M. Ciminello, P. Bettini, S. Ameduri, A. Concilio
Circular Patch Sensor Based on Distributed Fiber Optic Technology for Tensile and Bending Loads Identification
IEEE Sensors Journal, Vol. 17, N. 18, 2017, p. 5908-5914
doi:10.1109/JSEN.2017.2733619

Smart Patch Sensor for Load Identification

M. Ciminello, P. Bettini, S. Ameduri, A. Concilio

***Abstract*—The design, manufacturing and preliminary testing of a smart patch sensor named MonitoRing, are herein presented. The sensor is conceived to identify amplitude and direction of structural loads by distributed strain profile detection along its circular geometry. The sensor is manufactured by using flexible glass/epoxy laminates hosting a single standard telecom fiber optic. The fiber optic is embedded according to three loops, different by radius and quote. The sensor is then externally bonded on a structural element and able to follow the deformations under tensile and bending loading condition. The optical Rayleigh backscattering technology provide an interrogation of strain with high spatial resolution all along the fiber path. The load and direction identification is hence, provided by comparing amplitude, phase and sign of deformation spectrum of each loop. Preliminary numerical and experimental result, are reported and analyzed for simple test cases.**

***Index Terms*— Fiber optic, Load monitoring, Smart systems.**

I. INTRODUCTION

The evolution in aircraft industry highlights the importance of technology innovation as a factor of competitive advantage. Energy-saving, environmental compatibility, reliability and economic factors are becoming increasingly important, hence new developments in research and application have moved towards more accurate analysis methodologies, the realization of inspection procedures, the optimization of manufacturing processes and the use of new materials. Multifunctional systems have fundamental importance because they could detect defects and damage/degradation of structures during their service life, minimise effects due to unusual load conditions, reduce fatigue effects and unwanted vibration conditions. In this way, structural systems could be inspected since the manufacturing step. The scientific community is investigating different types of techniques and features able to monitor the health status of structures. Smart Structures with embedded sensors and actuators are able to monitor physical environments, to collect and interpret data and then, properly, react to changes. Smart Structures technologies may be successfully applied to Structural Health Monitoring (SHM) targets by implementing the continuous observation of even complex structural systems by using integrated sensors, whether bonded or embedded [1].

Among the various parameters, the knowledge of the external loads may be essential to understand the structural system evolution during its operational life. This understanding may enable the assessment of the damage levels after the occurrence of certain events and the statement of an updated estimation of the remaining lifetime. Direct measurements of the actual operational loads are very difficult and cost consuming but, in some cases, they can be derived by information connected to the structural response [2], identified by dedicated transducers [3, 4], able to measure strain and displacement fields.

The MonitoRing [5, 6], the authors previously developed for high displacements measurements within morphing applications scenario, is proposed in this paper with an innovative layout, for the preliminary identification of simple loading conditions. In this paper, the attention is devoted to the implemented methodology. The manufacturing process is also reported and details are given to the realisation of the test rig for the experimental campaign. Finally, the results gathered in laboratory are analysed and discussed.

II. METHODOLOGY AND MANUFACTURING

A. Methodology

A scheme of the MonitoRing is illustrated in Figure 1. The device consists of a circular laminated structure made of glass reinforcing fibers in which a single fiber optic is embedded in three different loops. Two loops lays in the same ply but having different radius; another loop is arranged at a higher quote (Figure 1a). This layout is designed to allow detection of different structural loads (Figure 1b). Normal stress is characterized by the same strain distribution in the cross section hence, upper and the lower fiber optic loops will detect the same deformations. A pure bending action induces, on the other hand, a linear strain distribution along the cross section, hence the fiber optic loop laying at different quote will provide different deformations. In this paper, the MonitoRing is realized according to a specific manufacturing process, an original test rig for normal and bending excitation is also

---

Manuscript received May 20, 2017.

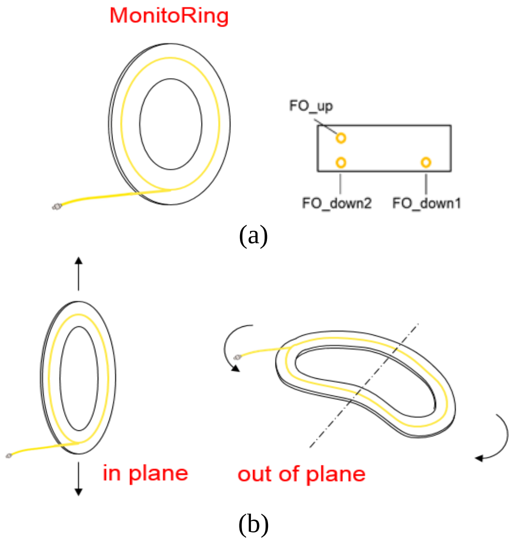
M. Ciminello is with the Italian Aerospace Research Center, Adaptive Structures Department, Via Maiorise snc, Capua, 81043 Italy (0039-0823-623535; e-mail: m.ciminello@cira.it).

