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A load identification sensor based on distributed fiber optic technology

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ABSTRACT

The manufacturing and the preliminary numerical and experimental testing results of a fiber optic based sensor, able to recognize different load paths, are herein presented. This device is conceived to identify load directions by strain detection along a circumferential geometry. A demonstrator is realized by manufacturing a circular shaped, flexible glass/epoxy laminate hosting the sensible elements. Three loops of optical fiber, laying at different quotes along its thickness, are there integrated. The sensor system is supposed to be bonded on the structural element and then able to follow its deformations under load. The working principle is based on the comparison of the strain paths detected at each fiber optic loop at homologous positions. Rayleigh backscattering optical technology is implemented to measure high spatial resolution strains. A finite element model is used to simulate the sensor behavior and assess its optimal configuration. A preliminary experimental campaign and a numerical correlation are performed to evaluate sensor performance considering in-plane and bending loads.

Keywords: Load identification, fiber optic, distributed sensing, Rayleigh backscattering, strain transducer, smart system.

1. 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 embedded¹.

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 response², identified by dedicated transducers^{3,4}, able to measure strain and displacement fields.

The MonitoRing transducer^{5,6}, the authors previously developed for morphing applications, 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.

2. METHODOLOGY AND MANUFACTURING

A scheme of the MonitoRing is illustrated in Figure 1. The system consists of a circular laminated structure made of glass reinforcing fibers in which three different fiber optic paths are embedded along its thickness. Two paths are deployed at the same layer with different radii; another one is co-located but arranged at a higher quote (Figure 1b). This lay-up is

chosen to allow detection of different loads, acting on the structure. For instance, an in-plane uniform action (normal stress) is characterized by the same strain distribution in the upper and the lower fiber optic loop. On the other hand, a pure bending action induces different strain values at the different sensing elements. In this paper, only pure in-plane normal and bending loads are considered for the preliminary assessment of the proposed device. The numerical analysis permits however highlighting its further potentiality to recognize many strain field features pattern, depending on a proper fiber optic layout.

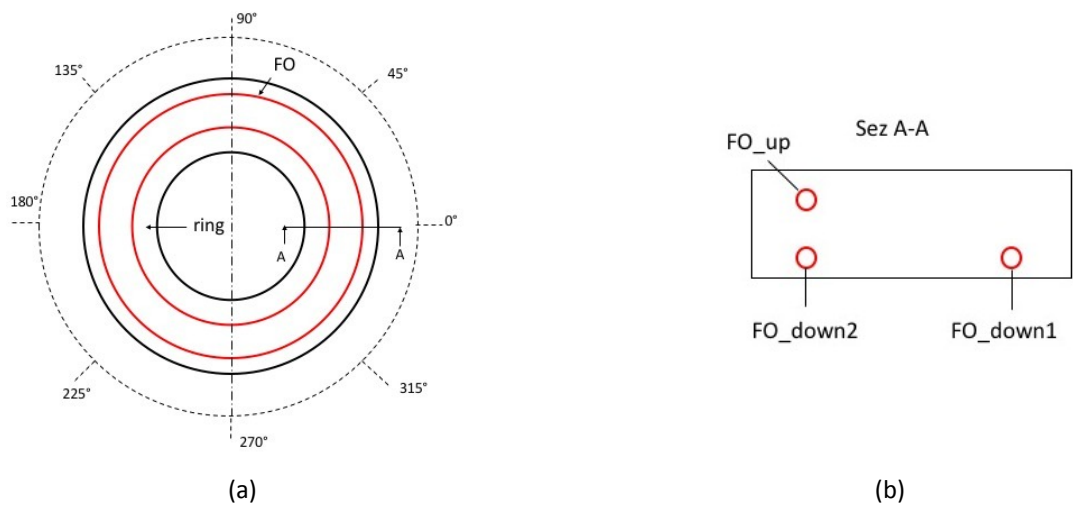


Figure 1: Scheme of MonitoRing: Top view (a); Thickness section (b).

A single commercial telecom fiber optic, arranged in more loops is integrated to make the device cost-effective. In this application, optical instrumentation based on Rayleigh backscattering is used; that 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 birefringence⁷. 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 (Rayleigh backscattering). By taking advantage of the uniqueness of this characteristic and the modulations caused by imposed loads, the resulting deformation field can be retrieved by applying an inverse technique⁸.

Main features of the MonitoRing are summarized in Table 1. The ring architecture is defined to ensure a good flexibility while guaranteeing the proper integration of the optical fiber.

Table 1: MonitoRing main features.

