Embedded fibre Bragg grating sensors as a tool for structural health monitoring of complex composite structures

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ABSTRACT

Composite materials are recently widely applied in many industrial branches (marine, aviation, civil engineering). In structural elements, damage (e.g. delamination, matrix cracking, fibre-matrix debonding) can appear due to external loadings, environmental factors or internal failures. The unpredictable evolution of damage mechanisms in a structure create the need for structural health monitoring systems for detection of damage initiation, subsequent tracking of its evolution and determination of the analysed element condition.

Fibre Bragg grating sensors have small size and weight, multiplexing capabilities, high corrosion resistance and absence of electric current in measurement array. Due to this, the sensors can be embedded into composite elements during their manufacturing process and permanently integrated with complex structures.

The paper presents an application of embedded fibre Bragg grating sensors array for evaluation of the complex composite element – a panel from a fast boat. The possibility of FBG sensors application for evaluation of static loading, impact incidents and artificial sea waves influence on the structure will be analysed. Additionally, the limitation of sensitivity and applicability of the proposed method for the complex composite structure will be established.

1. Introduction

Glass fibre reinforced composites (GFRP) are nowadays widely applied in many industrial branches like: marine⁷, energy⁸ or civil engineering⁹. Therefore composite elements are exploited in different environmental and loading conditions that influenced on the durability of structures. The high popularity of composites and safety requirements results in development of Structural Health Monitoring (SHM) methods. One of sensors type that can be an integral part of SHM systems are fibre Bragg grating (FBG) sensors. Due to their advantages (like: small size and weight, multiplexing capabilities, immunity to electromagnetic fields, high corrosion resistance) the sensors can be embedded into composite material during manufacturing process⁴. Such SHM systems are applicable to permanent monitoring of strain distribution in different structures e.g. bridges⁵ or aircrafts⁶.

Until now, the monitoring of marine vessels is primarily concerned on: navigation (e.g. course, position and speed)⁷, environmental influence (e.g. temperature, ice, waves and wind)⁵ and endangering situations (e.g. oil spills at sea)⁹ as well as machinery condition (e.g. propulsion system)⁸. Furthermore, since several years systems for ship/ vessel hull stress monitoring are developed. Capabilities of those systems are the stress indication of a hull structure during cruise and cargo operation⁹.
One of the sensors types that can be permanently integrated with a structure of marine vessel and used as a part of SHM system are FBG sensors. The sensors can be utilised for strain monitoring of both metallic and composite marine structures, e.g. ships hulls\(^{[13]}\), sailing ship mast\(^{[1]}\), submarine structure\(^{[14]}\) or offshore structures\(^{[15]}\).

In the paper the analyses related to possibility of application of embedded FBG sensors for SHM of a fast composite boat hull are presented and discussed. Firstly, embedding processes and FBG sensors behaviour are analysed on a glass composite laminate and composite sandwich panel with the same structure like the boat hull are analysed. Then the thermal and strain responses of the panel are presented. Next, a manufacturing process of the boat hull with FBG sensor array embedded into the structure is described. The analyses are focused on the process influence on the FBG sensors spectra shapes. Finally some conclusions are drawn.

2. Analysed composite samples

In the paper two types of composite samples are analysed. In every one an array of FBG sensors is embedded. The first one is a four-layer glass fibre reinforced polymer (GFRP) sample. While the second one is a sandwich panel with foam fulfilment and two GFRP outer skins.

2.1 Composite sample

The first analysed sample is four-layer GFRP sample (70 mm x 200 mm x 1 mm) with one embedded FBG sensor. The sample scheme is presented in Fig. 1. The sample was manufactured from bidirectional glass textile with fibres arrangement \(\pm 45^\circ\) and epoxy resin. Between the 1\textsuperscript{st} and the 2\textsuperscript{nd} layer counting from the bottom of the sample a fibre optic with FBG sensors with 10 mm gage length was embedded.

![Composite sample scheme](image)

Figure 1. Composite sample scheme

2.2 Sandwich panel

The second analysed structure is a complex composite sample – a sandwich panel. The overall dimensions of the sample are equal to 570 mm x 640 mm x 50 mm. It contains two-layer GFRP skins and polyvinyl chloride (PVC) foam fulfilment. The used glass textile have structure 0/45/90/-45. The materials used for the sample manufacturing as well as the sample prepared for the curing process are presented in Fig. 2(a). FBG sensors (with a gage length equal to 10 mm) array in a form of a rosette is embedded in one of the skin between the 1\textsuperscript{st} and the 2\textsuperscript{nd} layer.