P. Bettini is with the Politecnico of Milano, Department of Aerospace Science and Technology, Milano, Italy (0039-02-23998033; e-mail: paolo.bettini@polimi.it).

S. Ameduri is with the Italian Aerospace Research Center, Adaptive Structures Department, Via Maiorise snc, Capua, 81043 Italy (0039-0823-623556; e-mail: s.ameduri@cira.it).

A. Concilio is with the Italian Aerospace Research Center, Adaptive Structures Department, Via Maiorise snc, Capua, 81043 Italy (0039-0823-623342; e-mail: a.concilio@cira.it).

designed and assembled. The numerical and experimental test campaign follows for data correlations.



(a)

(b)

Figure 1: Scheme of MonitoRing: cross section (a); in plane and out of plane behaviors (b).

In this application, optical instrumentation based on Rayleigh backscattering is used. This physical phenomenon is an elastic process caused by the interaction of the light wave with the fiber silica impurities. They are associated with losses in the light transmission (Rayleigh loss) and represent a sort of “mark”, unique for each single fiber, frozen into the glass when it is cooled during fabrication. Such an inhomogeneity can be advantageously used to measure distributed losses and gains, induced stresses and strains, temperature and local birefringence [7]. As the light travels within the optical fiber, a small portion is scattered back in a diffusive manner and is again guided in the fiber core. By taking advantage of the uniqueness of this characteristic and the modulations caused by imposed deformation, the resulting amplitude and direction of the load field can be retrieved [8].

B. *Manufacturing*

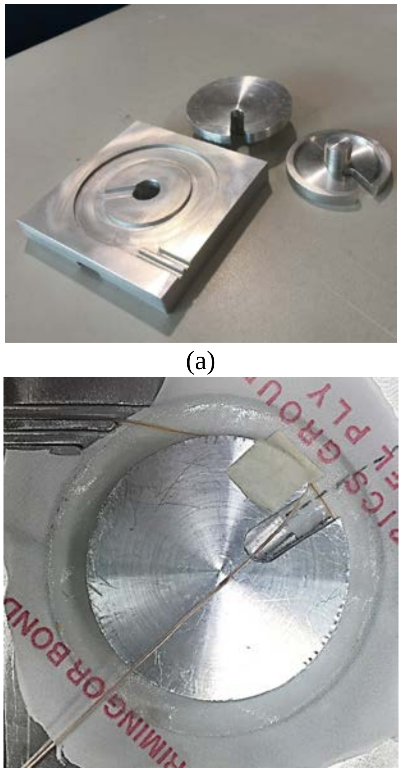
The main features of the MonitoRing are summarized in Table I. The ring geometry is defined to ensure a good flexibility while guaranteeing the proper integration of the optical fiber.

The ring is made of eight plies of a very thin fabric pre-preg (SAATI SEAL EE48 ET445 43%, 0.05 mm thick). The quasi-isotropic lamination sequence [0/45/-45/90]s determines a good in-plane homogeneity in terms of both stiffness and strength. The lay-up symmetry limits the component distortion and reduces the deformations coupling, especially between the layers where the fibers are embedded. Moreover, this configuration maximizes the mechanical properties along all the directions. A special mould (Figure 2) equipped with a flexible counter mould is adopted to ensure a good compaction and to provide net shape to the composite ring. The action of the counter mould permits to minimize void contents around FOs and prevents the leakage of the resin in excess during curing cycle (performed in oven vacuum assisted).

TABLE I
MONITORING MAIN FEATURES

Symbol	Quantity	Value
-	Ring material	Glass/epoxy
t	Ring thickness	0.4 mm
d_o	Outer diameter	80 mm
d_i	Internal diameter	50 mm
$E1$	Elastic moduli	20.7 GPa
$E2$	Elastic moduli	20.7 GPa
$E3$	Elastic moduli	7.6 GPa
$G12$	Shear moduli	3.7 GPa
$G31$	Shear moduli	1.84 GPa
$G23$	Shear moduli	1.84 GPa
$\nu12$	Poisson coefficient	0.16
$\nu13$	Poisson coefficient	0.34
$\nu23$	Poisson coefficient	0.34
N	Number of plies	8

Two different templates (Figure 2a) are used to manage FOs positioning at different radii. The assembly of the mould is shown in Figure 2b.



