figure 9). This is confirmed in a different example in Figure 12, where the damage indicators are visualized in function of the FBG location for both the BVID at location I1 in Figure 12 (a) as at location I2 in Figure 12 (b). Both impacts occurred in the top half of the coupon, as illustrated in Figure 1. The vertical dotted line denotes the BIVD’s centre location along the length of each part of the fibre. None of the damage indicators allows a straightforward derivation of the locations of both BVIDs at location I1 and I2.
Figure 11: effect on the Bragg peaks due to the presence of a BVID at location I2, visualized in 400 nm windows around the FBGs of Figure 10 (in order of increasing wavelength)

Figure 12: damage indicators for each FBG after application of a BVID at impact location I1 (a) and I2 (b). The centre location of the BVID along the length of the fibre is noted with a vertical dotted line.
From the example in Figure 11 and Figure 12, it can be concluded that, however the presence of the BVID seems to be sensed by several FBGs in the coupon, these are never the FBGs located closest to the BVID. It thus is difficult to pinpoint the exact location of the BVID with embedded optical fibre sensors.

4. CONCLUSION

We firstly demonstrated the detection and location of barely visible impact damage (BVID) on aerospace-grade composite coupons with surface mounted in-flight compatible optical fibre sensors. This result is in contrast with most studies reported in literature which deal with simplified materials, common telecom fibre or standard adhesives and a limited number of samples. We therefore hope this work contributes to increasing the technology readiness level (TRL) of optical fibre sensing serving condition-based maintenance of composite aerospace structures.

The surface mounted FBGs were able to detect the presence of all BVIDs with two damage indicators. Moreover, we were able to locate 21 out of 24 BVIDs vertically and 20 out of 24 BVIDs horizontally with the precision of ± 1 FBG position. Only one BVID was located wrongly and in the other cases the damage indicators did not yield enough statistics for an accurate location, yielding only 4% of false negatives. We also studied the repeatability and reliability of the methodology and concluded the measurements are not compromised by on-ground conditions. As such a pre-emptive time-based maintenance would no longer be required, and a more detailed inspection of the component can be performed when one of the two damage indicator rises above its threshold.

We have shown that embedded FBGs clearly detect the strain redistribution due to the presence of the BVID, but as compared to the surface mounted optical fibres, they are not straightforwardly able to determine the exact location of the BVID in the coupon. In addition, the sensitivity of the embedded FBGs showed to be smaller than that of surface mounted FBGs. Moreover, embedded optical fibre sensors still face other challenges in convincing the aeronautics sector on their potential for practical considerations during production and repair.

We conclude that at the moment surface mounted optical fibres are the way forward for the detection and location of barely visible impact damage (BVID) on aerospace composite structures, and we aim with this demonstration to contribute to an increase in TRL of optical fibre sensing in this application.

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