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Static Characterization of Curvature Sensors Based on Plastic Optical Fibers

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Abstract—Sensors able to measure curvature changes are emerging as an effective alternative to the more common strain gauges for structural health monitoring applications. Particularly interesting is the all-optical fiber implementation for its unique properties and the possibility of being embedded. The paper, after a brief description of curvature sensors using plastic optical fibers, focuses on their characterization in applications where high sensitivity is required, and compares their performance with commercial strain sensors based on fiber Bragg gratings. The choice of plastic optical fibers allows the realization of simple, compact and cheap sensors. A characterization setup to test different sensor typologies is proposed and the main uncertainty contributions are investigated.

I. INTRODUCTION

Monitoring structural deformations of buildings is important to evaluate their integrity over time both for preventive maintenance and in the aftermath of severe natural events, such as tornadoes, earthquakes, etc. Therefore, several sensing techniques based on mechanical, electrical and optical transducers have been deeply investigated yielding also to many commercial products. In particular, optical technologies have emerged in the last years as the most prominent approach for their excellent sensitivities combined with other relevant properties, such as immunity to electromagnetic disturbances, impossibility to start fires or explosions and capability of being easily embedded into structures. For example, optical strain gauges based on Fiber Bragg Gratings (FBG) in glass fibers similar to those used in telecommunications have demonstrated to easily resolve strains smaller than $1 \mu\epsilon$, even in severe environmental working conditions or in the presence of electromagnetic disturbances. Their deployment is, however, still currently limited by costs, mainly due to the interrogation system and the equipment for handling glass fibers. On the other hand, in the latest years there has been a growing demand for low cost devices able to monitor smaller and smaller deformations to realize distributed networks aimed at the early detection of the onset of structural damages. Hence, despite the large variety of sensors already available on the market, new types are still investigated to further improve the price-performance ratio. A typical example is the evaluation of the deflection of a beam. The easiest solution would probably be to measure the mechanical strain on the beam surface using electrical or optical strain gauges, given

that the strain is proportional to the beam deflection. However, this approach becomes too expensive when small deflections of thin beams have to be measured because, in this case, a very high resolution is required. Alternatively, curvature sensors could be used with the advantage that the beam curvature does not depend on its thickness, and thus no increment of performance is required, even for applications to thin beams [1]. Moreover, the curvature measure obtained at different positions can be employed to analyze the structure deformation in order to assess the loading effects [2].

Fiber optics is probably the most promising technology for the implementation of curvature sensors (also known as bending sensors), because fibers can be easily integrated inside elongated structures along the main deformation lines. Indeed, fiber sensors for curvature measurement have been recently proposed, both using single mode and multi-mode fibers. While standard FBG or long period gratings (LPG) are mainly used for measuring static or dynamic strains [3] [4], LPG [5], chirped [6] and tilted FBG [7] can be also designed to be sensitive to curvature. Other approaches include multi-mode interference [8] and polarimetric [9], [10] techniques. Intensity based sensors arranged using multi-mode fibers and exploiting the natural sensitivity of large core fibers to macro-bending have been considered as well, because of their very low interrogation costs. These sensors, however, are able to detect sharp bending only, so they are mainly employed as transducers in mechanics and biomechanics [11], [12]. However, the sensitivity to bending can be greatly enhanced by modifying the core/cladding interface [13], [14], thus obtaining transducers able to detect bending radius as large as some kilometers.

The paper presents the characterization of such high sensitivity all-fiber curvature sensors made using Plastic Optical Fibers (POF) instead of the more common glass fibers; the choice of this type of fibers allows combining the advantages typical of fibers, with low costs and simplified handling. The paper describes the sensor working principle first, then focuses on its characterization, describing a procedure suitable for the calibration of transmission and reflection based sensor topologies. The procedure is based on a properly shaped metallic cantilever, whose curvature is obtained deflecting the free end, and can be applied both to static and to dynamic conditions. The characterization of curvature sensors with such a high sensitivity plays a key role both for the sensor usage (to assess their metrological characteristics), and for the optimization of sensitivity enhancement techniques (to compare sensors developed using different fiber modification methods). Experimental validation of the proposed approach is then reported and, finally, conclusions are drawn.

