Determination of fatigue properties of 3D composite structure in bending and shear

Jiří Had, Milan Dvořák, Milan Růžička

?

Abstract—**An experimental investigation of fatigue properties of a novel type of composite structure is described in this paper. Five specimens were made from the so-called 3D carbon composite, with integrated Fiber Bragg Grating sensors. Fatigue tests were carried out to evaluate suitability of these sensors for structural health monitoring of 3D structures. 3D composite structure consists of combination of two materials for which S-N curves were measured. Comparison S-N curves of these basic material itself with final 3D composite structure was done. Fractography analysis was performed above failed samples and contribution of built par was analyzed.**

Index Terms—**3D composite, FBG sensors, fatigue, S-N curve**

INTRODUCTION

THE article is focused on experimental work performed on a novel type of the so called three dimensional (3D) composite. The advantages of the 3D composite are the much higher interlaminar shear strength and stiffness in comparison to the thick unidirectional composite part. These 3D composite parts are primarily used in complex thick-walled composite structures, for example spindle beams in machine tool applications [1]. Previous works were focused on the determination of material constants and elastic stiffness for finite element models of material ([2], [3]). Verification of material parameters of the 3D composite was performed using tensile, compression, three point bending (3PB) quasi-static tests and Iosipescu shear test of various specimens from the Carbon/Epoxy 3D composite [5]. Experimental results are compared with the calculations performed using homogenization technique.

Simple beam-shaped specimens and bending loading were used for experimental testing of fatigue. According to the main assumption of homogenization technique (properties of each representative volume element of the 3D composite are the same, as for the whole area filled by the 3D composite) a pure strain field was required. This assumption was not entirely fulfilled during the experiments, especially in the case of the often used 3PB test, because of the stress concentrations in places, where the active part of the loading device (support) is in contact with the specimen surface. Carbon fibres are very brittle in the direction perpendicular to the longitudinal axis, so the 3PB test configuration was not suitable for cyclic loading. Therefore a new test configuration was designed as four point bending (4PB) test using a hydraulic testing actuator. The 4PB configuration gives advantage of reducing the pressure under the supports and a constant bending moment between the supports of active part of the loading device. Maximal loading is therefore spread into larger area and damage phenomenon isn't so localized like in 3PB configuration.

Fibre Bragg Grating (FBG) sensors were integrated into the 3D composite structure to verify their suitability for structural health monitoring of parts made from such structure. The technique of manufacturing of the wounded carbon composite structures with integrated FBG sensors was adapted from the preceding works [4]. Different positions of the optic sensor were tested to verify optimal position for measurement such material integrated in a complex structure.

Fatigue properties are very needful in design point of view. The 3D composite structure is made from several building parts which each has own purpose itself. Fatigue properties of each building material were tested and compared with the final structure to demonstrate his advantage. Comparison was based on S-N curves measured on beam samples.

Determination of mode of failure is also important part of resulting knowledge. Rapture area of unidirectional composite from high strength fiber and high modulus fiber can get its contribution during failure of complex 3D composite structure. Fractography analysis over rapture area can get advantages or disadvantages of dividing 3D structure into smaller pieces.

I. STRUCTURE OF 3D COMPOSITE CELLS

The requirements for high performance composite structures, e.g. ultra-high stiffness, sometimes lead to the design of composite parts with thick-walled reinforcing members. For loading conditions in one dominant direction, it is necessary to orient maximum number of fibers in this direction. The very low shear static and fatigue strengths of such structures often limit their application. For example, to achieve maximum bending stiffness, axially oriented high

? ? Manuscript received December1, 2011, accepted December 20, 2011. This work was supported by the Grant Agency of the Czech Republic number 101/08/0299 and 101/08/H068. This work was also supported by Ministry of Education, Youth and Sports of Czech Republic by grant No. 1M0507.

Jiří Had, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic, (e-mail: jiri.had@gmail.com)

Milan Dvořák, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic, (e-mail: Milan.Dvorak@fs.cvut.cz)

Milan Růžička, Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic, (e-mail: Milan.Ruzicka@fs.cvut.cz)

modulus fibre tows should be used. However, due to low strength of the composite matrix and a multiaxial stress state, cracks arise in several points between the fibres (thick-walled pultruded composite flanges), or delamination occurs between laminas (laminated composite plates).