(a)

(b)

Figure 2: Mold designed and manufactured to manage FOs positioning (a); view of the fiber routing around the mold (b).

Once manufactured, the smart sensor patch Figure 3, is ready to be bonded with a certified structural adhesive Hysol 9394. An aluminium supporting plate representative of a thin aeronautical panel to which external loads are applied during testing activity is manufactured.

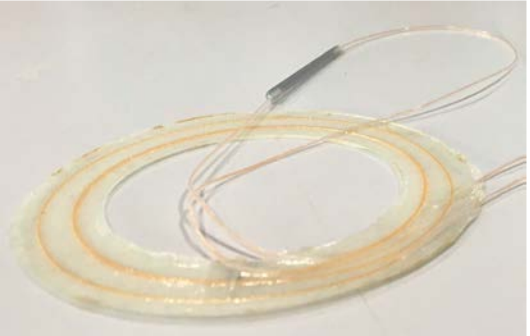


Figure 3: manufactured MonitoRing.

The plate is provided with clearance holes on two concentric circumferences to allow its clamping on the testing machine in 32 different angular positions so to apply normal loads and bending moments at different directions (Figure 4).

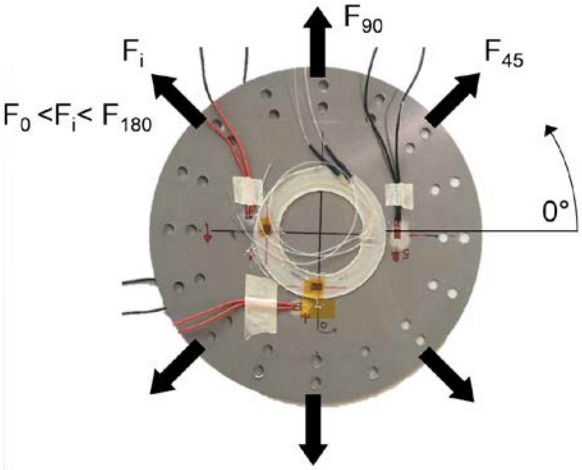


Figure 4: Aluminum supporting plate and sketch of the applied forces directions.

III. NUMERICAL MODEL

ABAQUS code is used to develop a finite element model of the device. In the model, Continuum Shell elements (SC8R) are chosen (Figure 5) for both the ring and the generic structure, assumed a perfect bonding (nodes coincidence at the interface). The stiffness of the optical fiber is neglected in the model. Deformations are acquired along circular paths, corresponding to the optical fibers position (Figure 5). Two of them are located between the seventh and the eighth ply along two concentric rings (FO_down1 and FO_down2 describe the external and the internal path, respectively); the third one (FO_up) is placed between the first and the second ply. The deformations are transmitted to the ring from the structure; the distributed sensing technology allows then the identification of the strain field along the three paths, at the same time.

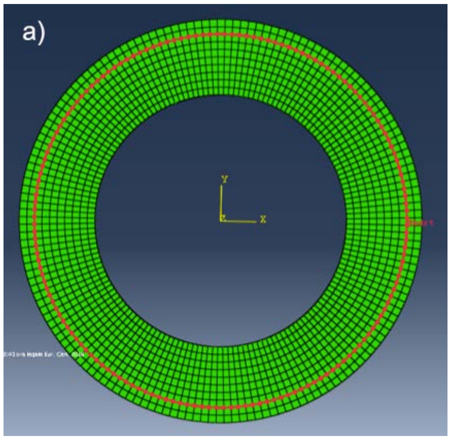


Figure 5: Detail of the FE model: Continuum Shell elements.

This plate geometry is properly designed to guarantee a constant deformation in the central region where the MonitoRing is attached (Figure 6 and Figure 7).

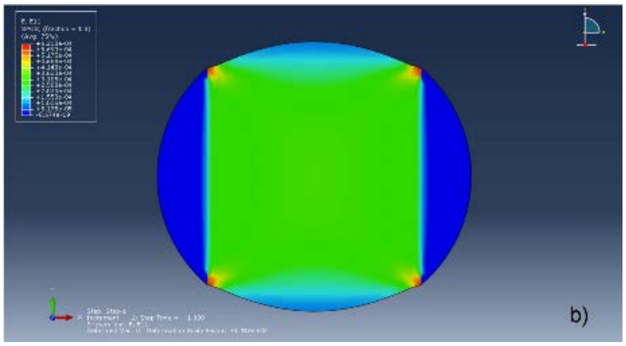


Figure 6: Strain field of the supporting plate under tensile load.