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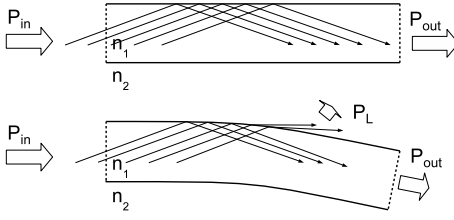


Fig. 1. Propagation of rays near the critical angle: higher loss occurs in the presence of the fiber bending.

II. CURVATURE SENSOR WORKING PRINCIPLE

Light propagation inside highly multi-mode fibers, like in POF, can be modeled using the ray approximation. Following this approach, light rays entering the fiber within the cone defined by the numerical aperture correspond to rays that are incident at the core/cladding interface of a straight fiber at an angle larger than the critical angle, and thus are reflected, whereas rays having a smaller incident angle are refracted and escape from the fiber core. For standard POF having numerical aperture of 0.5, the critical angle is about 70° . Fiber bending, however, causes a change of the incidence angle at the core/cladding interface, so even rays that are within the acceptance cone can be incident at the core/cladding interface with an angle smaller than the critical angle, and thus radiated with a reduction in the received power at the fiber end. Fig. 1 provides a simplified description of the origin of bend-induced losses; a group of rays having incidence angle near to the critical angle is shown: the rays are totally reflected when the fiber is maintained straight, but some of them are lost in the presence of bending.

In commercial POF, bending losses can be considered negligible for small curvatures C , that is for large curvature radii $R = 1/C$, but they become the main attenuation contribution when the bending radius is smaller than a certain critical radius, typically below 10 cm. This reduced bending sensitivity is appreciated in the telecommunication field, where the optical power budget is of primary concern, but it prevents the fiber use as an effective curvature sensor, at least in applications where large curvature radii have to be measured, like in the above mentioned structural applications.

Nevertheless, fiber sensitivity to bending can be significantly increased by modifying the core/cladding interface through mechanical, chemical and plasma-based approaches [15]. Among all the investigated modification techniques, the simplest are those based on mechanical approaches, such as the inscription of a series of grooves in the fiber by micro-mechanical milling. In any case the modified fiber acts as an intensity-based intrinsic sensor [16] that can be implemented as one of the embodiments shown in Fig. 2. In this way the optical power at the fiber output is related to the power losses and, through a calibration procedure, to the curvature of the fiber portion that has been sensitized. In several applications it is preferable to have transmitting and receiving fibers on the same side, as in Fig. 2 b) and c); these two embodiments have also the advantage of a double sensitivity, given the twofold light path. Structure b), however, leads to larger

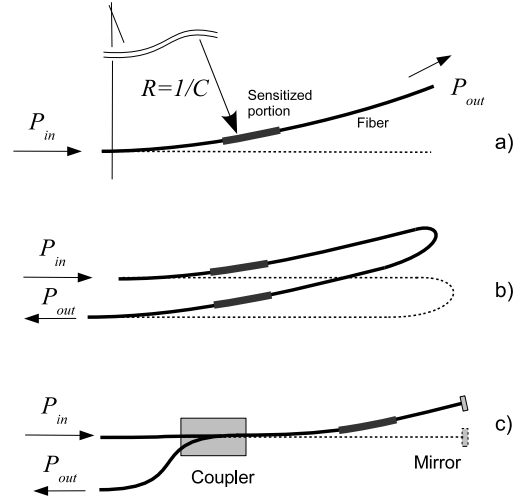


Fig. 2. Bending sensors structures: a) fiber in transmission mode, b) folded fiber in transmission mode and c) fiber in reflection mode. Dotted lines represents the fiber unperturbed position corresponding to null curvature C .

sensors since the fiber can not be sharply folded, while the more compact structure c) requires an optical coupler to separate incident and reflected signal, and couplers for POF have typically poor directivity with consequent limitations in the minimum signal-to-noise ratio for correct operation. For instance, structure c) has been recently used to develop all-fiber low cost acceleration sensors [17].

As an example of practical curvature sensors implementing these geometries, Fig.3 shows some prototypes made using a short span of step-index POF with nominal diameter of 1 mm and a numerical aperture of 0.5. The fiber has been sensitized for a length of about 2.5 cm by grooving the surface using a milling tool to realize 20 rectangular cuts with a depth of about 0.4 mm (Fig.3a)). Sensor designed to work in transmission mode have been fixed on a small rectangular thin plastic sheet using epoxy glue thus obtaining the embodiment shown in Fig. 3b), which has the advantage to be easily fixed in a non permanent way on the structure that has to be monitored by simply using double-sided adhesive tape. For sensors working in reflection mode the fiber has been cut after the sensitized zone, polished and then covered with a thin aluminum foil 3c) thus obtaining the structure shown in Fig. 2c).