An increase of inter-laminar shear strength is usually solved by various lamination techniques, such as stacking optimization of the composite layers, or the use of sandwich structures. This problem can also be solved technologically. Three-dimensional, fabric and 3D strengthening (transversal needling) can improve or partially eliminate delamination or matrix cracking. However, these techniques lead to a rapid decrease in stiffness in the dominant load direction.

Filament fibre winding technology with subsequent moulding was used to manufacture a three-dimensional fibre cell structure (see Fig. 1). This technology was developed by CompoTech Company Ltd, in research cooperation with the Czech Technical University in Prague. The main application of these 3D structures is for thick-walled or nearly solid beams with maximum bending strength (spars, wing flanges etc.) or with high stiffness (e.g. a spindle beam for the use in a machine tool). Example of such developed spindle beam can be seen in Fig. 2.

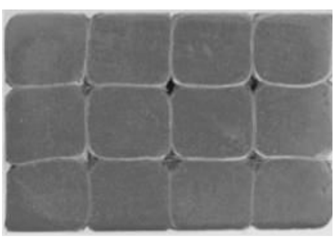

Fig. 1: Example of the 3D composite structure

Fig. 2: Cross section of a spindle beam based on the 3D composite structure

This bio-inspired structure in its cross section (in the y-z plane) creates sub-cells with a volume fraction of up to 75% axial fibers, see Fig. 3. The sub-cells consist of carbon fiber tows with axial orientation (axis x). The diameter of this bundle is usually between 4 and 8 mm.

In the next step, another thin layer is wound around this axially oriented core. The winding is created in the thickness between 0.2 and 1 mm. The thickness can be optimized, as well as the orientation of the winding fibers, which can vary from 0 to 89 degrees. The prefabricated bundles are then put into the form, moulded together and subsequently cured into the final shape.

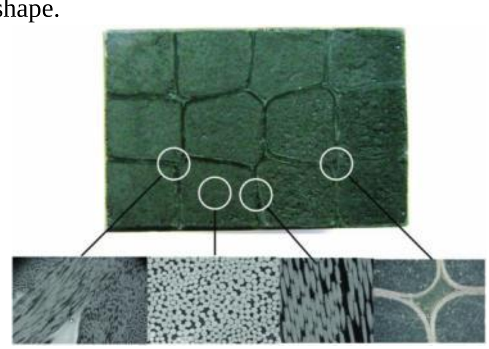

Fig. 3: Details of the parts of the 3D composite structure

II. SPECIMENS MANUFACTURING

To compare 3D composite structure with unidirectional composite, both 3D composite structure and pure unidirectional composite samples were made. Two types of 3D composite structure were made with different core material. Unidirectional composite samples were done from 2 types of core's material and one type of winding's material.

All specimens were made in a shape of beam, with dimensions 20 x 30 x 700 mm. The uniaxial fiber tows in core were made from the Nipon Granoc Yarn CN-80 or Mitsubishi Dialed K63712 pitch based ultra-high modulus carbon fibers. Their over-winding layer was made from the Toray T700 high-strength carbon fibers, with the orientation to the longitudinal axis in the range from 85 to 86 degrees. The matrix was the Hybtonite anhydride resin. Basic static properties are in the Table 1.

Table 1. Material data

Material		E_L [GPa]	E_T [GPa]	G_{LT} [GPa]	n_{LT} [-]
PAN	T700	235	15	50	0.30
PITCH	K63712	640	5	20	0.35
PITCH	CN-80	780	7	-	-
Anhydrid	Hybtonit	3	3	1.1	0.4

Fiber optic sensor was integrated into the 3 samples in a position depicted on Fig. 4

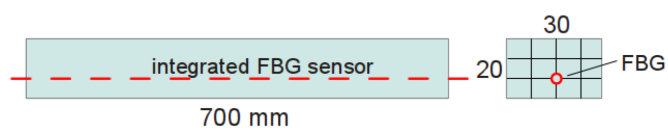

Fig. 4: Scheme of the specimen with main dimensions

FBG sensor is located in the middle of the specimen length, in the resin pocket in the interface between the sub-cells. Ingress point of the fiber is protected by using a small-diameter PTFE tube. Two types of fiber coating materials (polyacrylate and Ormocer®) were used to compare their properties during the embedding process and to determine possible difference in their fatigue life. In some cases FBG sensor was placed on the surface of the sample collaterally with strain gauge.