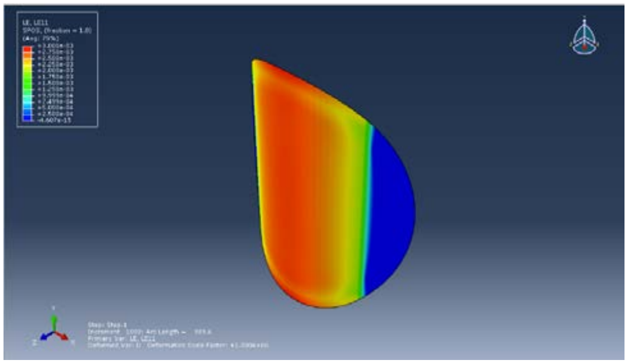


Figure 7: Strain field of the supporting plate under bending load.

A. *Tensile load*

When tensile load is applied, the tangential deformations are computed along the three fiber paths for different values of traction force (1500, 2000 and 2500 N). Figure 8 gives an example of the nominal strain curves along the three fiber optic paths under a 1500 N.

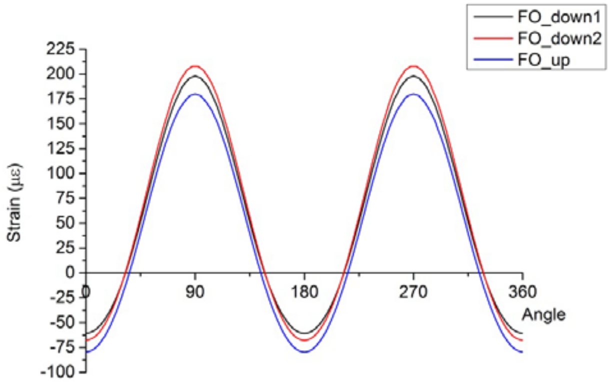


Figure 8: Numerical strain along the circumference for tensile test at 1500N.

As expected, numerical strain profiles are perfectly in phase and maximum values are reached at 90° with reference to loading direction. When direction of load is changed, a phase shift is measured, and the max values indicates the correspondent angular position of the applied tensile load (Figure 9).

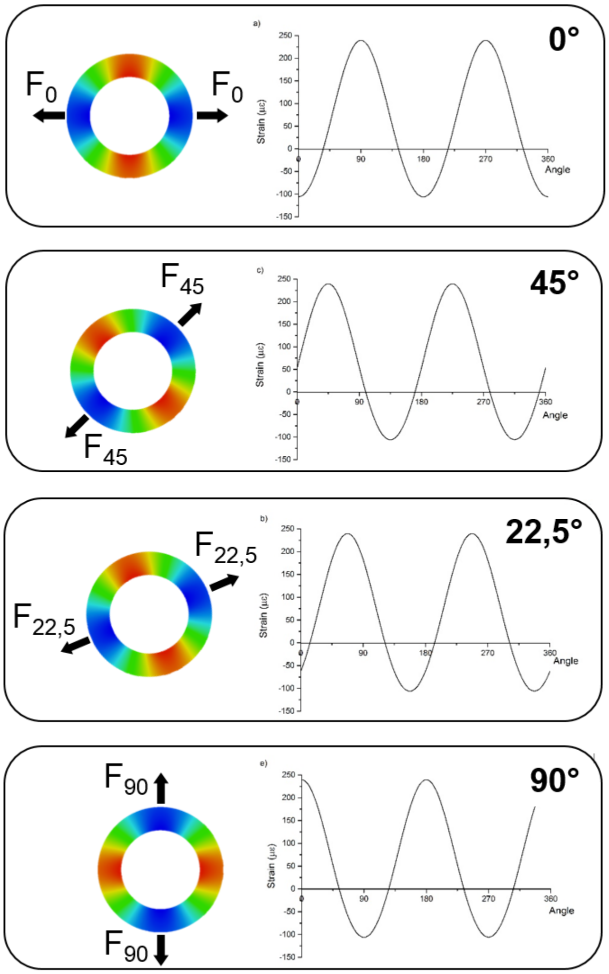


Figure 9: Tensile test: shift of strain due to different direction of application of load from 0° (upper picture) to 90° (lower picture).

In Table II the max deformations for each circular path and for the three loading levels are reported. Strains increase almost linearly for the considered loads.

