Temperature and humidity influence on glass fibre reinforced polymer samples under NDT and SHM studies

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KEYWORDS: composite structure; non-destructive techniques; structural health monitoring; temperature and humidity;

ABSTRACT

Composite materials are used extensively in many industry areas e.g. marine, aerospace, automotive, railway, wind energy. Due to their wide applicability, the high safety needs are required. Composites contain two main components: fibres and polymer matrix. Among them, the matrix is a weaker component that physical and chemical properties are strongly affected by environmental exposure. Polymer components are sensitive to ultraviolet radiation, freeze-thaw or elevated temperature cycles, moisture and many operational liquids like deicing chemicals. Among many environmental factors that affect the durability of composite structures, the mix of temperature changes and moisture has the strongest influence. Any failure occurrence can result in costs of the damaged structures repairs as well as in environmental contamination (ecological catastrophe). To overcome the problem of safeness is important to apply non-destructive testing (NDT) methods or structural health monitoring (SHM) systems.

The paper presents an application of SHM system based on FBG sensors for inspection and evaluation of the internal composite samples structure. The studied glass fibre reinforced polymer (GFRP) samples are instrumented with embedded FBG sensors array. Applying THz spectroscopy (THz-TDS) the simultaneous influence of temperature (form negative to room temperature) and different humidity levels changes on structures will be observed and analysed. The responses of FBG sensors during freezing and thawing processes will be measured and analysed.

The goal of this paper is to study the sensitivity and applicability limitations of proposed methods for composite structures.

1. Introduction

Composite elements (both Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer GFRP)) are widely used in e.g. aircraft, marine, civil engineering structures, where the specific strength and specific modulus are of importance, e.g. aircraft wings, helicopter rotor blades, wind turbine blades. The main advantage of CFRP and GFRP is mechanical strength to weight ratio. But any damage occurrence (matrix cracking, fibre-matrix debonding, delamination, and fibre fracture) results in degradation of its mechanical properties. One of the reasons of damage initiation in composites is the exposition to environmental factors. Influence of moisture and negative/ elevated temperature can induce a structural disintegration process that results in mechanical strength decreasing.

An influence of moisture/ water on internal structure of composite materials is nowadays analysed by scientist around the world[1][3]. Moisture presence has negative impact on strength of composite
adhesive bonding. Additionally composite material degradation due to negative/ elevated temperature influence is an important issue\cite{4-7}. One of the problem with polymers used in composites matrix is their tendency to absorb moisture from ambient. The moisture affects a polymer properties, like dimensional stability, mechanical, chemical and thermophysical properties\cite{8-9}. Due to fact that influence of temperature and humidity can affect the state of composite materials in various ways, diverse NDT and SHM methods are utilized.

One of known result of soaking is the increase of volume related to state of strain/stress changes\cite{10}. To determine the strain induced volume changes due to moisture absorption in epoxy composites FBG sensors were used\cite{11}. Additionally, FBG sensors were utilised to monitor the effects of hygrothermal ageing on the axial strains in a cylindrical epoxy specimen. The FBG sensors response also indicates the appearance of progressive debonding after sufficient exposure to moisture\cite{12}. Moreover FBG sensors were an effective tool for determination of amount of moisture in composite adhesive layer\cite{13}.

Due to ageing effects it is crucial to monitor objects subjected to cyclic freezing and thawing. The FBG sensors are employed in this area as well. Optical sensors are used for both composites\cite{14-15} and concrete structures\cite{16-17}. It was confirmed that strain changes due to freeze-thaw cycles are measurable and capable to monitor with use of FBG. Moreover moisture influence is possible to take into account.

Another technique used for moisture analysis in composite materials is THz spectroscopy. Spectral range of electromagnetic radiation is divided into several parts for which the distinguish mark is the way of interaction between electromagnetic wave with material and their applications. The THz spectroscopy is related to electromagnetic waves from a range 0.1 – 10 THz. The technique can be used for evaluation of internal structure of GFRP elements and can be applied for detection, localisation and determination of size of many different discontinuities. Any discontinuity can be detected only if its occurrence affects minimum one of three THz wave parameters: refractive index, absorption coefficient or wave scattering. The technique can be used for identification of fibre optics\cite{18}, mechanical defects\cite{6,19} or moisture\cite{18,20-21} and Teflon layer\cite{22} in composites. Moreover the THz spectroscopy is effective method for detection/observation of thermal degradation process of GFRP material\cite{5}.