Ring material	glass/epoxy laminate
Ring thickness [mm]	0.4
Outer diameter [mm]	80
Inner diameter [mm]	50

The ring is made of eight plies of a very thin fabric pre-preg (SAATI SEAL EE48 ET445 43%, 0.05 mm thick). The composite characteristics are reported in Table 2. 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 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). The assembly of the mould is shown in Figure 2a. Two different templates are also used to manage FOs positioning.

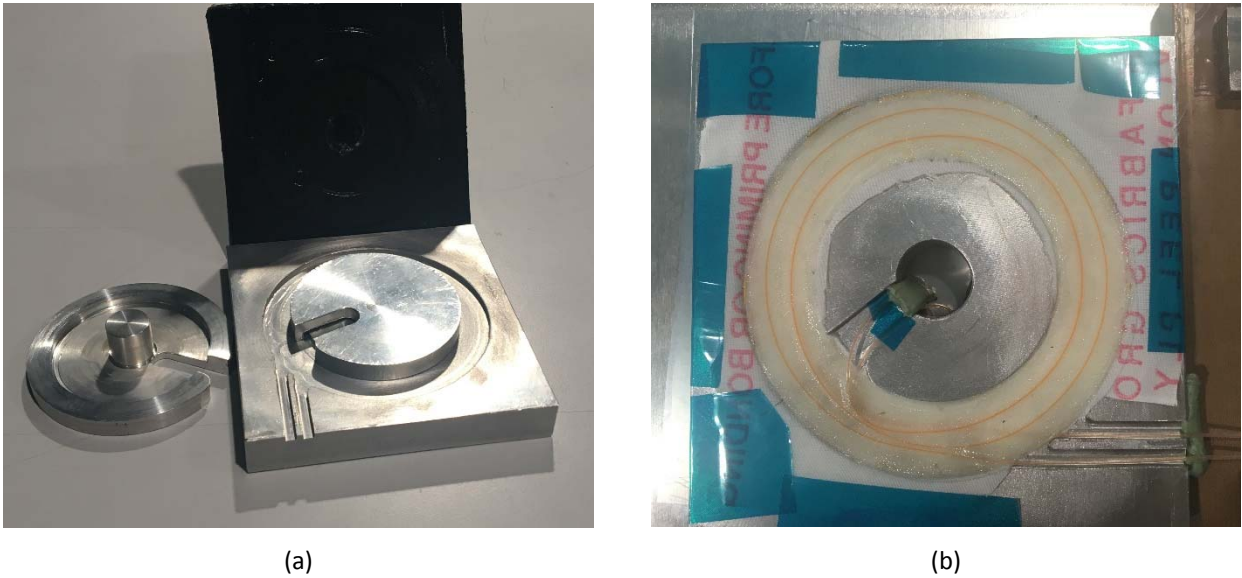


Figure 2: Technological process for a MonitoRing equipped with 3 FO circular paths: assembly of the special mould designed and manufactured to manage FOs positioning (a) and view of the laminate at the end of the curing cycle (b).

Table 2: Engineering constant of glass/epoxy laminate.

Elastic moduli [GPa]			Shear moduli [GPa]			Poisson's coefficients		
E1	E2	E3	G12	G31	G23	ν12	ν13	ν23
20.7	20.7	7.6	3.7	1.84	1.84	0.165	0.34	0.34

Table 3: Supporting structure main features.

Supporting structure material	aluminium 2024-T6
Thickness [mm]	0.5
Diameter [mm]	200
Inner diameter [mm]	50
Elastic modulus [MPa]	73850
Poisson's ratio	0.34

The MonitoRing is then bonded to an aluminium supporting plate to which external loads are applied during testing activity. This plate is designed to properly size the clamping area and to guarantee a constant deformation in the centre region where the MonitoRing is attached. More in details, the plate is provided with 32 clearance holes on two concentric circumferences to allow its clamping on the testing machine in 32 different angular positions so to apply loads at different

directions. 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. The main features of the supporting structure are summarized in Table 3. Once manufactured, the ring and the supporting plate are connected as in Figure 3.