TABLE II
TENSILE LOAD

Fiber loop	1500 [N]	2000 [N]	2500 [N]
FO_down1	198 με	263 με	329 με
FO_down2	208 με	278 με	347 με
FO_up	180 με	239 με	299 με

B. *Bending load*

When bending load is applied, the deflection of the circular plate is obtained by inducing compression buckling. Deformations are calculated for different imposed negative displacements along the axis of the plate (1, 2, 4 and 6 mm). All deformations are positive because the fiber optic paths are located over the neutral axis but are significantly modulated by their location along the thickness, as expected. In Figure 10, the three fiber optic strain paths are reported for 1 mm of imposed displacement.

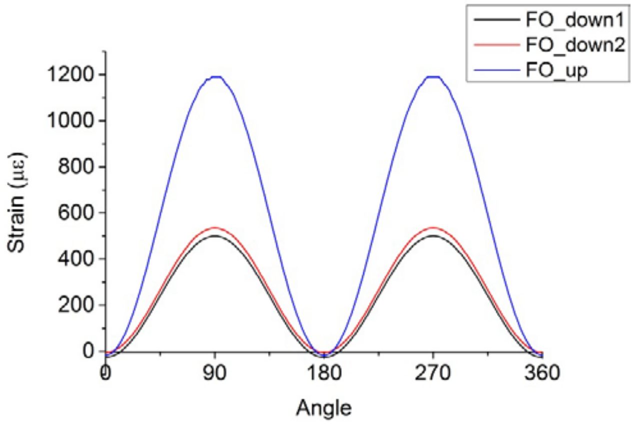


Figure 10: Numerical strain along the circumference for bending test with axial displacement of 1mm.

When direction of load is changed, a phase shift is again measured, and the max values indicates the correspondent angular position of the applied bending load (Figure 11). In Table III, the max strains are indicated, for all the considered load cases. Differently from the previous tensile test, no linear correspondence between excitation levels and deformation output can be noticed.

TABLE III
BENDING LOAD

Fiber loop	1 [mm]	2 [mm]	4 [mm]	6 [mm]
FO_down1	499 με	676 με	955 με	1150 με
FO_down2	536 με	723 με	1010 με	1220 με
FO_up	1190 με	1630 με	2320 με	2810 με

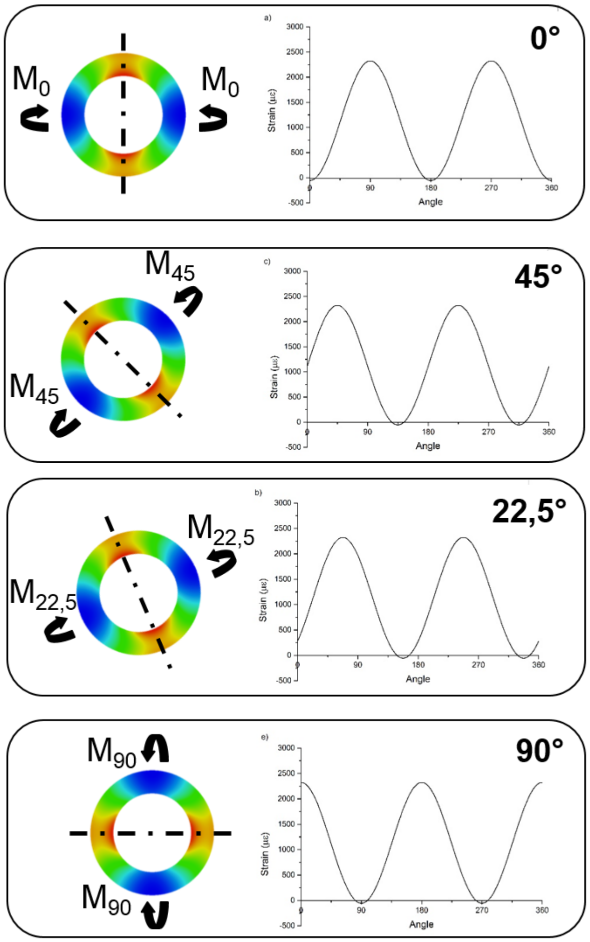


Figure 3: Bending test: shift of strain due to different direction of application of axial displacement from 0° (upper picture) to 90° (lower picture).

IV. EXPERIMENTAL TEST

In the experimental test campaign, an optical interrogator based on Rayleigh backscattering technique [9] is used. The sampling rate of the acquisition system is 250Hz with a spatial resolution of 5mm, providing more than 400 sensing points along the fiber optic.

A. Test rig

A dedicated testing machine able to apply both tensile and bending loads is designed and produced. As shown in Figure 12, a mechanical load is applied by exploiting a worm screw, 16 mm diameter, which moves back and forth a sliding block. This block hosts an insert where the sensor plate can be accommodated; such insert can rotate so to simulate a hinge. The other end of the screw is connected to a dual insert, which is blocked.