2. Experimental Investigations

In the paper the determination of sensors limitations as well as structural disintegration (degradation) due to environmental (cross-relation between moisture and temperature) influence on Glass Fibre Reinforced Polymer (GFRP) sample is analysed.

The proposed tools to solve the problem are Fibre Bragg Grating (FBG) sensors and Terahertz Time Domain Spectroscopy (THz-TDS). The FBG sensors method is used for strain changes measurements and determination of damage occurrence development and THz-TDS method allows to observe internal structure of composite material.

2.1 Sample & Set-up Details

All measurements were conducted in the climate chamber MyDiscovery DM600C (Angelantoni Test Technologies Srl, Italy). The pictorial photo of climate chamber as well as sample and sensors are presented in Fig. 1 and main parameters of the climate chamber are collected in Table 1. The climate chamber is monitoring and supervise by MyKratos™ software. The application is present on-board the machine and can be accessed from PC via Internet browser or form a mobile device via the MyKratos App\cite{23}. To monitor the sensors behaviour two FBG interrogators were use: Micron Optics® sI425-500 for strain and temperature changes measurements and Fibre Sensing FS4200 Portable BraggMETER
for spectra observation. For experiment five FBG strain sensors – three 10 mm (Micron Optics) and two 1 mm (Fiber Logix) – and one FBG temperature probe (Micron Optics) were used.

Figure 1. (a) Set-up: climate chamber, interrogators and laptop; inside chamber: sample and sensors in (b) water-free and (c) iced environmental conditions

Table 1. Main parameters of climate chamber MyDiscovery DM600C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>-75ºC ÷ +180ºC</td>
</tr>
<tr>
<td>Temperature fluctuations</td>
<td>±0.1ºC ÷ ±0.3ºC</td>
</tr>
<tr>
<td>Temperature change rate</td>
<td></td>
</tr>
<tr>
<td>heating</td>
<td>4.5K/min @ -70ºC ÷ +180ºC</td>
</tr>
<tr>
<td>cooling</td>
<td>4K/min @ +180ºC ÷ -70ºC</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>10% ÷ +98%</td>
</tr>
<tr>
<td>Relative humidity fluctuations</td>
<td>±1% ÷ ±3%</td>
</tr>
</tbody>
</table>

During all measurements sensor $S_1$ (coloured in green) stays free, sensor $S_2$ (coloured in blue) stays woven into fibreglass textile, sensor $S_3$ (coloured in grey) stays glued on the sample surface, sensors $S_4$ and $S_5$ (coloured in purple and magenta, respectively) stay embedded into sample and temperature probe $S_7$ (coloured in red) stays free – Fig. 2. Originally sensors $S_1$, $S_2$, $S_3$ formed rosette embedded (between 1st and 2nd layer counting from the bottom) into the four-layered rectangular composite GFRP sample with a dimension as follow: 50 mm x 200 mm x 1.6 mm. Due to the broken fibre optic embedded into the sample the sensor $S_3$ was replaced by sensor $S_3$ glued on surface of the sample, in such a way that the sensors still form a ‘rosette’. The sample was manufactured using infusion method from bidirectional material (glass SGlass) and epoxy resin. During preparation process the material was laying on a metal plate covered by polytetrauoroethylene PTFE layer allowing easy removing sample. The material plies were covered by additional material layer in a purpose of an equal distribution of the resin during the manufacturing process. Due to this the bottom surface of the sample is smooth while the top one is rough.
2.1.1 Internal structure of composite sample by THz spectroscopy

The internal structures of the intact composite sample with an array of FBG sensors was examined using THz spectrometer (TPS Spectra 300 THz Pulsed Imaging and Spectroscopy from TerraView®) in reflection mode. The measuring heads were arranged in an angle of 22° between them. As the electromagnetic waves in THz range are sensitive to moisture in the ambient all measurements were performed with air dryer that removes moisture from the working heads area and air conditioner that stabilise laboratory temperature on assumed level equal to 20°C. During scanning process the measurement step was equal to 0.2 mm and THz signals were registered with 10 averaging. During measurements the samples were put on a metal table that surface was parallel to the spectrometer's heads.