The finished sample with marked location of FBG sensors is presented in Fig. 2(b). The panel have a characteristic concave shape with FBG sensors embedded into the skin on the bottom part of the sample. The sample internal part structure is identical like designed composite boat hull structure. The sample designing allowed to analyse influence of the manufacturing process on FBG sensors and
connecting fibre optics arrangement inside the structure as well as the boundary between embedded and free parts of fibre optics. The investigations were focused on problems related to fibre optics bending inside the structure as well as their breakage at the remained boundary. The achieved results were used for designing the FBG sensors array for embedding into the fast boat hull structure.

![Composite sandwich panel with marked FBG rosette location (black arrows): (a) internal structure: A – glass textile, B – foam, (b) finished sample with an array of analysed points](image)

**Figure 2.** Composite sandwich panel with marked FBG rosette location (black arrows): (a) internal structure: A – glass textile, B – foam, (b) finished sample with an array of analysed points

### 3. Embedding process

All samples were manufactured using infusion method. During the manufacturing process the material stack was built on a metal plate covered by polytetrafluoroethylene (PTFE) layer allowed to easy remove the finished element. The top of the stack was covered by an additional material layer providing an equal distribution of a resin during the manufacturing process. Due to this the samples surfaces roughness differ. The bottom surface was smooth while the top one – rough, like it is presented in Fig. 1 for the GFRP sample. The total curing process duration was 22-24 h, while the epoxy flow and the exothermic reaction with maximal temperature ca 155°C lasted 40-55 min\(^{[17]}\).

#### 3.1 Composite sample

During whole curing process the FBG sensors were connected to the interrogator (si425-500 from Micron Optics). Due to low speed of the process the measurement frequency was chosen as 1 Hz. Before and after the end of the embedding process the FBG sensor spectra were measured using Fibre Sensing FS4200 Portable BraggMETER interrogator.

![Strain changes measured by FBG sensor during embedding process](image)

**Figure 3.** Strain changes measured by FBG sensor during embedding process
The strain values measured by FBG sensor during its embedding process are presented in Fig. 3. The measuring process started at the moment when FBG sensor was put on the textile and finished at the end of the polymerisation process of the resin. So, the measurements contained the sample preparation process, resin introduce and the curing process. The total length of the process is equal to 22 h. The wavelength values registered after the end of stacking sequence arrangement of the sample were treated as the base wavelengths. The sample operations (covering by a special material applied for equal distribution of resin and the vacuum pomp equipment attachment) are visible as strain decrease. The introduction of pressure (about 0.9 bar), that was set during whole intrusion process, was visible as significantly strain decrease. The epoxy resin flow influence was not visible in strain changes. The strain peak related to exothermic reaction during epoxy resin curing is slightly visible as a strain increase (about 0.5 h). The more noticeable strain increase (after 1 h) is related to the local increasing of material stiffness due to the resin curing process in the FBG sensor location. The strongly visible strain peaks (about 3 h) are related to disconnection of the vacuum pump. The slow strain decrease (after 4 h) and then the rapid strain increase (about 18 h) are mostly related to temperature changes in the room.

Figure 4. Spectra changes related to embedding process: F – free, E – embedded

A comparison of spectra registered before (denoted as F) and after (denoted as E) of the embedding process is presented in Fig.4. The process do not influenced significantly the FBG sensor spectrum shape. It was slightly wider and showed that the curing process results in tension occurrence.

3.2 Sandwich panel

The positive results achieved from GFRP sample with embedded FBG sensor results in attempt to embed FBG sensors into a sandwich panel structure. The manufacturing process was similar to the one described above for GFRP sample, but the strain changes were not registered.