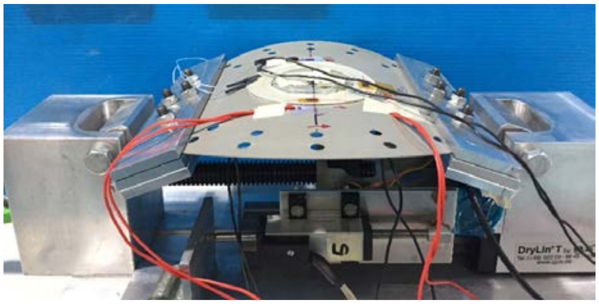


Figure 12: Testing machine in bending configuration.

B. Tensile test case

By turning the screw, a tensile load is applied as the block slides away, Figure 13.

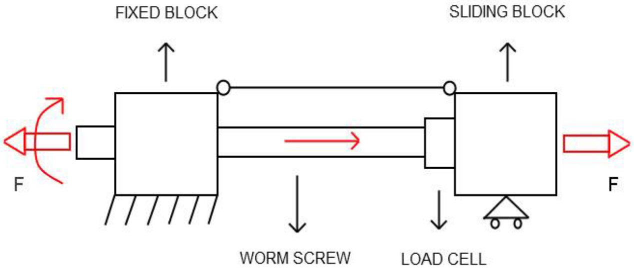


Figure 13: Schematic drawing of tensile tests device.

Tensile test results are shown in Figure 14 where the FO signals are reported. Raw data, originally referred to the position along the optical fiber, require to be filtered and transformed in degrees in order to provide load direction information (as reported in subsequent figures).

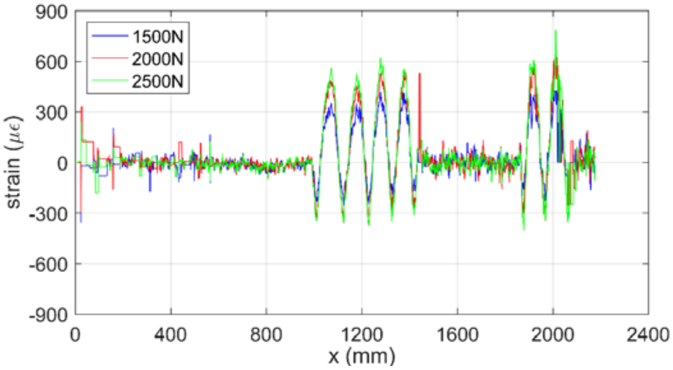


Figure 4: Data acquisition from distributed technique at different cycles of load in tensile tests.

Strain curves for 2000 N are shown in Figure 15. The shape and the values are the expected ones, similar for the three rings.

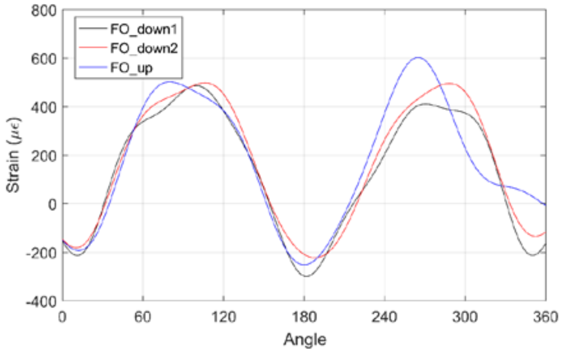


Figure 5: Experimental results for tensile tests: strain along the three fiber optic paths at 2000N of applied load.

However, some deviations from the theoretical curves can be noted. In particular, the "tail" of FO_int2 signal around 360° can be originated by a not perfect FO egress during the manufacturing process. The slight fluctuations can be instead explained with a non-perfect fiber positioning. In Figure 16, the phase shift are reported for the load direction of 0 deg and 90 deg.

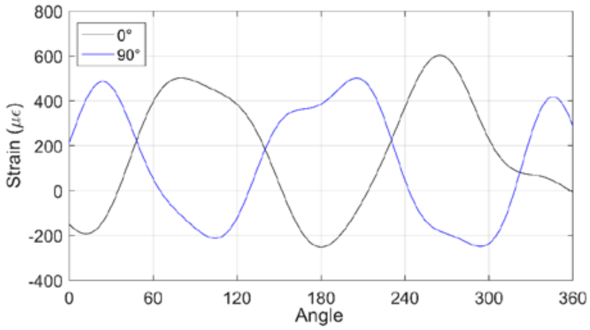


Figure 6: Tensile test: shift of strain due to different direction of application of load.