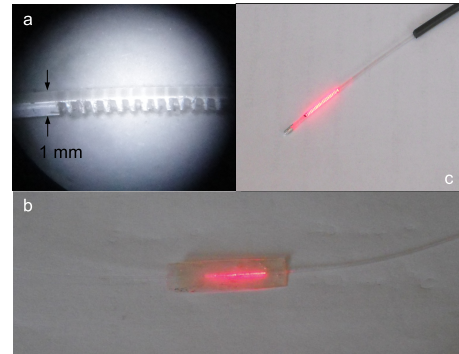


Fig. 3. Detail of the sensitized area a) and different sensor embodiments working in transmission b) and reflection c) mode.

III. SENSOR CHARACTERIZATION SETUP

Curvature sensors can be characterized by mounting them on bend poses having known curvature or using rotation stages [18], [19]. These setups, however, are mainly suitable for applications where the quantity under measurement is the bend angle and the expected curvatures are quite large. Alternatively, the fiber forming the sensor can be clamped loose between two locks [5], [8]; this will induce a curvature whose expression can be determined in close form, but the curvature is not uniform along the sensor length and, moreover, it is suitable for large curvatures only.

With the aim of characterizing high sensitivity sensors, in the considered case the measurement of the bending sensitivity is obtained fixing the fiber sensors on the surface of a thin metallic beam, firmly locked at one side and deflected at the free end, realizing the cantilever structure shown in Fig. 4. This way, the fiber is subjected to the same cantilever curvature C that, for a rectangular structure having length L and for small deflections D , depends on the distance x from the lock as [20]:

$$C = 3 \cdot D \cdot \frac{L - x}{L^3} \quad (1)$$

The curvature is maximum at the lock position and null at the opposite end, as shown in Fig. 5 (red curve). Despite the limited sensor length, the curvature is not constant along the sensor and this introduces a not negligible error in the determination of the curvature. As an example, an error below 1% requires a cantilever longer than 1 m for a 2 cm long sensor, but such a long cantilever is suitable to assess the sensor sensitivity in static conditions only. The cantilever thickness has an important effect on the characterization results, because the sensor is fixed on the surface and it is thus exposed both to curvature and strain. For this reason, a cantilever with thickness of about 2 mm has been employed in the proposed setup, thus obtaining a negligible strain effect. Alternatively, the modular structure described in [21] allows the sensor to be characterized along the neutral axis, that is in the presence of null strain.

To reduce the non constant curvature effect without requiring an impractically long cantilever, the authors have turned to non rectangular shapes. A triangular cantilever would provide a constant curvature, but it is not practical since it requires to apply the force to deflect the beam at the triangle vertex. A better compromise is a trapezoidal cantilever, such as the one shown in Fig. 6, which is easier to be employed and presents a reduced curvature change, at least in the first part of the structure [22].

Fig.5 compares the curvatures of two cantilevers having same length (181 mm) but different shapes. The rectangular structure has a constant width of 30 mm whereas the trapezoidal one has a width changing from 30 mm to 11 mm. The figure also shows the positions A and B where the fiber sensors will be fixed. Tab.I reports the curvature as obtained considering the models reported in Eqn. 1, for the rectangular shape, and in [22], for the trapezoidal one. In both cases the cantilever tip deflection is 1 mm. The table also reports the relative curvature change $\Delta C/C$ along the sensor area, considering a sensor length of 25 mm: it is possible to see that

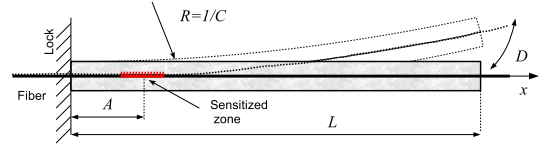


Fig. 4. Rectangular cantilever hosting a fiber sensor working in transmission mode.

the trapezoidal structure provides a reduced curvature change at both positions A and B.