Figure 5. Spectra changes related to embedding process: F – free, E – embedded
A comparison of the sensors spectra measured before (denoted as F) and after (denoted as E) embedding process is presented in Fig. 5. The embedding process influence on S_a sensor is almost neglected. For the sensor S_b the process results in widening of the reflected spectrum and additional wavelengths reflections occurrence. Probably it is an influence of the complex structure of glass textile and location of FBG sensor in reference to the fibre bundles of the textile. But those two sensors seems to be useful for measurements of internal strain distribution of the structure. Unfortunately, the embedding process had negative influence on sensor S_45. The spectrum of the embedded sensor is divided into two parts, both with maxima with an amplitude levels higher than 0.75. It suggests an occurrence of unequal strain distribution over the FBG sensor gage length. Probably it is a reason of remaining strains influence or local bending of the fibre optic on glass fibre textile bundles.

4. Experimental results of the sandwich panel

In the next step the sandwich panel with embedded FBG sensors was investigated experimentally. The analyses were related to thermal response of embedded FBG sensors and their behaviour under impact excitation by modal hammer in selected points.

4.1 Thermal response

Firstly, the temperature influence on the sensors responses was analysed. The measurements were performed in laboratory for temperatures in a range between 23°C and 28°C. Before experimental validation the temperature in the laboratory was stabilised by 2 h of air condition continue work with stable temperature (23°C). During whole calibration process the temperature was measured using temperature probe attached to the sample surface close to the FBG sensors rosett e. After turning the air condition off the temperature in the room increased quickly as it is presented in Fig. 6(b).

Figure 6. Changes of (a) strain and (b) temperature

The strain values for all FBG sensors related to the temperature changes are presented in Fig. 6(a). As it is visible the sensors S_a and S_b are affected by the temperature while the sensor S_45 seems to be almost insensitive on the temperature changes. The averaged values of wavelengths and strain changes related to increase of 1°C are presented in Table 1. The calibration was related to discrete points measured after every 300 s. The values achieved for sensors S_a and S_b are almost two times higher than for FBG sensors embedded into adhesive layer of an adhesive joint[16]. In that case the value was equal to 9.15ε 10^-5 [m/m°C][16].

The observed differences related to values presented in Fig. 6(a) and Table 1 are probably due to quick changes of the temperature in the laboratory (measured by the temperature probe) and slower changes inside the sandwich panel due to material properties of its internal structure. The values presented in the Table 1 are related to more stable temperature conditions although the wavelengths and strains
values related to temperature influence can be smaller/ or higher because of differences in internal and external temperature of the sample. To overcome the problem measurements in environmental chamber with stable temperature and humidity level are planned. However, the results presented above indicate problem related to proper temperature measurements and compensation of its influence during experimental investigations performed in real conditions.

**Table 1.** Temperature calibration of embedded sensors

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<tr>
<td></td>
<td>$S_a$</td>
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<tr>
<td>$\lambda \ [nm/^\circ C]$</td>
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<tr>
<td>$\varepsilon \ 10^{-6} \ [m/m^\circ C]$</td>
<td>14.1406</td>
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### 4.2 Impact excitation

Next the FBG sensors response on impact excitation in chosen points on the structure was investigated. Similar measurements were performed on a composite sandwich plate filled with honeycomb core. The sample contained two GFRP skins and one Nomex® inner layer – all together bonded with epoxy resin. In that case an array of FBG sensors was attached to the surface of the sample using cyanoacrylate glue. The details of the investigations are described in[18].

The scheme of the FBG sensors rosette in used coordinate system is presented in Fig. 7. The sensor denoted as $S_b$ is parallel to the x-axis, while the sensor denoted as $S_a$ is parallel to the y-axis. So, the $\alpha$ and $\beta$ angels are equal to 180° and 45°, respectively. The scheme of analysed points array with marked rosette location (denoted as R) is also presented in Fig. 7. The internal part of the sample (see Fig. 2) with a dimension of 400 mm x 250 mm was divided into an array of 6 x 9 points denoted by letters (A to F) and numbers (1 to 9). The FBG sensors responses were analysed using modal hammer impacts excitation in chosen points on the structure. In every point an external loading in a form of seven impacts was introduced with an average impact energy equal to 0.03 J. The calibration procedure of the impact hammer was described in details in[18]. In recent work the rubber (black) tip (soft hardness) was used due to the fact that the tip is hard enough to excite the plate without local damage.