III. EXPERIMENT DESCRIPTION

Fatigue experiments were carried out using a standalone hydraulic actuator IST-PL40N with the 40 kN loadcell and the displacement range up to 125 mm (see Fig. 5). Specimens were loaded using the 4PB loading device, which consists of two parts. The passive part with the support span of 600 mm is fixed to the loading frame. The active part with the support span of 200 mm is connected through a ball joint to the hydraulic actuator (see Fig. 6). The specimens were loaded by force controlled load with the frequency of 5 Hz until the final fracture. Changes in stiffness of the specimen were evaluated from the quasi-static loading to F_{MAX}. Breaks were repeated during loading approximately every 20000 cycles. The loading level was derived from the preceding quasi-static 4PB test and fatigue cyclic level was about 65% to 85% of static strength.

Fig. 5: 4PB experiment configuration

Fig. 6: Detail of the specimen and the active part of the 4PB loading device

During the experiments, the following measuring configuration was used:

The multichannel measuring device HMB Spider8 was used to capture signal from the strain gauges (one or two pieces of HBM 1-LY11-6/350), the PT100 thermometer and force plus movement from the hydraulic actuator. The signal was captured with the frequency from 50 to 100 readings per second.

The two-channel optical interrogator Safibra FBGuard was used to capture signal from the FBG sensor (length of grating of about 8 mm, polyacrylate or Ormocer® coating, central wavelength from 829 nm to 848 nm). The sampling frequency of 70 readings per second was used.

Dakel Xedo acoustic emission analyzer was used to capture data from four pieces of the AE sensors IDK-09 (ceramic type, diameter 6 mm) with preamplifiers AS-3.

The strain gauges were placed on the specimen surface, collocated to the FBG sensors in the centre of the specimen (see Fig. 7). The acoustic emission sensors were used as well to help recognize the beginning of the specimen degradation.

Fig. 7: The specimen for the 4PB test, equiped with the acoustic emission sensors (marked AE) and strain gauge (marked SG). Supports are marked with S, loading points are marked with L

IV. DAMAGE MONITORING

Six specimens were tested so far. Each specimen was tested until the final rapture on the same loading level. One of the tested specimen was loaded on the lower loading level to compare strain sensors on long-term basis.

It was found that FBG sensor integrated in the resin pocket area of the 3D composite structure is not suitable for structural health monitoring of such structure. It is caused by cracking of the epoxy matrix. Strain transfer to the FBG sensor is limited, therefore lower strain readings from sensors are indicated [6].

In the next step, it will be necessary to integrate the FBG sensor directly into the uniaxial fiber tows.

Strain readings (from strain gauges and FBG sensors), acoustic emission readings, temperature readings, loading force and movement from testing actuator's loadcell were obtained. Change of stiffness during loading together with deflection of beam is depicted in following graph (see Fig. 8).

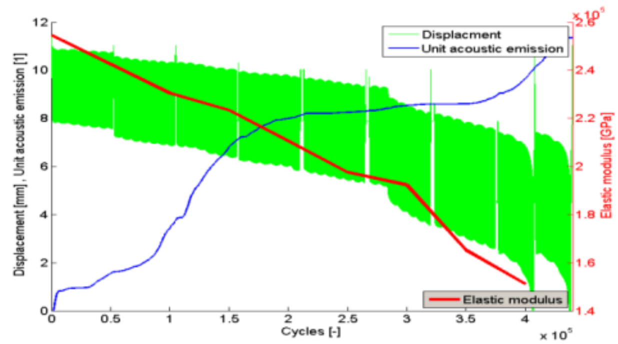

Fig. 8: Deflection of beam, elastic modulus and acoustic event counts during the specimen life (spec. no. 4)

Cumulated signal of acoustic events during the loading is indicating rate of growing damage inside of specimen. Comparison of strain ranges measured by the surface mounted SG and the integrated FBG can be seen in Fig. 9.