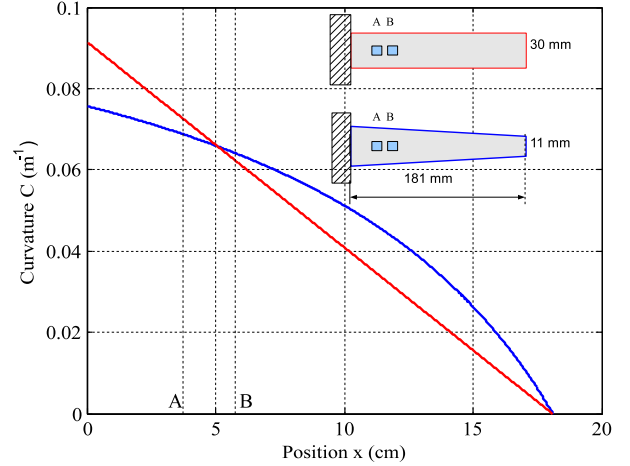


Fig. 5. Curvature comparison between the rectangular and trapezoidal structures.

TABLE I
THEORETICAL CURVATURE FOR RECTANGULAR AND TRAPEZOIDAL STRUCTURES AND RELATIVE DEVIATION FROM THE VALUE AT THE MIDDLE OF THE SENSOR.

Cantilever	Sensor position	C (m^{-1})	$\Delta C/C$
Rect.	A	0.1391	$\pm 9\%$
Rect.	B	0.1138	$\pm 11\%$
Trap.	A	0.1349	$\pm 4\%$
Trap.	B	0.1226	$\pm 5\%$

After that the sensor has been fixed on the cantilever, it is interrogated using an intensity based detection system whose block diagram is shown in Fig. 7. The optical power is provided by a red LED driven at constant current and the light intensity at the fiber output is detected using a photodetector (PD) having good sensitivity in the visible part of the optical spectrum. The photocurrent is then converted to a voltage signal using a double stage trans-impedance amplifier having an overall gain of 10 M Ω and a bandwidth limited from 1 Hz to 1 kHz. The gain for the DC coupled signal is 1 M Ω and the second stage provides a further amplification of 10. The signals are thus acquired using a conventional acquisition system based on a 16 bit digital acquisition board and a personal computer.

The cantilever is deflected using a computer-controlled linear translation stage, whose main uncertainty contribution is the linearity that is of a few micrometers.

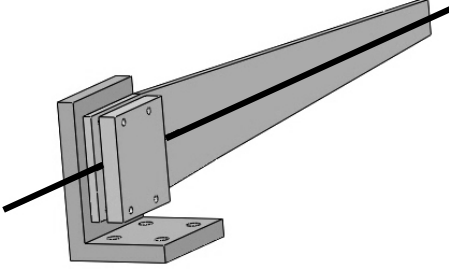


Fig. 6. Sketch of the trapezoidal structure.

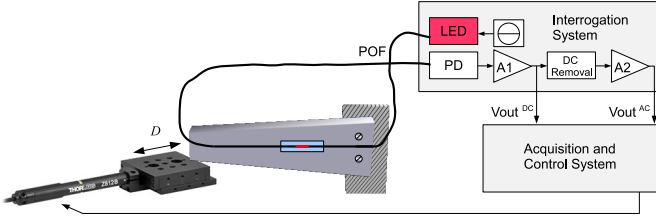


Fig. 7. Block diagram representation of the system employed to test curvature sensors working in transmission mode.

The testing of sensors working in reflection mode requires a different setup, since the reflected light is routed to the photodetector using a 50% / 50% optical coupler. Commercial POF couplers have large insertion loss and thus they produce a significant reduction of the sensor sensitivity. Moreover, these couplers have also a poor directivity, so about 1% of the launched optical power is expected to be routed directly to the PD. In many applications this contribution can be tolerated but here it represents a serious problem since this cross-talk signal can be one or more order of magnitudes larger than the useful signal. For this reason the curvature sensor working in reflection mode is most suited to measure deformations in dynamic conditions, because in that case the cross-talk signal is spectrally separated from the curvature related signal. Hence, to evaluate the dynamic performance, the cantilever tip is deflected using an electrodynamic shaker, as described in [21], where the shaker is controlled to force a low-frequency sinusoidal displacement. Alternatively, when the displacement can not be known with the required accuracy, the cantilever deflection can be monitored using electrical or optical strain sensors [23].