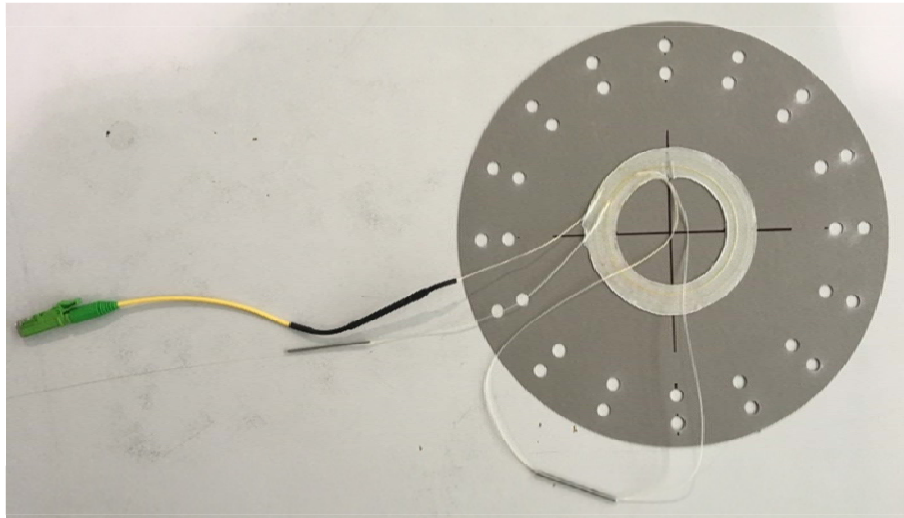


Figure 3: Supporting structure with surface bonded MonitoRing.

3. NUMERICAL DATA

A Finite Element model simulates the transducer behavior under tension and bending, trying to reproduce the experimental occurrences. ABAQUS code is used. In the model, Continuum Shell elements (SC8R) are chosen for both the ring and the generic structure, assumed perfectly bonded (nodes coincidence at the interface) (see Figure 4). The stiffness of the optical fiber is neglected in the model.

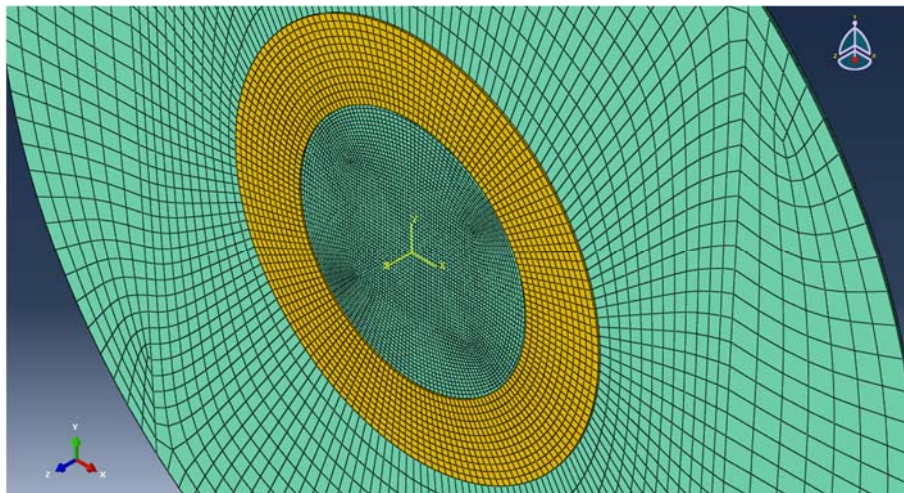


Figure 4: Detail of the FE model: nodes of the MonitoRing are merged with nodes of the supporting structure.

Deformations are acquired along circular paths, corresponding to the optical fibers position. 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 (Figure 1b).

For tensile tests (see sketch in Figure 8a), the tangential deformations are computed along the three fiber paths for different values of traction force (1500, 2000 and 2500 N). Figure 5 gives an example of the nominal strain curves along the three fiber optic paths under a 1500 N. As expected, numerical strain profiles are perfectly in phase between them and maximum values are reached at 90° with reference to loading direction where the maximum tangential deformation is applied to the ring (90° and 270° in Figure 1a).

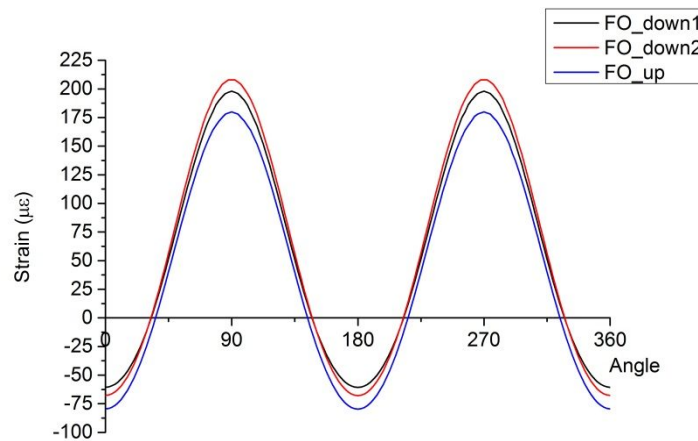


Figure 5: Numerical strain along the circumference for tensile test at 1500N.