C. *Bending test case*

A bending action can be instead generated by turning the screw in the opposite direction: by moving the blocks closer, a force is generated that rotates the specimen at the hinges, Figure 17.

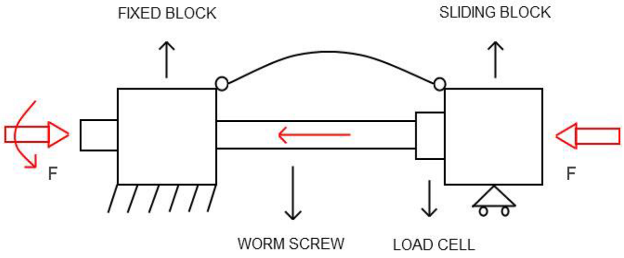


Figure 17: Schematic drawing of bending tests.

Bending test results are shown in Figure 18 where the FO signals are reported. Raw data, require again to be filtered and transformed in degrees in order to provide load direction information.

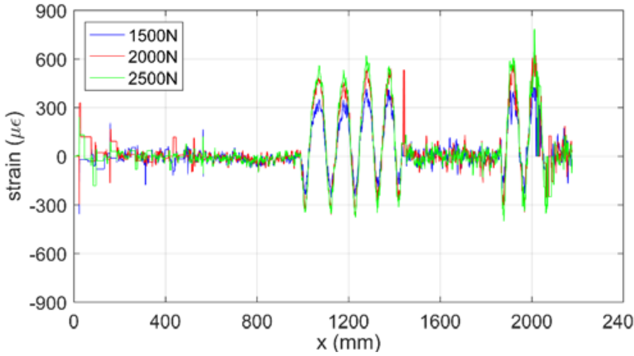


Figure 18: Data acquisition from distributed technique at different cycles of load in bending test.

A difference of the measured values is reported in Figure 19 according to the FOs position along the thickness, as numerically predicted.

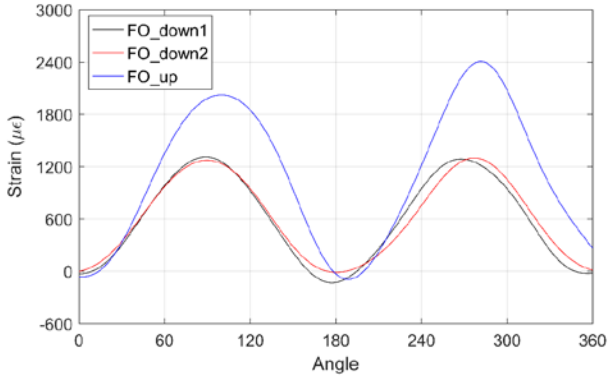


Figure 7: Experimental results for bending tests: strain along the three fiber optic paths at 4 mm.

A comparison among the different directions of the load application is illustrated in next figures. Figure 20 refers to bending test case. As expected, the curves show a shift of 90° due to a rotation of 90° of the applied load. Hence, the load application direction may be reconstructed starting from this information.

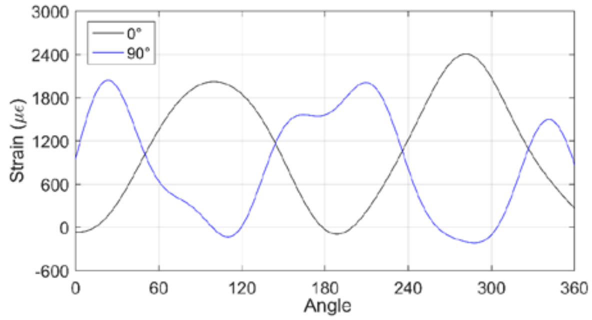


Figure 20: Bending test: shift of strain due to different direction of application of axial displacement.

V. CONCLUSION

The research activity reported in the paper at hand, highlights the properties of a smart patch structural sensor for simple load cases identification. The working principle of the device (MonitoRing) is to detect deformations data that, elaborated, may give information about the amplitude and direction of tensile and bending loads. Strains are derived from distributed fiber optic sensors, embedded in circular paths within a laminated ring.

Numerical and experimental results provided quite good correlation. Some slight differences e may be linked to a non-perfect fiber positioning and to some micro bending effects due to the laminates curing phase, producing the sine pick splitting.

The MonitoRing shows then characteristics that can make it a valid sensor for understanding the composition of stresses acting on a general structure.