IV. CANTILEVER CALIBRATION

The value of the cantilever curvature can be computed using an analytical model, such as the one described in [22], which has been developed considering a uniform metallic beam and a perfect mechanical joint. Anyway, the curvature expression, besides for being approximated, it also considers a perfect lock, which can be hardly arranged in the considered setup. For these reasons, the actual cantilever curvature has been obtained in an experimental way before the sensor characterization. The measurement procedure is based on a displacement

sensor (LVDT, Linear Voltage Differential Transformer) that is employed to record the deflection along the part of the cantilever where the sensor will be fixed; then the actual curvature is obtained using a circle fitting procedure based on a full least-square method [24]. Fig. 8 shows the experimental setup composed by two translation stages and an LVDT. One stage is employed to bend the cantilever, whereas the second is employed to shift the LVDT in order to acquire the deflection in a portion 25 mm large around the position where the fiber sensor will be fixed. Using this procedure the curvature has been measured in two points: position A, at a distance of 31 mm from the lock, and position B at 56 mm. Fig. 9 shows three curves: the displacement measured around position B when the cantilever tip is deflected by 2 mm (thick curve), the deflection obtained using the analytical model (solid curve), which significantly differs from the theoretical one, and also a portion of the circle best fitting the measurements. Results obtained repeating the measurements both at position A and B are summarized in Table II. The difference between theoretical and measured curvature is of about 1%, in position A and about 4% at position B and, in both positions, the standard deviation of the measured curvature is of about 4%, thus showing a certain agreement between measurements and theory. Anyway, a further investigation concerning the curvature uncertainty would require a more complex mechanical setup, and more accurate displacement sensors so, at least for the purpose of this work, the measurement obtained with the LVDT is considered as the conventional curvature value and its standard deviation is considered as the main uncertainty contribution.

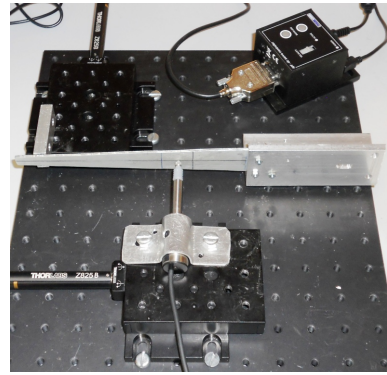


Fig. 8. The mechanical setup employed to calibrate the cantilever.

V. FIBER SENSOR CHARACTERIZATION

A sensor prototype working in transmission mode and manufactured as shown in Fig. 3b) has been tested using the trapezoidal cantilever previously calibrated.

The sensor has been tested in static deformation conditions using the setup shown in Fig. 10 by repeatedly forcing a known deflections having 1 mm amplitude. The DC output of the conditioning circuit has been acquired and the sensor sensitivity has been obtained as:

$$S = 100 \cdot \frac{(V_1 - V_0)/V_0}{C} \quad (\% \cdot \text{m}) \quad (2)$$

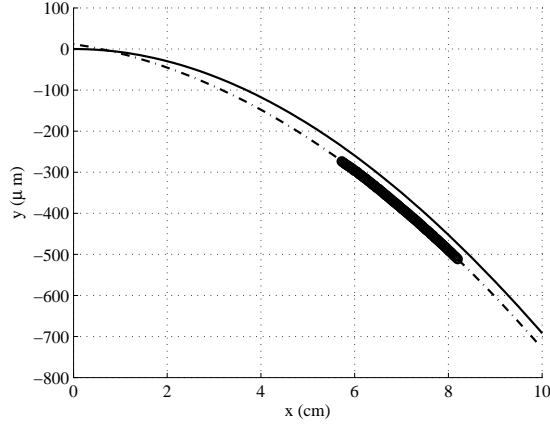


Fig. 9. Comparison between theoretical curve (solid line), measured deflections (thick line) and data fitting of the experimental data (dashed line) obtained at position B.

TABLE II
COMPARISON BETWEEN THE MEASURED AND THE THEORETICAL CURVATURE FOR TRAPEZOIDAL CANTILEVER

Sensor position	C_{theo} (m^{-1})	C_{meas} (m^{-1})	σ_{REL}
A	0.1349	0.1366	$\pm 5\%$
B	0.1226	0.1177	$\pm 4\%$

where V_1 and V_0 are the output voltages in the presence and in the absence of deflection, and C is the curvature as measured in the previous section. The sensor sensitivity has been devised in a ratiometric way thus compensating for optical power fluctuations, whose effects have been quantified in [25].