In Table 4 the max deformations for each circular path and for the three loading levels are reported. The curves shape is the same for each load and follows the expected trend. In fact, when a tensile force stresses the MonitoRing, the max tangential strain is expected along the normal direction (the ring deforms elliptically, undergoing a compression in the normal direction and a tension along the load line). Moreover, it is possible to observe that a pure tensile test does induce the same deformation values along the three different fiber optic paths. The diagram symmetry indicates that it is possible to reconstruct all the sigmoidal shape of deformations by studying only a disc quarter. Strains increase almost linearly for the considered loads.

Table 4: Maximum numerical strain on the three circular paths for the three tensile loading levels.

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

For bending tests (see sketch in Figure 8b), 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).

In Figure 6, the three fiber optic strain paths are reported for 1 mm imposed displacement. In Table 5, the max strains are indicated, for all the considered load cases. Once again, the strain distribution shapes are almost the same and coincide with the expected ones. 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. Therefore, it appears reasonable to detect a bending-type

excitation by this sensor arrangement. Differently from the previous tensile test, no linear correspondence between excitation levels and deformation output can be noticed in this case (see Table 5).

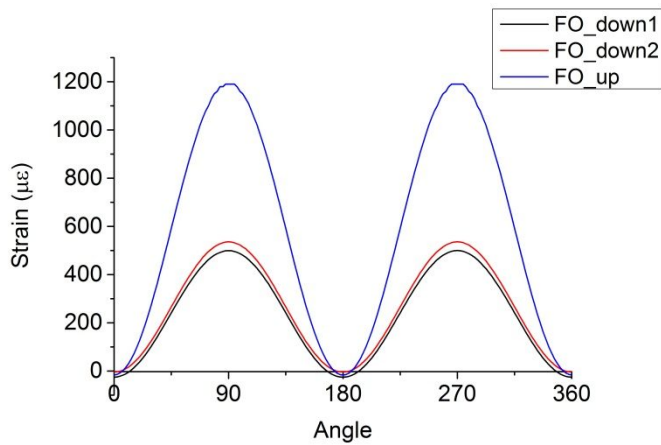


Figure 6: Numerical strain along the circumference for bending test with 1 mm of axial displacement.

Table 5: Maximum numerical strain on the three circular paths for the three axial negative displacement levels.

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

4. EXPERIMENTAL RESULTS

A preliminary concept demonstrator of the sensor system is manufactured for the experimental verification of its behavior and the numerical model validation. In the experimental campaign, a commercial optical interrogator is used, based on Rayleigh backscattering technique⁹ and the three FO paths are connected in series configuration in order to be interrogated at the same time. Such a distributed technology is very sensible and the signal can be easily attenuated for the dynamic structural deformations linked to the system vibration. Indeed this effect poses a limit of the usable length of the fibers. Within those limits, the macroscopic strains may be easily revealed real-time, then getting direct info on their variation.

A dedicated testing machine able to apply both tensile and bending loads is designed and produced. As shown in Figure 7, 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. By turning the screw, a tensile load is applied as the block slides away, Figure 8-a. 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 8-b. To validate optical data, a discrete number of strain gages is also installed on the MonitoRing surface. An example of sensor data comparison is provided in Figure 9, where the FO_up path and the strain gage curves refer to the output of a tensile action.

Tensile test results are shown in Figure 10 where only the FO signals are reported. Raw data, originally referred to the position along the optical fiber (as it can be seen in the figure), require to be filtered and transformed in degrees in order to provide load direction information (as reported in subsequent figures). Strain curves for 2000 N are shown in Figure 11. The shape and the values are the expected ones, similar for the three rings. 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 deployment of the fiber.