B-scans and C-scan of the analysed areas of the sample are presented in Fig. 3. In every image fibre optics with FBG sensors are denoted as $S_3$, $S_4$ and $S_5$ according to the scheme presented in Fig. 2. All fibre optics locations can be properly determined on all B-scans between the 1st and the 2nd layer of the sample counting from its top. The first B-scan is performed for $x=-10$ mm, while the second one for $y=-80$ mm. Each of them presents a couple of sensors. The C-scan is presented for the area between the 1st and the 2nd layer of the sample. To minimise the influence of the surface roughness a filtering method was proposed based on the determination of the locations of signals maxima related to the sample surface. The presented image allowed to determine the fibre optics arrangement between layers. The achieved results will be used for determination of influence of thermal and moisture on internal structure of the sample especially in close area of the FBG sensors.
2.2 Experimental Details

To estimate the limitations (sensors and GFRP material) resulting from the influence of environmental factors (cross-relation between moisture and temperature) on the sensors and the sample, the following environmental conditions were analysed (Fig. 2(a), (b)):

- container with sensors and sample dry (water-free), temperature -20°C, relative humidity 20%,
- container with sensors and sample dry (water-free), temperature -20°C, relative humidity 95%, (pouring water into container)
- container with sensors and sample wet (iced), temperature -20°C, relative humidity 20%,
- container with sensors and sample wet (iced), temperature -20°C, relative humidity 95%.

![Spectra changes dependent on environmental conditions (D – dry, W – wet, I – iced)](image)

During every above-mentioned stage the spectra of sensors $S_1$-$S_5$ were collected and are presented in Fig. 4. It is easy to notice that: for sensor $S_4$ and $S_5$ (both 1 mm) full width at half maximum (FWHM) is wider than for sensors $S_1$, $S_2$ and $S_3$ (three 10 mm); that reflectivity $R$ vary from 0.8 to 1 (details in Table 2), especially for sensor $S_2$ and $S_5$; due to temperature changes the wavelength $\lambda$ maximum peak shifts - the wavelength variation range is around 2.5 nm. In Fig. 5 it is easy to observe that for sensors water-free and water conditions (ca +23°C) do not cause significant changes in the wavelength shift. Contrary, negative temperatures (-20°C and -50°C) cause up to 2 nm changes in the wavelength shift regardless of dry or wet environmental conditions – details in Fig. 5 and Table 2.
Figure 5. Sensors wavelengths shifts (maximal values, $x$ – nominal wavelength @23ºC) caused by different environmental conditions: $S_1$ – green, $S_2$ – blue, $S_3$ – grey, $S_4$ – purple, $S_5$ – magenta

Table 2. Changes in wavelengths shifts and reflectivity due to different environmental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>$S_1$ x=1552@23ºC</th>
<th>$S_2$ x=1552@23ºC</th>
<th>$S_3$ x=1544@23ºC</th>
<th>$S_4$ x=1538@23ºC</th>
<th>$S_5$ x=1564@23ºC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda_B$ [nm]</td>
<td>$R$ [-]</td>
<td>$\lambda_B$ [nm]</td>
<td>$R$ [-]</td>
<td>$\lambda_B$ [nm]</td>
<td>$R$ [-]</td>
</tr>
<tr>
<td>D +23ºC</td>
<td>+0.230 0.99</td>
<td>+0.345 0.86</td>
<td>-0.005 0.99</td>
<td>+0.320 0.99</td>
<td>-0.005 0.93</td>
</tr>
<tr>
<td>D -50ºC</td>
<td>-0.510 0.99</td>
<td>-0.550 0.94</td>
<td>-1.570 0.99</td>
<td>-0.960 0.99</td>
<td>-1.555 0.87</td>
</tr>
<tr>
<td>D +24ºC</td>
<td>+0.280 0.99</td>
<td>+0.365 0.84</td>
<td>-0.020 0.99</td>
<td>+0.395 0.99</td>
<td>-0.000 0.99</td>
</tr>
<tr>
<td>W +24ºC</td>
<td>+0.195 0.99</td>
<td>+0.360 0.85</td>
<td>-0.100 0.99</td>
<td>+0.240 0.99</td>
<td>+0.035 0.98</td>
</tr>
<tr>
<td>I -20ºC</td>
<td>-0.205 0.99</td>
<td>+0.150 0.81</td>
<td>-1.690 0.99</td>
<td>-0.595 0.99</td>
<td>-1.045 0.94</td>
</tr>
</tbody>
</table>

