ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

# ANALYSIS OF FIBRE BRAGG GRATINGS SENSORS OPTIMAL PLACEMENT FOR MONITORING OF DAMAGE PROPAGATION IN LAMINATE COMPOSITES

**Mikhail A. Tashkinov**[1]

[1] Perm National Research Polytechnic University
Komsomolsky Ave., 29, Perm 614990, Russia
e-mail: m.tashkinov@pstu.ru

**Keywords:** Numerical models, laminate composites, damage modes, delamination, FBG sensors.

**Abstract.** *Composite materials are widely used in a broad field of applications due to their unique properties. However, development and propagation of inherent microstructural defects occurred in composites during their manufacturing or exploitation can be critical for overall performance of structural elements. Failure of composite structures can be predicted by creation of advanced monitoring systems utilizing sensor elements. One of the promising technologies is based on the optical fibre sensors with Bragg gratings, which are being embedded between the plies and can measure the changes of internal mechanical state as well as some physical properties. In order to be able to capture the growth of the defects, it is necessary to evaluate the distance between a defect and the sensor at which the latter can measure the respective state changes. This can be done by preliminary numerical modelling of defects behaviour. The scope of this work is numerical studies of the delamination growth in GFRP composite plate subjected to compression load using finite element analysis. Virtual crack closure technique was used as a computational instrument for delamination modelling. Evaluation of the damage effect on the internal strain fields was performed. Recommendation for FBG sensors positions were developed basing on specifics of strain field changes in the plies.*

# 1 INTRODUCTION

Over the past decades, the aircraft industry has significantly expanded the scope of composite materials, including polymer-based composites. The advantages of composites over traditional materials are high strength to weight ratio, high stability against fatigue loads and corrosion, possibility of manufacturing of complex-shaped parts with tailored properties. On the other hand, compared to traditional materials (aluminium and titanium alloys) applied in aircrafts, one of the factors restricting the application of composites in this area is a rather high sensitivity of these materials to microstructure damage including delamination, fibre rupture, fluid absorption, impact damage, matrix fracture, decrease in strength and stiffness at high temperatures, etc., produced by operational factors. The necessity of early detection of such defects leads to the requirement of the efficient control of the current state of structures and further maintenance for extension of their operational life.

The prospective approach for monitoring of composite structures during exploitation is connected with creation of smart-materials and smart-systems with the sensor elements, which can significantly improve the safety and reduce the maintenance costs [1]. The solution was found with the development of the technologies based on the optical fibre sensors with Bragg gratings (fibre Bragg gratings, or FBG sensors) [2-4]. Such sensors can be embedded between the layers of the material during its manufacturing and are able to measure changes of magnetic, strain and temperature fields. The sensors allow to obtain data, which, subject to the further analysis, can be used for diagnostics of damage initiation as well as for prediction of damage progression and residual life of structures.

One of the main questions is how the FBG sensors should be placed in composite structures in order to be able to register changes in mechanical and physical parameters in critical zones. Within this scope, the important task is to develop configurations of the FBG sensors network for specific composite structures under operating loading conditions.

The aim of this work is to develop recommendations concerning optimal placement of FBG sensors basing on numerical modelling of mechanical behaviour of composite laminates.

# 2 MONITORING OF COMPOSITES USING FBG SENSORS

## 2.1 Optical fibres with Bragg gratings sensors

One of the important challenges in non-destructive testing of composite structures nowadays is development of instruments which would allow continuous monitoring of structures' conditions during exploitation for timely detection of occurred damage and prevention of its propagation. The popular solution is to construct a structural health monitoring (SHM) system based on optical fibres with Bragg gratings. Fibre Bragg grating is formed by inducing a periodic modulation of the refractive index in the core of a single mode optical fibre [5, 6]. Thus, FBG filters a broadband light, which is transmitted into the fibre core, reflecting light at a single wavelength [7, 8]. The form of FBG is changing subject to external micro-mechanical loads and so does the grating spectral response. The direct application of such feature is strain measurement. The relations for transformation of the light spectrum data into mechanical characteristics are presented, for instance, in [8].