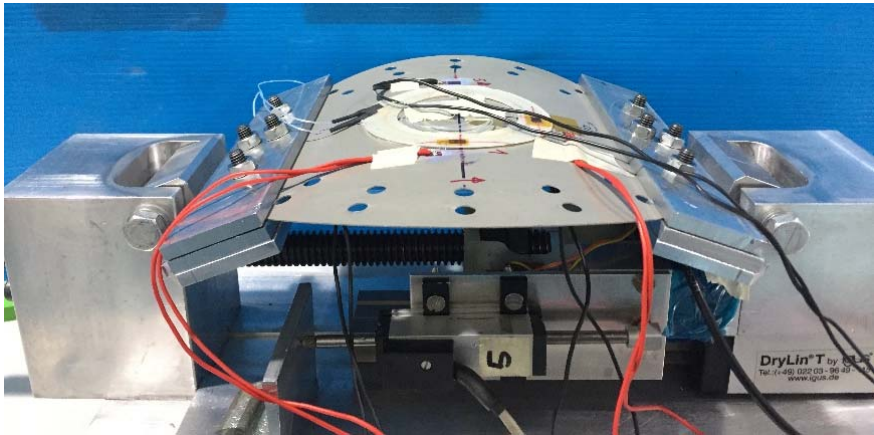
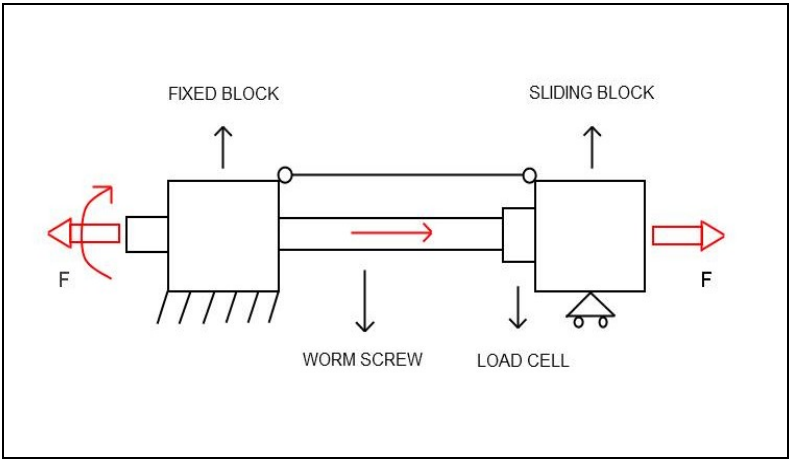
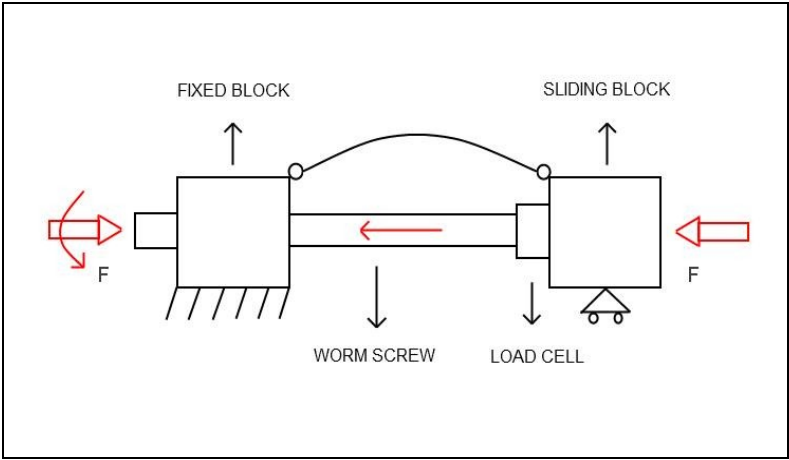


Figure 7: Testing machine in bending configuration.



(a)



(b)

Figure 8: Schematic drawing of tensile (a) and bending (b) tests.

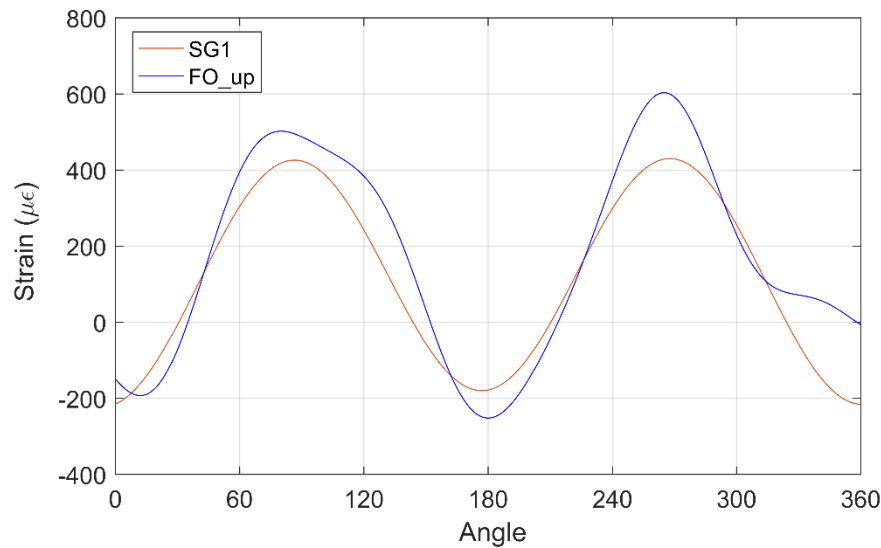


Figure 9: Monitoring of measurement with strain gage respect the FO_up path under tensile test.