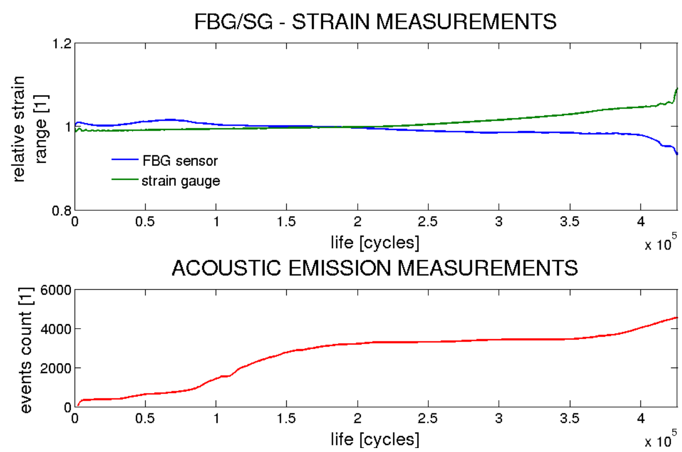

Fig. 9: Comparison of strain range SG and FBG sensor

Other conclusion can be made from comparison of sensors glued on a surface of the specimen, see Fig. 10. Sensitivity of FBG sensor to strain amplitude is higher than the strain gauge in the case of long term fatigue test, aprox. 10^6 cycles. Strain gauge shows only nonsignificant rate of strain contrary to clear trend in the case of FBG. Moreover some of the strain gauges even haven't survived whole time of experiment, especialy the HBM 1-LY11-10/350 type. Strain gauge HBM 1-LY11-6/350 was used in the subsequent tests.

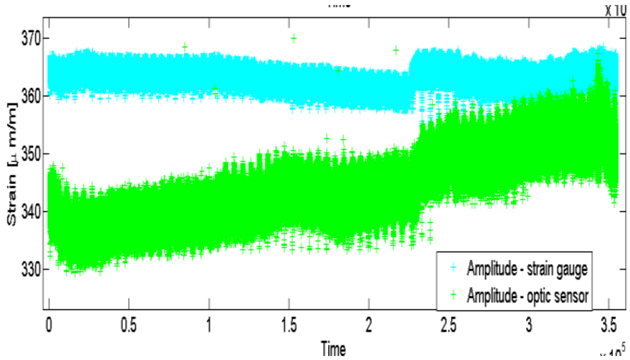

Fig. 10: Comparison of amplitude of strain from SG and FBG sensor (both sensors on surface)

V. FATIGUE LIFE TESTING

A two basic 3D configurations of the hybrid structures (3D structure CN80/T700 and K63712/T700) were compared with the equivalent specimen made without cells structure and containing unidirectional fibre tows only (1D structure), i.e. with sample from material T700, K63712 and CN80. Stress level of fatigue loading for testing residual strength was set from aprox. 65% up to 85% of static strength. S-N curves of 3D structure and unidirectional samples are in Fig. 11-13.