As a rule, optical fibre carries several Bragg gratings. This gives an opportunity to arrange a combination of sensing points with a single fibre, what is major advantage for creation of monitoring systems, integrated into materials.

By now, many works were devoted to investigation of possibilities of employing FBG sensors for detection of strain and temperature changes in laminate composite parts and structures [9]. Technological solutions allow the optical fibres to be embedded between the plies or to be attached on the surface. The questions of operability of such embedded fibres were also discussed – it has been proved, that fibres can stand different regimes of composite manufacturing, including autoclave forming [10].

Recent computational and experimental studies showed that embedded fibres effect on initial mechanical properties of laminate composites can be considered negligible [10, 11], what is important conclusion for the further development of SHM systems for composite structures based on FBG sensors.

### 2.2 Detecting damage using FBG sensors

The important and high-promising field of FBG sensors application is prediction of damage and failure. One of the major failure mechanisms in laminated composite structures is delamination. There are many factors that can stimulate the delamination growth, both induced during manufacturing process and appeared during exploitation, such as impact damage. Delamination is often difficult to reveal since it occurs inside the structure. Thus, the promising solution is to detect such kind of damage using the internal sensor systems.

There is a large number of research works were devoted to studying possibility of delamination and other defects detection using embedded FBG sensors [12-16]. However, due to limited sensibility of sensors, the results strongly depend on the distance between the defect and the sensor. It is necessary to understand where exactly the optical fibres as well as Bragg gratings should be positioned in the structure in order to be able to capture the critical changes of mechanical state, caused by propagating damage. This is also important for development of cost-reducing practical solutions for implementation of the sensors scheme, which gives the accurate measurement results with less number of gratings.

Preliminary numerical modelling can be performed in order to assess the non-uniform strain field near defects as well as their growth. The purpose is to study the delamination growth between the skin layers to see if the modelled defect will cause any changes in the strain field, which could be directly measured by FBG sensors.

## 3 DELAMINATION MODELLING

### 3.1 Geometrical and material properties

The subject investigated in this work was laminate composite plate made of GFRP, which represents skins of sandwich panels. It had dimensions of 50x50mm and consisted of 14 plies with 0.3mm thickness, each oriented 0 degree. The normalized mechanical properties of plies are presented in Table 1.

Initial delamination was modelled as a centred circular section with 6mm radius. An additional layer with 2mm thickness and significantly reduced mechanical properties was introduced between 5th and 6th ply of this section.

| Ex/Ez,, GPa | Ey/Ez, GPa | Ez/Ez, GPa | νxy | νyz | νxz | Gxy/Ez, GPa | Gyz/Ez, GPa | Gxz/Ez, GPa |
|---|---|---|---|---|---|---|---|---|
| 4.1 | 3.1 | 1 | 0.15 | 0.18 | 0.42 | 0.6 | 0.5 | 0.5 |

Table 1: Normalized mechanical properties of glass fibre/epoxy material.

The critical strain energy release rates were taken as presented in Table 2. The overall dimensions of the studied plate are schematically presented on Fig. 1. Compression load, equal to 45kN has been applied to the top edge of the panel.

| $G_{IC}$ , N/mm | $G_{IIC}$ , N/mm | $G_{IIIC}$ , N/mm |
|---|---|---|
| 0.07 | 0.45 | 0.45 |

Table 2: Critical strain energy release rates.