The sensitivity has been measured at different sensor positions according to the sequence reported in Tab. III. In this way it is possible to account for some uncertainty contributions such as the sensor reproducibility, since the sensor has been fixed and removed after each test, and the time drift, since the tests have been carried out in some hours. The sensitivity measurement has been repeated about 50 times in order to highlight possible stability issues due to the mechanical setup. The standard deviation of the results, also reported in the table, shows that this contribution can be neglected.

The sensor sensitivity measured at the two positions are in good agreement, confirming that the sensor sensitivity does not depend on the position where the characterization is performed. The average value of the results reported in Tab. III has been considered as the nominal sensor sensitivity, and it

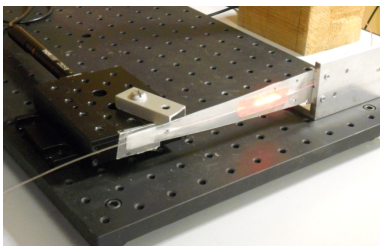


Fig. 10. Setup employed to characterize the curvature sensors.

TABLE III
CHARACTERIZATION RESULTS AT DIFFERENT SENSOR POSITIONS

Test	Sensor position	Sensitivity S ($\% \cdot \text{m}$)	σ_{REL}
1	A	5.68	0.01
2	B	5.78	0.015
3	A	5.50	0.01
4	B	5.68	0.015
5	A	5.70	0.015
6	B	5.72	0.01

is $S = 5.68\% \cdot \text{m}$.

The sensor uncertainty is still under investigation since some contributions, such as the long term stability and the effect that the fiber path has on the light modal distribution, have not been quantified yet. Anyway, a preliminary uncertainty evaluation can be carried out by considering the contributions up to now analyzed, such as the curvature standard uncertainty (4%), the sensor reproducibility during the calibration (2%) and the non-constant cantilever curvature along the sensor area (5%). The overall uncertainty is thus larger than the one provided by other fiber sensors for structural monitoring, like the Fiber Bragg Gratings (FBG). Anyway, other sensor features must be taken into account, such as the very low cost (both of the sensing part and of the interrogation system), and the larger bandwidth limited by the interrogation system and by the fixing method only. Moreover, this sensor does not present the typical limitations that arise in the FBG use, since curvature sensors do not require an efficient bonding to transfer the strain to the fiber core, and they can work along the structure neutral axis where the strain nullifies [1], [13].

VI. EXPERIMENTAL RESULTS

The POF sensor, characterized as described in the previous section, has been employed to measure the deformation of a thin metallic beam (dimensions 12 cm x 3 cm x 2 mm) to assess the performance in operating conditions. The sensor has been fixed using adhesive tape and the beam has been bent using the same translation stage already employed during the sensor characterization. For comparison purposes the beam deformation has also been measured with another fiber sensor, although sensitive to strain and not to curvature since no curvature fiber sensors were found on the market. To this aim, a commercial FBG (produced by Welltech), having a nominal peak wavelength of 1535 nm and a nominal gauge factor of 1.2 $\text{pm}/\mu\epsilon$, has been fixed on the same beam, but on the opposite side, as shown in Fig. 11, in order to undergo the same deformation. The FBG strain has been measured with a commercial FBG analyzer built around a CCD spectrometer having resolution and accuracy of about 100 pm and 15 pm, respectively. The analyzer returns the optical spectrum of the reflected signal, whose peak position is related to the sensor strain. A more accurate estimation of the peak position has been obtained with a subsequent processing based on a gaussian interpolation algorithm that allows improving the resolution to 1 pm.

In order to compare the sensor results, the beam curvature C measured with the POF sensor has been employed to estimate

the strain ϵ using the relationship $\epsilon = h \cdot C/2$ where h is the beam thickness [20].

The POF sensor has been interrogated using the system shown in Fig. 7 and the curvature C has been computed using the sensor sensitivity S determined as shown in the previous section.