![Figure 7. Schema of analysed points array with marked rosette location (R) and FBG sensors rosette](image)

In Fig. 8 the calculated sensitivity distribution of each sensor individually is presented. It is presented in a form of normalised strain values in particular points in relation with the highest strain value received for a particular sensor. It is visible that both sensors $S_a$ and $S_b$ show directional behaviour agreed well with their direction according to the coordinate system presents in Fig. 7. The highest strain values are related to the sensors locations (point C5) and its close neighbourhood but only in directions agreed with the sensor direction. Slightly smaller values are in zones with dimension of
three points per six points. The sensor $S_{45}$ behaves differently. It shows high strain levels in a right-angled triangle with a hypotenuse on the sensor and almost no responses for the other points. For all sensors small responses in a level of 5-10% of the maximal strain also occur in the other points.

![Figure 8. Individual FBG sensor sensitivity for impact energy 0.03 J](image)

In Fig. 9 the distribution of every FBG sensor response is showed. It is presented in a form of a maximised normalised measured strain amplitude and calculated by a following formula:

$$I_{L,W} = \max \left( \overline{A_{c,r}} \right), \quad \text{where} \quad \overline{A_{c,r}} = \frac{A(i,j)}{A_{\max}} \quad \text{for} \quad i=1,\ldots,9; \quad j=1,\ldots,6$$

where $\overline{A}$ is normalised strain amplitude value, $A$ – a strain amplitude value measured in each point, $A_{\max}$ – a maximum strain amplitude value, $c$ – column, $r$ – row, while $L$ and $W$ – according to Fig. 7. The sensors $S_a$ and $S_b$ show their directional behaviour with maximal values in the points related to the FBG sensors locations. Also the indexes $I_L$ and $I_W$ levels are higher for parts of the structure agreed with the sensors direction. Sensor $S_{45}$ behave differently. In every case it shows high values (ca 1) for three neighbouring points and small values (less than 0.2) for the others.

The achieved results confirm possibility of embedding FBG sensors into a complex sandwich composite panel. The sensors survive whole manufacturing process. However all preliminary investigations related to thermal and impact excitation loading shows that FBG sensor located with an angle of 45° according to the coordinate system does not responses correctly.

5. Composite boat hull

Based on the preliminary investigation results performed on a composite panel an array of embedded FBG sensors was designed for a fast patrol boat hull. A photograph of the boat is presented in
The length of the boat is equal to 15 m. Its hull had sandwich structure similar like the composite panel described previously. In a part of the hull (in a starboard) an array of four FBG sensors (with a gage length equal to 10 mm) was embedded – see Fig. 10(b).

**Figure 10.** The fast patrol boat (a) a photo, (b) starboard with denote FBG sensors locations

### 5.1 Embedding process

The schema of the boat with marked FBG sensors locations and a part of the hull where the sensors array was installed are presented in Fig. 11. Based on the previously described results achieved for the composite panel, with identical structure like the hull, the sensors were designed as parallel and perpendicular according to the starboard shape.

**Figure 11.** A scheme of embedded FBG sensors location in the boat structure and a photograph of a part of the hull where the sensors were installed

The embedding process of FBG sensors was performed on almost ready hull without a part where the sensors array was planned to be located. This part was manufactured in a similar way like the previously described samples – using infusion method. During the process the wavelength changes were measured using Fibre Sensing FS4200 Portable BraggMETER interrogator with a measurement frequency equal to 1 Hz.

The strain values determined for the manufacturing process are presented in Fig. 12. The strain values are calculated in relation with the sensors wavelengths measured for material with finished arrangement of fibre optics, covered by appropriate materials and with connected vacuum pump system. Unfortunately, a part of the signal (about 1800) between the end of the resin flow and the beginning of the curing process was not registered. Although the observed process course is similar to the first 2 h part of the one presented in Fig. 3 for the GFRP sample. All of the FBG sensors shows similar behaviour. During the first part of the measurement the strain levels were almost stable, except
one peak (sensors $S_1$ and $S_2$) and visible strain decrease observed for the sensor $S_4$. The strain increase related to the increase of the material stiffness due to the curing process of the resin is visible on all sensors in the second part of the measured signal (after 2700 s).