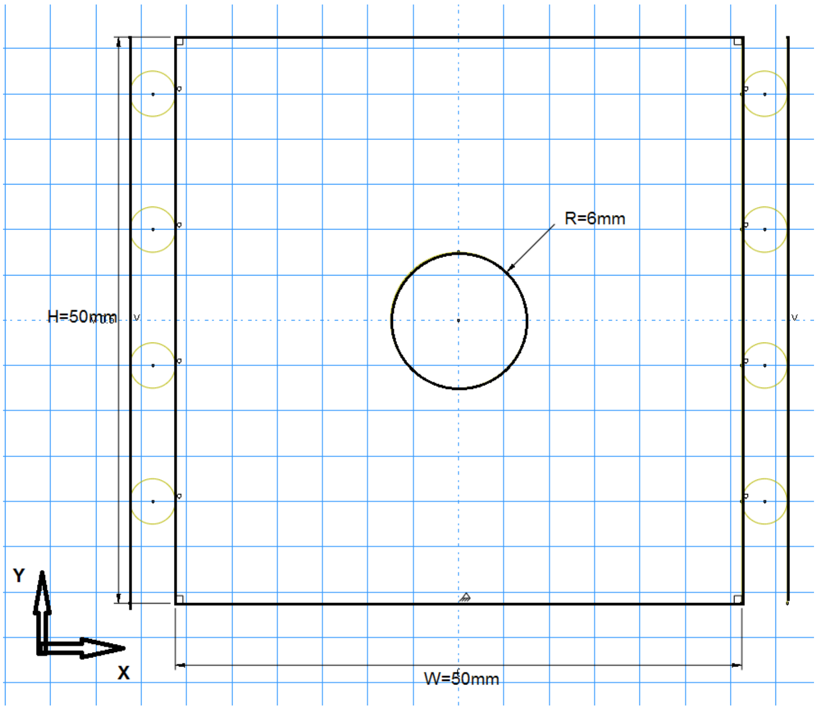



Figure 1: Graphical dimensions of the laminate panel.

### 3.2 Virtual crack closure technique

Delamination behaviour of laminated composites can be modelled using different concepts. One of the most commonly used approaches is the virtual crack closure technique (VCCT) [17], which assumes that the energy released when a crack is extended by a certain amount is the same as the energy required to close the crack. According to VCCT, the strain energy release rate can be calculated using the following relation [17]:

$$G = \frac{1}{2\Delta l}\int_0^{\Delta l} u(r)\sigma(r-\Delta l)dr\,, \tag{1}$$

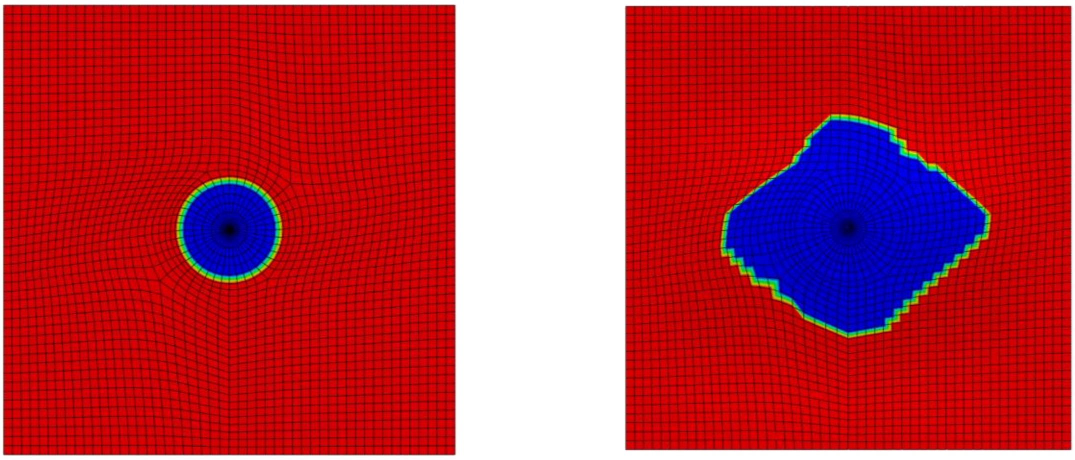
where $\Delta l$ is length at which crack is extended, $r$ is a distance from the crack tip, $u(r)$ is corresponding displacements, $\sigma$ is the stress. In general case, the crack will open when $G/G_C \geq 1$, where $G$ is calculated equivalent strain energy release rate, $G_C$ is critical equivalent strain energy release rate based on strength properties of the interface. The mixed-mode criteria can be used for calculation of critical equivalent release rate $G_C$. The Benzeggagh-Kenane model was used, which involves values for modes I, II, and III:

$$G_C = G_{IC} + \left(G_{IIC} - G_{IC}\right)\left(\frac{G_{II} + G_{III}}{G_I + G_{II} + G_{III}}\right)^n, \tag{2}$$

where $G_{IC,IIC,IIIC}$ and $G_{I,II,III}$ are, respectively, calculated and critical equivalent strain energy release rate for modes I, II and III.

## 4 NUMERICAL RESULTS AND DISCUSSION

The 3D finite element analysis was performed using shell elements. Compression loading leads to buckling of the laminate, which expedite the delamination process. The growth of the delamination between 5th and 6th layer is shown on Fig. 2.



*a* *b*

Figure 2: Growth of delamination under compression.

Each ply was analysed in order to assess the delamination effect on the strain fields. The modelled components $\varepsilon_Y$ of strain fields on the top of the plies are presented on Fig. 3 for the plies, closest to delamination.

The analysis has shown that induced delamination affect only strain fields of the nearest plies. With distancing from the delamination, the correlation between delamination and strain is becoming much less obvious due to contribution of interaction of plies between each other. This means that to detect the growing defect using direct strain field measurement, the FBG sensors need to be positioned in the vicinity of defect, not farther than 2 or 3 plies distance from the delamination.

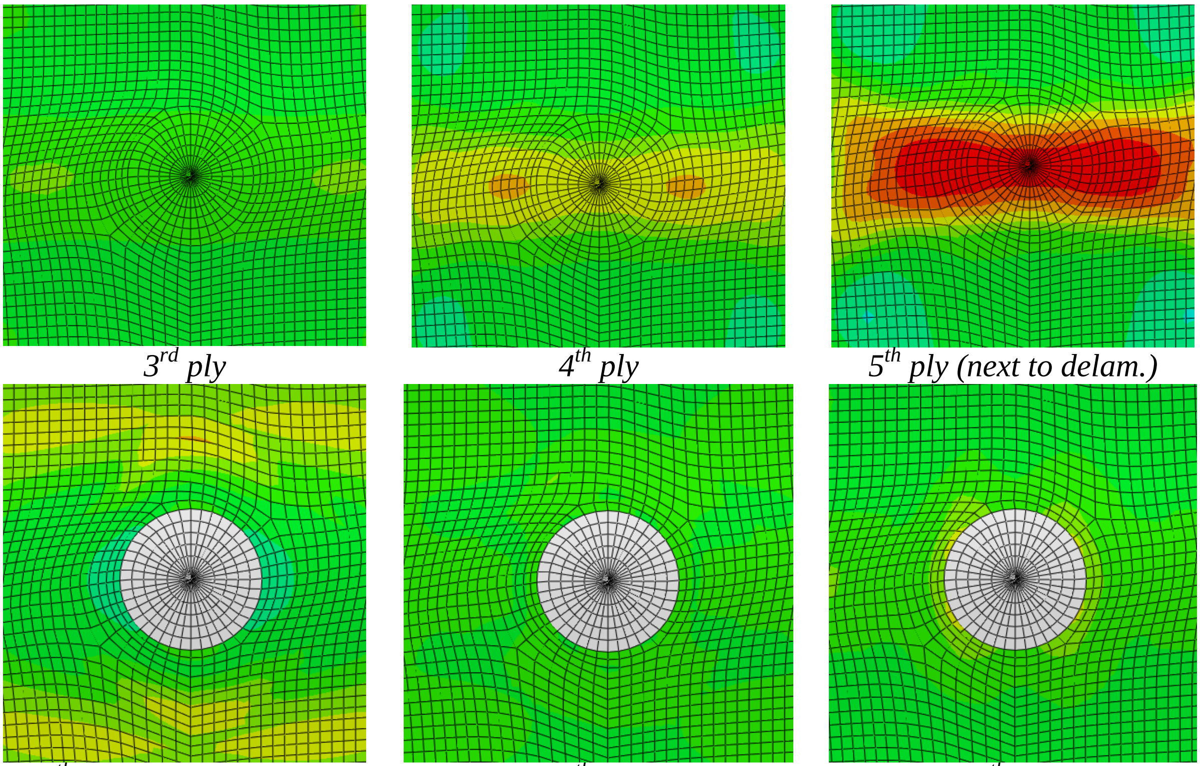



Figure 3: Strain fields in plies on the different distance of delamination. The maximum $\varepsilon_Y$ logarithmic strain value is $19\times10^{-4}$, the minimum is $-15\times10^{-4}$.