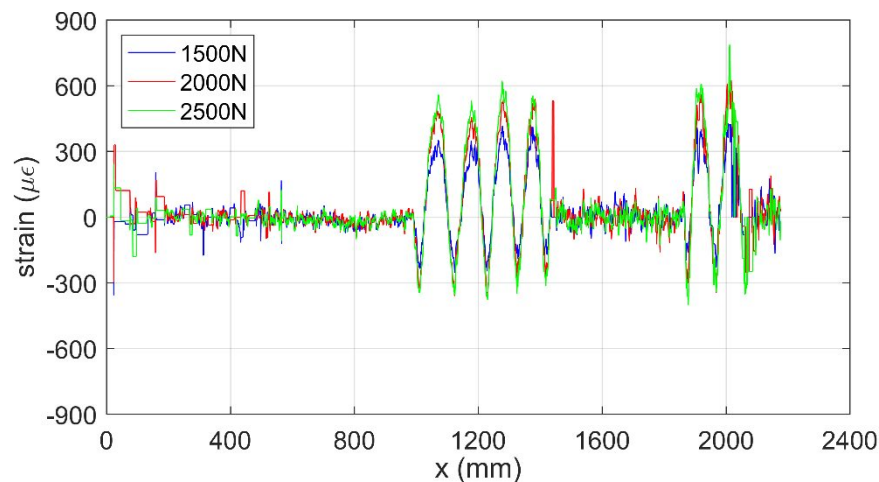


Figure 10: Data acquisition from distributed technique at different cycles of load in tensile tests.

The bending test produces the expected trend as well. A difference of the measured values is reported in 12 according to the FOs position along the thickness.

A comparison among the different directions of the load application in both test cases is illustrated in next figures, for both the numerical and the experimental activities.

Figure 13: refers to tensile 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.

The same conclusion can be done for the bending test. Numerical and experimental results match quite well and the shape is the expected one, with a higher value of deformations at 90° , with respect to the load direction. A comparison between numerical and experimental data is reported in Figure 14.

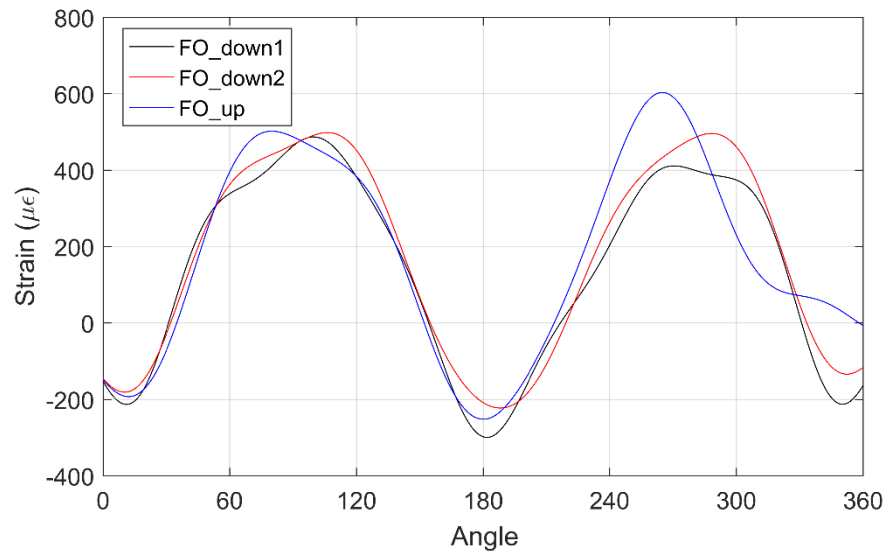


Figure 11: Experimental results for tensile tests: strain along the three fiber optic paths at 2000N of applied load.