Three comparison tests are here reported. During the first test, the linear stage has been programmed to force known deflections from 0 mm to 1 mm at 0.05 mm steps and Fig. 12 shows the absolute value of the strain evolution as measured with the two sensors. The maximum strain change obtained with the FBG is of about $119 \mu\epsilon$, in good agreement with the strain change measured with the POF sensor that is of about $121 \mu\epsilon$. The test also shows that the POF sensor has a good linearity, since the maximum deviation between the sensors is of about $4 \mu\epsilon$.

However, as well known, fiber sensors made with plastic optical fibers suffer from severe stability issues [26]; so the test has been repeated, forcing the same deflection for about 12 minutes, in order to highlight this aspect. The results obtained with the FBG sensor are shown in Fig. 13, where it is possible to see that this sensor presents a drift of about $8 \mu\epsilon$ mainly due to the non-negligible FBG temperature sensitivity, which depends both on the silica refractive index variation (it accounts for about $10 \text{ pm}/^\circ\text{C}$) and on the beam thermal expansion (it accounts for about $22 \text{ pm}/^\circ\text{C}$). During the same test, the POF sensor has shown a larger drift of about $18 \mu\epsilon$, shown in Fig. 14, which is not only due to the temperature effects on the fiber and on the interrogation system, but also on the contribution of the fiber span between the sensor and the interrogation system that in our setup could not be maintained steady. Several techniques have been developed to mitigate these instability effects at least in the short term, such as the usage of reference fiber sensors [18] or dual-wavelength approaches [26]. Nevertheless, these techniques have not been implemented in our setup being not relevant to assess the effectiveness of the proposed characterization setup.

Anyway, a further analysis of the sensor response has shown that the instability affects the offset but not the sensitivity S defined as in Eqn. 2. This is an important result because it implies that the sensor does not require a frequent recalibration. The instabilities in the offset, however, suggest that the sensor is best suited for applications in which the offset is not relevant, such as in the monitoring of low-frequency vibration signals or when the offset can be nullified immediately before the usage (for example when it is possible to load and unload a beam). The sensitivity stability has been experimentally verified during the third test, in which the beam has been deflected every 20 minutes for about 16 days. The strain change has been recorded at each deflection and it is reported in Fig. 15. The measured strain is almost constant, also confirmed by the FBG sensor, and it presents a trend of about $-3 \mu\epsilon/\text{year}$ and a standard deviation of about $0.8 \mu\epsilon$.

VII. CONCLUSION

Sensors able to measure the curvature of structures are attracting an increasing interest because they can overcome

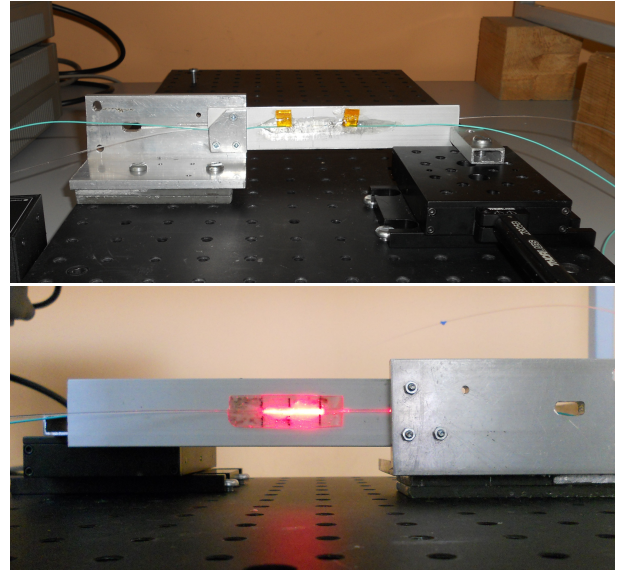


Fig. 11. Set-up employed to compare Bragg (top) and POF (bottom) sensor responses.

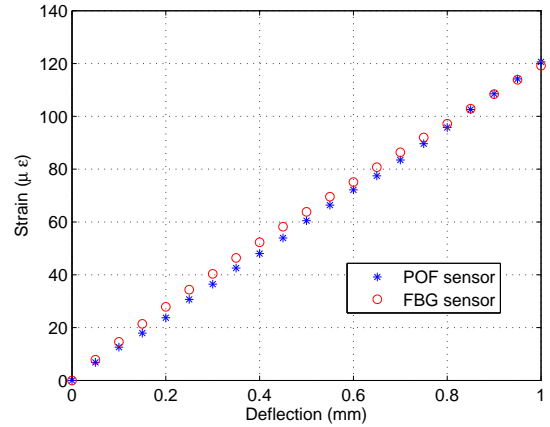


Fig. 12. POF and FBG sensor responses during a single deflection from 0 mm to 1 mm.