All sensors wavelengths values shifts for temperatures ca 23ºC are not higher than ca 0.5 nm, only the negative temperatures caused noticeable wavelength shifts. The biggest wavelength shift is for sensor $S_3$ (glued, coloured in grey) for negative temperature -20ºC and water in container – it means that the sensors due to iced environmental is highly compressed. The smallest wavelength shifts (despite temperatures levels) are for sensors $S_1$ and $S_2$ probably due to theirs ‘freedom’.

3. Results

In this paragraph the results of above-mentioned environmental conditions influence on sensors will be presented, discussed and analysed.

3.1 Climate chamber program

To achieve the goals the following climate chamber program was written (Fig. 6 and Table 3) and run. Program is divided into six (I-VI) fully automatic and controllable stages. Each climate chamber run is preceded by stage 0, in which the chamber is manually heated up to +30ºC – in order to establish controlled initial conditions for all tests. Last stage VII is fully uncontrollable – as it is the stage after chamber stops running and internal conditions are controllable naturally (no human or chamber program intervention). During all stages I-VI the relative humidity is equal to 20% or 95%, but under +10ºC the chamber do not register changes. The temperatures and time conditions are detailed presented in Table 3.
Figure 6. Climate chamber program

Table 3. Climate chamber program detailed parameters

<table>
<thead>
<tr>
<th>Stage</th>
<th>Process</th>
<th>Temperature [ºC]</th>
<th>Humidity [%]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>heating</td>
<td>to 30</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>cooling</td>
<td>to 20</td>
<td>20 or 95</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>-</td>
<td>20</td>
<td>20 or 95</td>
<td>1800</td>
</tr>
<tr>
<td>III</td>
<td>cooling</td>
<td>to -20</td>
<td>20 or 95</td>
<td>3600</td>
</tr>
<tr>
<td>IV</td>
<td>-</td>
<td>-20</td>
<td>20 or 95</td>
<td>1800</td>
</tr>
<tr>
<td>V</td>
<td>heating</td>
<td>to 20</td>
<td>20 or 95</td>
<td>7200</td>
</tr>
<tr>
<td>VI</td>
<td>-</td>
<td>20</td>
<td>20 or 95</td>
<td>1800</td>
</tr>
<tr>
<td>VII</td>
<td>heating</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In all figures (Fig. 7 – Fig. 12) below four different environmental conditions for each sensor S1-S5 as well as for temperature probe S_T are presented. Sensors, temperature probe and sample environmental conditions were as follow: program was running for temperatures as it is in Fig. 6 and Table 3 and (i) relative humidity was equal to 20% and the container was water-free, (ii) relative humidity was equal to 95% and the container was water-free, (iii) relative humidity was equal to 20% and the container was filled with water, (iv) relative humidity was equal to 95% and the container was filled with water. The mentioned-above environmental conditions in Fig. 7 – Fig. 12 marked as follow: (i) D 20% coloured in blue, (ii) D 95% coloured in red, (iii) I 20% coloured in green, (iv) I 95% coloured in magenta, where D is water-free container and I is water-filled container.

In Fig. 7 the behaviour of sensor S_1 is presented. Sensor S_1 is fully free. It is possible to observe that the changes in strains curves mapping the climate chamber program (compare with Fig. 6). Interesting is that for free sensor conditions the sensor is more sensitive to relative humidity than for dry or iced environmental. Please notice that D 95% and I 95% curves are similar to each other as the same it is possible to observe for strain curves marked as D 20% and I 20%. For all curves the moment ca 0ºC is also well visible as local disturbance.