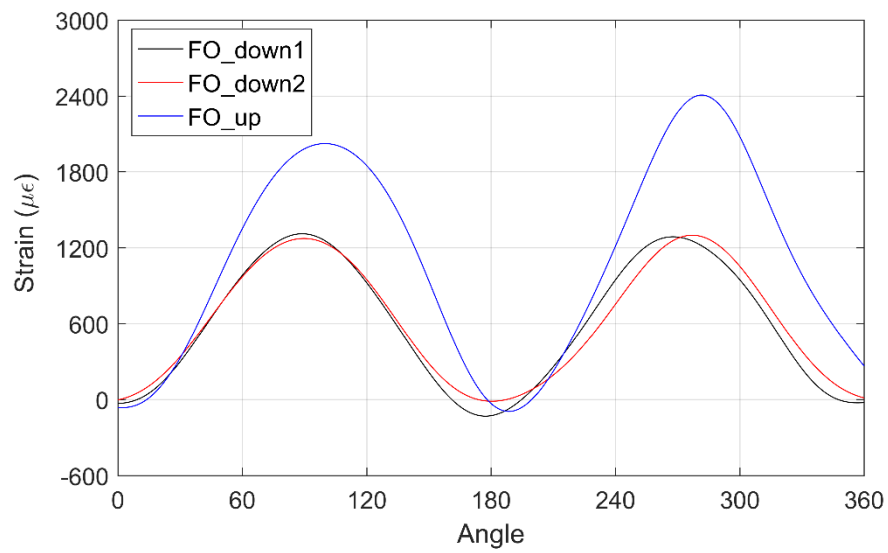
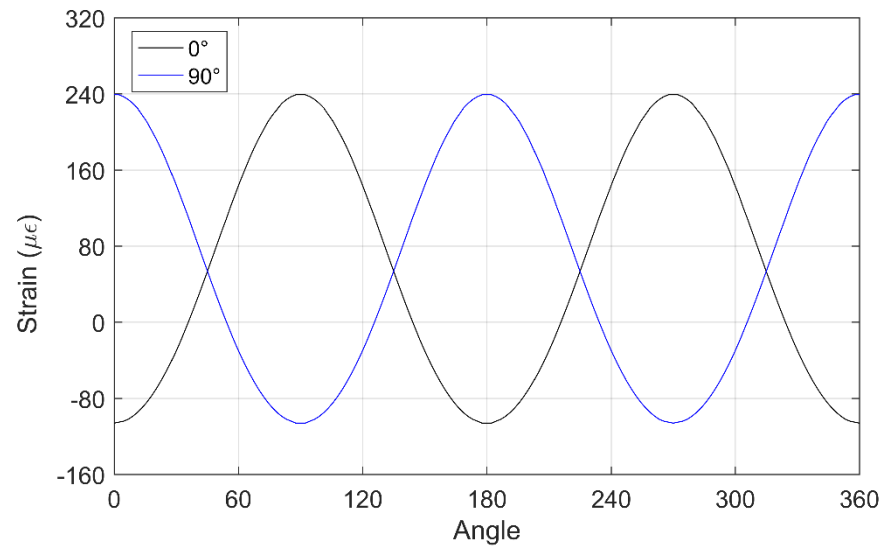
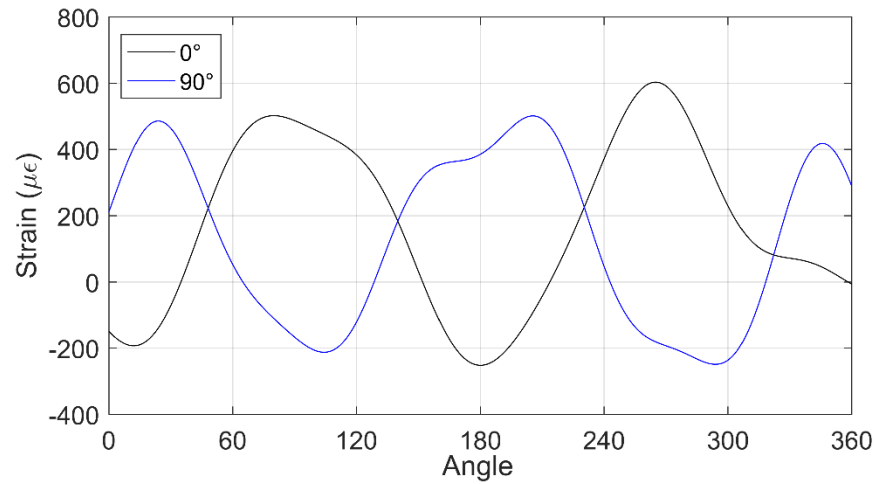


Figure 12: Experimental results for bending tests: strain along the three fiber optic paths at 4 mm of applied axial displacement.