The changing of strain field in the nearest to delamination ply in dependence of growing compression load is shown on Fig. 4. For the studied case, the strain field homogeneity was influenced on the distance of approximately three radius of the initial delamination. At the same time, the delamination brings inhomogeneity to the strain field of the nearest ply at loading values between 20 and 30 kN, which means that correctly placed FBG sensors can detect the early stage of its growth. It should be noted that Bragg gratings can output the incorrect data if they will be affected by debonding process.

In order to avoid dense sensor network, monitoring of delamination in complex composite structures using mechanical characteristics, interpreted from FBG sensors data, can be reliable only for preliminarily determined critical zones, where possibility of defect emergence is predicted. Further studies are required for developing of effective FBG sensors-based monitoring system, which would be able to response on accidentally caused damage or manufacturing-induced defects.

There are also several other approaches, connected with damage detection irrelatively of direct displacements and strain measurement. For instance, Takeda et al. [18], proposed approach that is aimed to find a correlation between the obtained form of spectrum, reflected from Bragg gratings, as well as the intensity ratio of spectrum peaks to the delamination length. In practical implementation, the difficulty of such method is distortion of the spectrum caused by inhomogeneity of the strain field near the defect. This could be tackled by using multiplexed short FBG sensors, which allow to restore quasi-continuous strain profiles along the sensor [18, 19].