In Fig. 8 the behaviour of sensor S_2 is presented. Sensor S_2 is woven into fibreglass textile. It is possible to observe that the changes in strains curves mapping the climate chamber program (compare with Fig. 6) only in dry cases (D 20% and D 95%).
For sensor woven into fibreglass textile being in iced conditions the strain changes (wavelength shifts) are more related to behaviour of freezing the textile than of sensor itself. It is possible to conclude that in the case the textile is stretched due to freezing process also the sensor is stretched. Strain values increased contrary to all cases with negative temperatures.
In Fig. 9 the behaviour of sensor $S_3$ is presented. Sensor $S_3$ is glued on the sample surface. It is possible to observe that the changes in strains curves mapping the climate chamber program (compare with Fig. 6), especially for iced environmental. It is easy to observe that for positive temperatures sensor responded similarly regardless of the temperature and humidity conditions. Only at a negative temperature is possible to distinguish if sensor is in dry or in iced environmental.

In Fig. 10 and Fig. 11 the behaviour of sensor $S_4$ and sensor $S_5$ is presented, respectively. Sensor $S_4$ and sensor $S_5$ are embedded into the sample. Sensor $S_5$ is embedded along shorter axis of the sample and sensor $S_4$ at an angle of $45^\circ$ to sensor $S_5$. It is possible to observe that the changes in strains curves mapping the climate chamber program (compare with Fig. 6) also for sensors embedded into the sample. In the case of embedded sensors again the problem of environment (dry, iced) is not an issue – differences in strain levels are not significant.

![Figure 10. Strain-time dependence for sensor $S_4$](image)

![Figure 11. Strain-time dependence for sensor $S_5$](image)

In Fig. 12 the behaviour of temperature probe $S_T$ is presented. The temperature probe $S_T$ stayed fully free under all measurements. It is clearly visible that the temperature probe for all environmental conditions mapping the climate chamber program (solid grey line in Fig. 12). It is possible to observe the temperature probe delays, especially for freezing and thawing processes (iced cases). Also it is possible to conclude that the freezing process is a bit shorter than the thawing one. For dry (D 20%, D 95%) cases the temperature probe tracks are almost the same as the climate chamber program track.

Detailed minimum strain and temperature values achieved by sensors $S_1$-$S_5$ and temperature probe $S_T$ under different environmental conditions are collected in Table 4. Due to the fact that for iced
environmental for sensor \( S_2 \) the freezing process affects the textile more than sensor itself (compare with Fig. 8) the results were omitted.

![Figure 12. Temperature-time dependence for temperature probe \( S_T \)](image)

**Table 4.** Maximal strains and temperature values achieved for different environmental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_4 )</th>
<th>( S_5 )</th>
<th>( S_T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>D -20°C 20%</td>
<td>-1.403</td>
<td>-2.545</td>
<td>-6.043</td>
<td>-4.877</td>
<td>-5.517</td>
<td>-17.96</td>
</tr>
<tr>
<td>D -20°C 95%</td>
<td>-1.455</td>
<td>-2.732</td>
<td>-5.920</td>
<td>-4.494</td>
<td>-4.641</td>
<td>-18.20</td>
</tr>
<tr>
<td>I -20°C 20%</td>
<td>-1.145</td>
<td>-8.440</td>
<td>-5.189</td>
<td>-6.687</td>
<td>-17.04</td>
<td></td>
</tr>
<tr>
<td>I -20°C 95%</td>
<td>-1.229</td>
<td>-9.820</td>
<td>-5.605</td>
<td>-7.384</td>
<td>-17.96</td>
<td></td>
</tr>
</tbody>
</table>

3. Conclusions

The paper presents the sensitivity and limitations of FBG sensors for different environmental conditions (positive/ negative temperature, low/ high relative humidity, dry/ iced surrounding) as well as for sensors boundary conditions (free, glued or embedded). The behaviour of all cases are detailed presented, analysed and discussed. Achieved results successfully showed that despite environmental and boundary conditions FBG sensors are an excellent tool for evaluation and assessment of composite structure as well as liquid (water). Due to the analyses carried out the limitation for application of FBG sensors can be determined in the case of future studies.

The THz spectroscopy was applied for inspection of internal structure of a composite sample with embedded FBG sensors rosette. The technique allowed to determine fibre optics locations and arrangement. The authors plan to apply the THz spectroscopy method to analyse influences of thermal and moisture influences on the sample internal structure.

Due to the promising results 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.

**Acknowledgement**

The research was supported by the project entitled: The influence of temperature and moisture interaction effect on anisotropic structures: from theory to experimental investigation (2016/23/B/ST8/03088) granted by National Science Centre in Poland.
The opinions expressed in this paper do not necessarily reflect those of the sponsors.

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