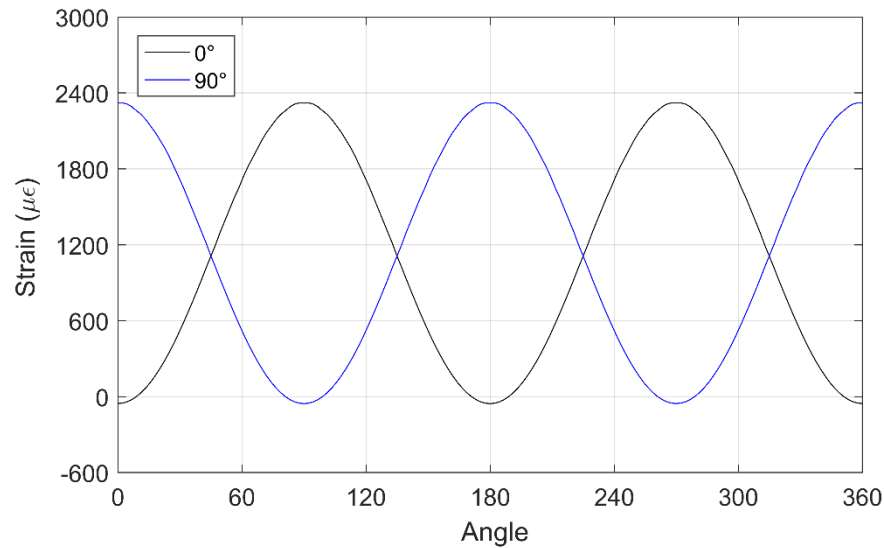


(a)

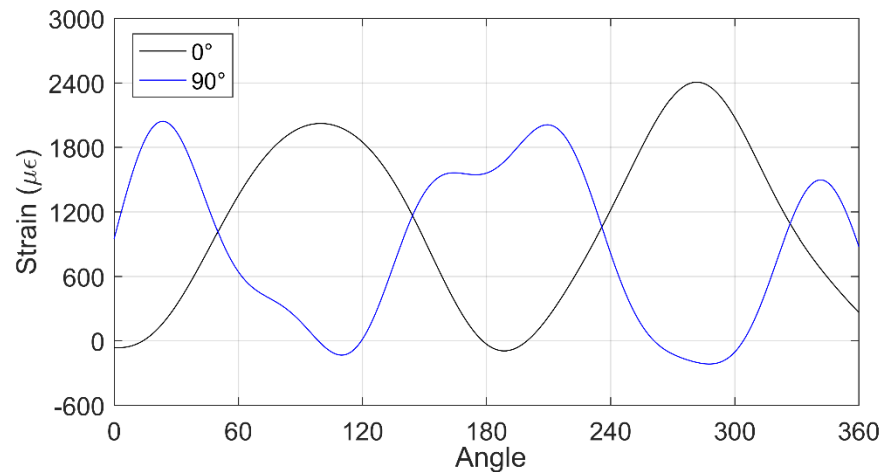


(b)

Figure 13: Tensile test: shift of strain due to different direction of application of load for a) numerical analysis and b) experimental data (response of FO_up at 2000 N).



(a)



(b)

Figure 14: Bending test: shift of strain due to different direction of application of axial displacement for a) numerical analysis and b) experimental data (response of FO_up at 4 mm).

5. CONCLUSIONS

The research described in this paper is focused on the development of a smart structural sensor for load identification.

Based on the knowledge of the strain response, the external loads can be determined. The basic principle of the presented device (MonitoRing) is to detect deformations data that, elaborated, may give information about the applied load type.

Strains are derived from fiber optic sensors, embedded in circular paths within a laminated ring, different for size and location along the thickness.

For the preliminary assessment of the MonitoRing, it is bonded on a generic structure, undergoing bending and tensile loads. The adopted interrogation distributed technique is able to give real time, dense deformation distribution changes. Some slight differences in the qualitative behaviour of the sensors, between the numerical and experimental output may

be linked to a non-exact deployment of the fiber and some imperfections on the host laminate occurred during the manufacturing.

In spite of these small differences, bending and tensile actions can be recognised easily because substantial different overall distributions of strains both along the circumferences and the thickness can be observed. The MonitoRing results very sensible to the load application direction.

The ring configuration evidences a general symmetry in the deformation curve: two peaks can be observed at a 180° interval in correspondence of the larger strain. These same peaks are indexes of the load application direction. The multiple circular paths give further hints on the nature of the excitation, taking advantage of the recorded differences along each active circle. 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 other type of loads acting on the same demonstrator: in particular, shear and torsion loads will be investigated, very common on aeronautical structures. Numerical and experimental investigations will be carried out, aimed at setting a proper design tool. After that, activities concerning the action of mixed loads are planned. In that case, it will be tried to separate the different contributions and then, recognising the actual load, acting on the structural reference system. The shapes of the deformation maps could also provide details about the loads direction.

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