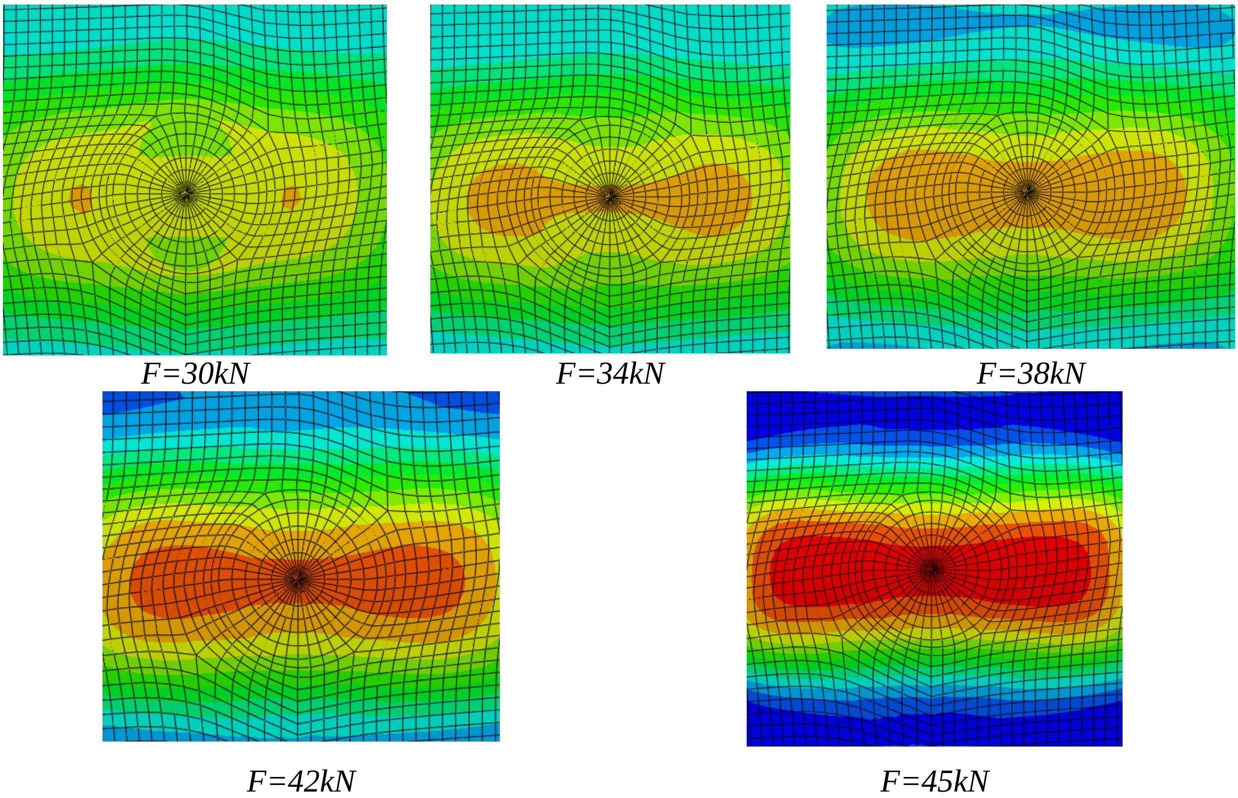



Figure 4: Strain field changing in the 6th ply, in dependence on applied compression force *F*. The maximum $\varepsilon_Y$ logarithmic strain value is $19\times10^{-4}$ , the minimum is $-15\times10^{-4}$ .

## 5 CONCLUSIONS

- The problem of the delamination detection in composite laminate structures using the embedded optical fibres sensors with Bragg gratings was examined.
- Modelling of delamination in composite laminate panel was performed using VCCT in order to analyse the effect of defect growth on the strain field in the internal plies.
- Some conclusions were made regarding the optimal placement of the fibres which would allow to detect the damage propagation using the mechanical data interpreted from FBG sensors.
- The obtained numerical results can be used further to control the adequacy of experimental data collected from embedded FBG sensors.

## ACKNOWLEDGEMENTS

The research was performed at the Perm National Research Polytechnic University, with the support of the Russian Science Foundation (project №15-19-00243). Computations were performed at Institute of Continuous Media Mechanics of Russian Academy of Science.

## REFERENCES

[1] Daniel F.O. Braga, S.M.O. Tavares, Lucas F.M. da Silva, P.M.G.P. Moreira, Paulo M.S.T. de Castro, Advanced design for lightweight structures: Review and prospects,

*Progress in Aerospace Sciences*, **69**, 29-39, 2014, http://dx.doi.org/10.1016/j.paerosci.2014.03.003.

[2] K.I. Tserpes, V. Karachalios, I. Giannopoulos, V. Prentzias, R. Ruzek, Strain and damage monitoring in CFRP fuselage panels using fiber Bragg grating sensors. Part I: Design, manufacturing and impact testing, *Composite Structures*, **107**, 726-736, 2014, http://dx.doi.org/10.1016/j.compstruct.2013.09.053.

[3] Jeannot Frieden, Joël Cugnoni, John Botsis, Thomas Gmür, Dragan Ćorić, High-speed internal strain measurements in composite structures under dynamic load using embedded FBG sensors, *Composite Structures*, **92** (8), 1905-1912, 2010, http://dx.doi.org/10.1016/j.compstruct.2010.01.007.

[4] Fabiano Colpo, Laurent Humbert, John Botsis. Characterisation of residual stresses in a single fibre composite with FBG sensor, *Composites Science and Technology*, **67**, 1830–1841, 2007.