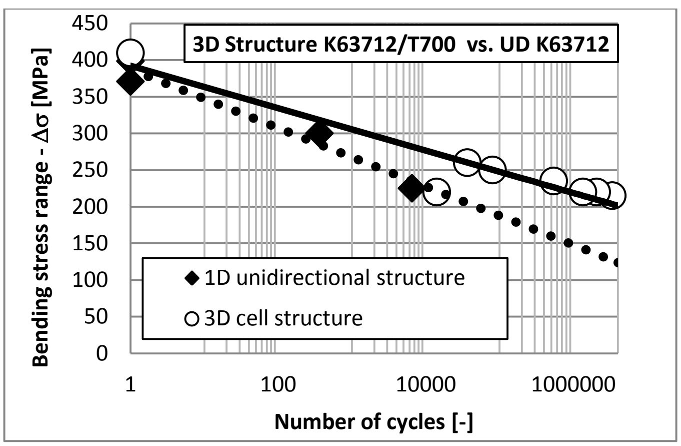

Fig 11: Fatigue properties of the hybrid 3D cell structure K63712/T700

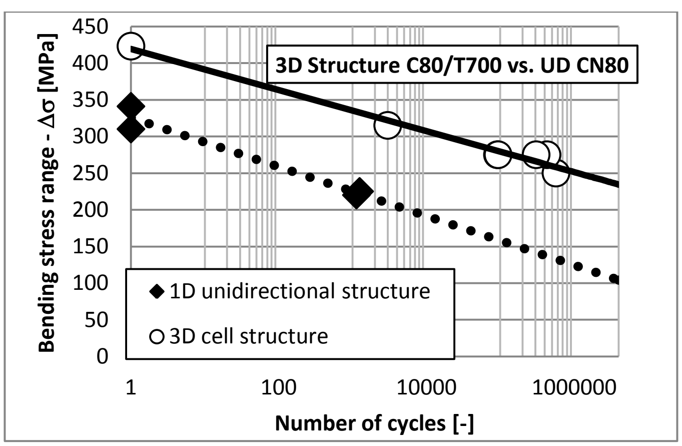

Fig 12: Fatigue properties of the hybrid 3D cell structure CN80/T700

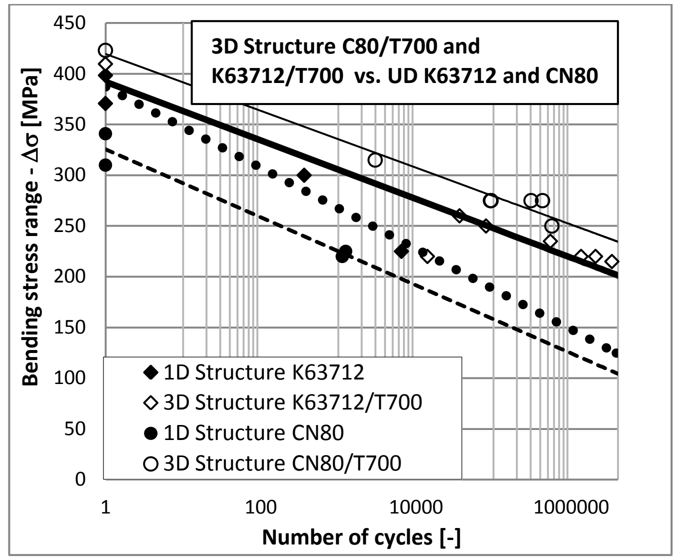

Fig. 13: Comparison of the fatigue properties of the hybrid 3D cell structures - CN80/T700 and K63712/T700

The 3D cell structure has higher static strength than the unidirectional 1D configuration, significantly for CN80/T700 cell fibre combination. Similar trends can be observed in the S-N curves. Range of the fatigue stresses is much higher for 3D structure as for the 1D configuration. For the K63712/T700 cell fibre combination the benefit on the fatigue limit (on $2 \cdot 10^6$ cycles) is about 28 % and for the CN80/T700 cell fibre combination even up to 85 %. Comparison of all discussed S-N curves can be seen in Fig. 15. The slopes of the approximated S-N base lines are very close together for all curves and statistic values of the S-N curve exponent for all curves give the exponent m=13.26 ±0.71.

VI. FRACTOGRAPHY ANALYSIS

Analysis of failed sample gets answer to causes of final rapture and contribution of each individual part. There are different types of material and different type of mode of failure has to be expected. Example of failure area of the sample HM-K63712/T700 is on the Fig. 14. Area of the compressive and tensile failure is figured out there. It's clearly evident much more significant compressive failure in the figure. A skewed fracture plane is in every cell caused by compressive mode of failure.

Fig. 14: Rapture area of the sample K63712/T700

Comparing failure unidirectional composite with high strength (Fig. 15) and high modulus fiber (Fig. 16) there is a obviously different mode of failure.

Fig. 15: Rapture area of the sample with high strength fiber T700

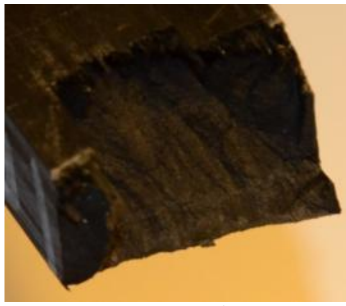

Fig. 16: Rapture area of the sample with high strength fiber K63712

Documented failures came from failure loading. There is no difference between failure mode based on static failure and fatigue failure. This state is proved by fractography analysis on SEM on fracture area.

Further analysis based on SEM observation proves advantage of dividing cross-section into smaller domains. Failure is then localized only in each cell and crack is stopped by boundary of winding, see Fig.17 and Fig.18.