Further step of the research will address to shear and torsion loads. In addition, some numerical activities concerning neural network training for automatic recognition of complex load cases will be taken into consideration by defining a main features vector including amplitude, phase, sign, of the strain full spectrum profile.

REFERENCES

[1] Khan A., Zafar S., Khan N., Mehmood Z., “History, current status and challenges to structural health monitoring system aviation field”, Journal of Space Technology 4(1), 67-74 (2014).

[2] Uhl T., Petko M., “Smart sensor for operational load measurements”, Journal of Theoretical and Applied Mechanics 40(3), 797-815 (2002).

[3] Ciminello,M., Ameduri S., Flauto D., “Design of FBG based-on sensor device for large displacement deformation”, IMOC2013. Proc. IEEE 113971.

[4] Evenblij R., Kong F., Ciminello M., Dimino I., Koimtzoglou C., Concilio A., “Shape sensing for morphing structures using fibre bragg grating technology”, Smart Intelligent Aircraft Structures (SARISTU) Proceedings of the Final Project Conference, Wölcken, Piet Christof, Papadopoulos, Michael (Eds.), ISBN 978-3-319-22413-8.

[5] Ciminello M., Bettini P., Ameduri S., Guerreschi E., Cuneo G., “Experimental validation of a sensorized ring based on optical fiber for strain monitoring of morphing structure”, IAS2014.

[6] Ciminello M., Bettini P., Ameduri S., Sala G., Concilio A., “Monito-Ring: an original FO System for Morphing applications”, JIM-14-216.

[7] Soller B., Wolfe M., Froggatt M., “Polarization resolved measurement of Rayleigh backscatter in fibre-optic components”, OFC Technical Digest, 1-6 (2005)

[8] Bettini P., Sala D., Sala G, (2013) Numerical and experimental study of fibre Bragg grating sensors for structural health and usage monitoring systems. In: Italian Association of Aeronautics and Astronautics XXII conference, Naples, 9–12 September.

[9] Luna Innovations. Available online: http://www.lunainc.com.

BIOGRAPHIES

Monica Ciminello received her Master Degree in Physics, at “Federico II” University of Naples, with a specialization in cybernetics for computer vision applications. publications on semi-active piezo-shunt control systems and vibro-acoustic coupled systems modelling, and gained two Ph.D. in Aerospace Engineering at “Federico II” University of Naples and Mechanical Engineering at Conservatoire National des Artes et Metiers (CNAM) of Paris under a co-tutoring thesis, with a mention of excellence. From 2011 she is a permanent researcher at the Italian Aerospace Research Centre at the adaptive structures department with a specialization of design and integration of smart sensors. She worked on the design of a sensor system network based on FBG optical extensimeter for shape reconstruction of an adaptive trailing edge in the Saristu project leaded by Airbus. At the moment she is the responsible for the design of a SHM system.

Paolo Bettini, photograph and biography not available at the time of publication.

Salvatore Ameduri, after defending his PhD thesis (University of Naples “Federico II”) dealing with the design of smart structure systems, entered CIRA in 2002 as senior researcher in the Smart Structures and Materials Department. Author of about 60 Journal and Conference papers (smart structures and materials, morphing, noise and vibration, acoustics), author and co-author of two National and International Patents on a drop nose LE and a SMA based variable chamber TE, reviewer for Journal of Intelligent Material Systems and Structures and Smart Materials and Structures (IOP), awarded in 2014 at the ICMAE Conference for best presentation, played coordination and scientific roles for many Projects; among the most recent ones: 2016: Project manager of “Graphene-Polymeric Spray Sensor for Shape Recognition of Super-Deformable Structures, GRAPSS” CIRA Internal Project (2016 – 2018); the main

Antonio Concilio, He took his degree in Aeronautics Engineering with honour at the University of Napoli “Federico II” (Italia) in 1989; there, he was awarded his PhD in Aerospace Engineering in 1995. In 2007 he completed the ECATA Master in Aerospace Business Administration, at ISAE-Supaero, Toulouse (France). Since 1989, he works as a Researcher at the Italian Aerospace Research Centre (Italia), where he is currently the Head of the Adaptive Structures Division, since 2014, one of the ten scientific areas of the Italian Aerospace Research Centre. His main research interests are smart structural systems design; vehicles noise and vibration control for increased comfort and devices protection; morphing of aircraft wing and control surfaces. For CIRA, he was the Scientific Responsible of several EU and nationally funded research contracts on smart structures and noise and vibration control. Recently, he led an International team for developing an Adaptive Trailing Edge within the EU SARISTU project (Smart Aircraft Intelligent Structures, 2011-2015). He is author of around 170 scientific papers, 36 of which published into specialised Journals.