[5] Jian Cai, Lei Qiu, Shenfang Yuan, Lihua Shi, PeiPei Liu and Dong Liang. *Structural Health Monitoring for Composite Materials, Composites and Their Applications*, Prof. Ning Hu (Ed.), InTech, 2012.

[6] Loayssa A. Optical Fiber Sensors for Structural Health Monitoring. In: Mukhopadhyay S. (ed.) *New Developments in Sensing Technology for Structural Health Monitoring*. Heidelberg: Springer-Verlag; 335-358, 2011.

[7] Ramzyzan Ramly, Wahyu Kuntjoro, Mohd. Kamil Abd. Rahman, Using Embedded Fiber Bragg Grating (FBG) Sensors in Smart Aircraft Structure Materials, *Procedia Engineering*, **41**, 600-606, 2012, http://dx.doi.org/10.1016/j.proeng.2012.07.218.

[8] L. Sorensen, *The response of embedded FBG sensors to nonuniform strains in CFRP composites during processing and delamination*, EPFL, 2007.

[9] KSC Kuang, WJ Cantwell, Use of conventional optical fibers and fiber Bragg gratings for damage detection in advanced composite structures: A review, *Appl Mech Rev*, **56**, (5), 493-514, 2003.

[10] Guemes, J.A., Mcnendez, J.M., Frovel, M., Fernandez, L, Pintado, J.M.. Experimental analysis of buckling in aircraft skin panels by fibre optic sensors. *Smart Materials & Structures*, **10**(3), 490-496, 2001.

[11] Carrion. G., Frovel, M., Pintado. J.M., Cabrerizo, F.. Extensive characterisation of the intrusiveness of fibre Bragg grating sensors embedded in a carbon fibre reinforced polymer. In: *4th European Workshop on Structural Health Monitoring*, 2008.

[12] E. Farmand-Ashtiani, J. Cugnoni, J. Botsis, Monitoring and characterization of the interfacial fracture in sandwich composites with embedded multiplexed optical sensors, *Composite Structures*, **96**, 476-483, 2013, http://dx.doi.org/10.1016/j.compstruct.2012.08.059.

[13] G. Pereira, C. Frias, H. Faria, O. Frazão, A.T. Marques, On the improvement of strain measurements with FBG sensors embedded in unidirectional composites, *Polymer Testing*, **32**(1), 99-105, 2013, http://dx.doi.org/10.1016/j.polymertesting.2012.09.010.

[14] Xuefeng Zhao, Jihua Gou, Gangbing Song, Jinping Ou, Strain monitoring in glass fiber reinforced composites embedded with carbon nanopaper sheet using Fiber Bragg Grating (FBG) sensors, *Composites Part B: Engineering*, **40**(2), 134-140, 2009, http://dx.doi.org/10.1016/j.compositesb.2008.10.007.

[15] Christopher K.Y. Leung, Zhenglin Yang, Ying Xu, Pin Tong, Stephen K.L. Lee, Delamination detection in laminate composites with an embedded fiber optical interferometric sensor, *Sensors and Actuators A: Physical*, **119**(2), 336-344, 2005, http://dx.doi.org/10.1016/j.sna.2004.10.007.

[16] Prabhugoud. M.. Peters, K.. Efficient simulation of Bragg grating sensors for implementation to damage identification in composites. *Smart Materials & Structures*, **12**(6), 914-924, 2003.

[17] Rybicki, E.F., Kanninen, M.F., A Finite Element Calculation of Stress Intensity Factors by a Modified Crack Closure Integral, *Engineering Fracture Mechanics*, **9**, 1977.

[18] S. Takeda. S. Minakuchi, Y. Okabe, and N. Takeda. Delamination monitoring of laminated composites subjected to low-velocity impact using small-diameter FBG sensors. *Composites Part A-Applied Science and Manufacturing*, **36**, 903-908, 2005.

[19] D. S. Canovas, *Advances in fibre Bragg grating sensors for damage detection in composite laminates: application in quasi-static and fatigue delamination tests*, Universitat de Girona, 2013.