**Figure 12.** Strain changes measured by FBG sensors during embedding process

**Figure 13.** FBG sensors spectra: F – free, $E_S$ – beginning, $E_F$ – the end of the embedding process, R – the finished hull of the boat, T – boat after some tests
The FBG sensors spectra measured in different stages are presented in Fig. 13. The spectra changes were registered in five stages: free sensor (denoted as F), beginning (E$_S$) and the end (E$_F$) of the embedding process, the finished hull (denoted as R) and after some tests (denoted as T). For all sensors the spectra shapes registered for free (F) and the beginning of the embedding process (E$_S$) are similar. The only differences are related to compression that occur for sensors due to the pressure and the resin flow. The end of the embedding process (E$_F$) was understand as the moment about 2700 s related to strain increase (tension occurrence and exothermal reaction during curing process). For all sensors spectra deformations (additional maxima) are visible. Although only for the sensor S$_3$ the additional maximum amplitude is higher than 20% of the main peak amplitude. The spectra shapes determined for sensors when the boat was ready (R) are visible wider than the original ones. However in all of them the maximal peak can be easily determined. For sensor S$_1$ the additional reflection with a very close wavelength value is observed and results in the spectrum deformation. For sensors S$_2$ and S$_3$ the additional maxima also occur but are not higher than 20% of the maximal peak amplitude. The higher modifications of the original spectrum shape are visible for the sensor S$_4$. It is not only almost three times wider but also have additional maxima with amplitudes about 80% and 40% of the maximal peak amplitude. Measurements performed after some tests of the boat (T) indicates that the FBG sensors spectra shapes are almost unaffected.

The achieved results shows that all of the sensors survived the embedding process. However they also indicates problems related to probably unequal strain distribution over the sensors gages lengths or fibre optic shape deformation as well as some remain strain occurrence.

The strain changes related to the boat manufacturing process are presented in Fig. 14 and collected in Table 2. Their values were determined based on the wavelengths related to amplitudes of the measured maxima with relation to the wavelengths measured for peak maxima of free sensors – see Fig. 13. Their shows that at the beginning of the process (E$_S$) the strain values of all sensors were on similar level. Some differences were visible for the end of the process E$_F$. For the last two measurements

![Figure 14. FBG sensors spectra: E$_S$ – beginning, E$_F$ – the end of the embedding process, R – the finished hull of the boat, T – boat after some tests](image)

<table>
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<th>Stage</th>
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<tbody>
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<td></td>
<td>S$_1$</td>
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<tr>
<td>E$_S$</td>
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</tr>
<tr>
<td>E$_F$</td>
<td>3.3870</td>
</tr>
<tr>
<td>R</td>
<td>-5.7450</td>
</tr>
<tr>
<td>T</td>
<td>-5.2380</td>
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</table>
(R and T) the differences between strain values measured by the two group of sensors (S₁, S₂ and S₃, S₄ – see Fig. 11) became visible. It is probably due to the sensors locations in the hull structure and differences in their loading.

6. Conclusions

In the paper analyses related to possibility of application of embedded FBG sensors for SHM of composite boat hull are presented and discussed. The problems related to embedding of FBG sensors arrays into composite structures (sample, sandwich panel and boat hull) are described. The analyses are mostly related to the survivability of the sensors and their spectra deformations.

The achieved results show that all embedded sensors were able to be used after the end of the manufacturing process. Although due to unequal strain distribution over FBG sensor or deformation of its cross-section one of the sensors being a part of rosette embedded into the sandwich panel became useless. As its spectrum was divided into two almost separated parts is was almost insensitive on thermal influence and responses very locally on impact excitation. All information related to behaviour of embedded FBG sensors were taken into consideration during designing FBG sensors array that was planned to be embedded into a composite boat hull. Due to problems related to diagonal sensor (S₁₅) this direction was not applied in the array proposed for the hull structure.

The embedding process of FBG sensors into the hull structure was monitored. A comparison of spectra registered for the sensors for different stages of the boat manufacturing process was presented and discussed. Some disturbances in spectra shape of the FBG sensors embedded into the hull structure were observed. The problems can be related to uneven strain distribution along FBG sensor gage length as well as its deformation or remain strain occurrence. The most visible deformations were observed after the end of the boat manufacturing process, when all elements including deck, fuel tank or engine were installed.

The utility of the SHM system for fast composite boat based FBG sensors will be tested during sea trials in the near future. The authors wish to continue their work in this area of research in the future to overcome all the problems and difficulties encountered during the line of work presented in this paper.

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