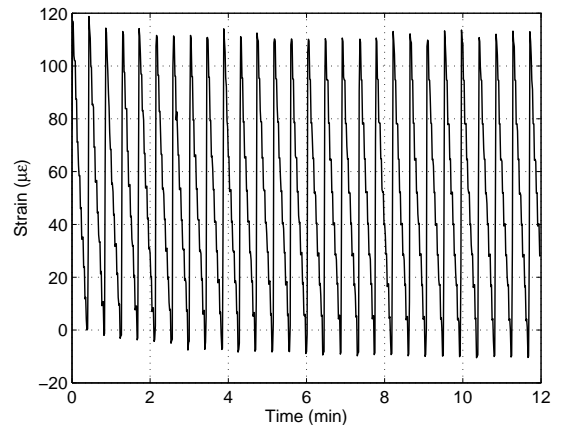


Fig. 13. FBG response during the repeated deflection test.

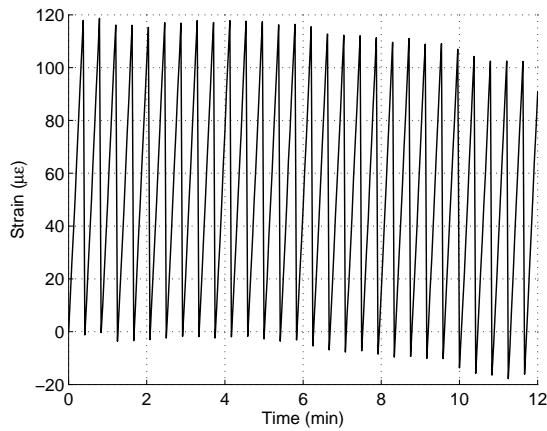


Fig. 14. Response of the POF based sensor during the repeated deflection test.

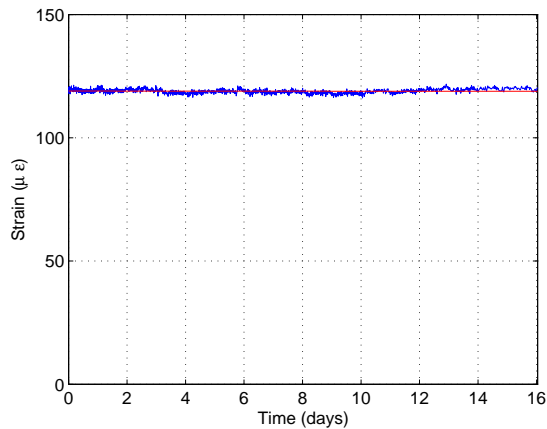


Fig. 15. Beam strain measured at each deflection using the POF sensor.

the cost versus resolution limitations that arise in traditional optical or electrical strain gauges when applied to monitor small and thin structures. A compact fiber-based, yet low-cost, curvature sensor has been investigated and some prototypes based on standard 1 mm plastic optical fiber (POF) have been arranged, both in transmission and in reflection modes.

The characterization of these sensors plays an important role not only to assess the sensor metrological characteristics but also to quantitatively compare sensors developed using different techniques in order to optimize the development procedures. Static and dynamic characterization setups have been devised to work with sensors in transmission and reflection mode. In particular, the paper deals with the static case analyzing and quantifying the main uncertainty contributions, such as the non-uniformity of the curvature, the sensor reproducibility and the curvature uncertainty.

A sensor working in transmission mode has been characterized using a specifically designed trapezoidal metallic cantilever whose curvature has been measured by means of a displacement sensor and a translation stage. The sensor has been subsequently employed to measure the curvature and the strain of a metallic beam. The same beam has been monitored

using a commercial FBG and the results obtained with the two fiber sensors are in agreement. The POF sensor has shown a larger uncertainty and a large stability error, but it presents a very low cost and a larger bandwidth, thus confirming its effectiveness in structural health monitoring, not only in civil but also in industrial applications, e.g. for vibration monitoring of moving parts.

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