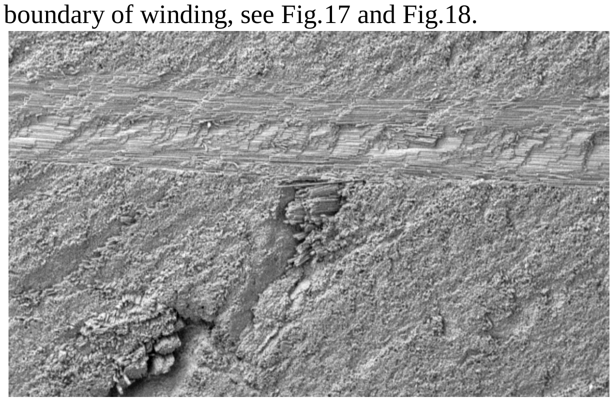

Fig. 17: Growing rapture from core to winding boundary of the sample K63712/T700

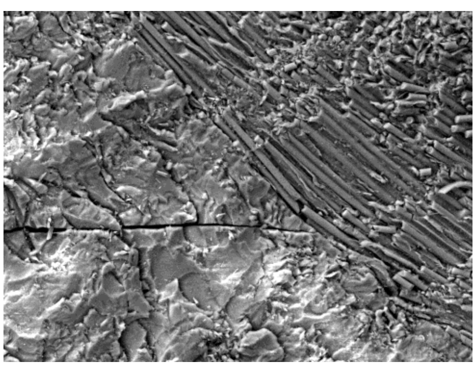

Fig. 18: Growing crack from resin between cell to winding boundary of the sample K63712/T700

VII. Conclusion

Different analyses were performed to determine measurement possibilities and fatigue properties of 3D composite structures. Strain readings from the FBG sensors integrated into the resin pockets between the carbon fiber tows were found to be unreliable, similarly as in case of strain gages. FBG sensors installed on the surface of the specimens are provided more apparent trend in a change of strain range than strain gages. Another advantage is their performance during the long term fatigue tests.

Measured fatigue properties get fundament knowledge about 3D hybrid composite and get basic introduction into microanalysis such structure and comparing of S-N curves advantages of 3D composite over unidirectional composite has shown. Besides this purpose of using windings layer was proved by fractography analysis.

Acknowledgment

The authors would like to thank the Ministry of Industry and Trade of the Czech Republic for the support of this research within projects no. 101/08/H068 and 101/08/0299. This work was also supported by Ministry of Education, Youth and Sports of Czech Republic by grant No. 1M0507. Support from the CompoTech Plus Company in manufacturing the composite specimens is also gratefully acknowledged.

References

[1] Uher, O., Smolík, J., Růžička, M.: " Novel concept of three-dimensional thick composite structure made from pitch based carbon fibre for machine tool applications" in Proceeding of the 17th International Conference on Composite Materials, Edinburgh, UK (27-31 July 2009).

[2] Růžička, M., Kulíšek, V., Had, J., Prejzek, O. 2009. "Determination of elastic constants of novel concept 3D composite" in Bulletin of Applied Mechanics, Vol 5, No 19, ISSN 1801-1217.

[3] Růžička, M., Kulíšek, V., Had, J., Prejzek, O. 2009. "Finite Element and Experimental Study of Novel Concept of 3D Fibre Cell Structure", in Proceedings of 17th ICCM, Edinburgh, United Kingdom (27-31st July 2009).

[4] Růžička, M., Uher, O., Blahouš, K., Kulíšek, V., Dvořák, M. 2007. "Integrated High Performance Joint In Composite Vessels" in Sixteenth International Conference on Composite Materials, Japan Society for Composite Materials, Kyoto, pp. 1400-1401.

[5] Had, J., Růžička, M., Kulíšek, V. 2010. "Stiffness Study of Novel Concept of 3D Composite Structure" in Proceeding of Mechanics of Composite Materials, Riga, Latvia (24–28. October 2010).

[6] Dvořák,M., Had, J., Růžička, M., Pošvář, Z.: "Monitoring of 3D Composite Structures Using Fiber Optic Bragg Grating Sensors", in Proceedings of the 8th International Workshop on Structural Health Monitoring, Stanford University, Stanford, 2011, vol.2, ISBN No. 978-1-60595-053-2,pp. 1595-1602, DEStech Publications.