Photonic crystals for monitoring fatigue phenomena in steel structures

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This paper introduces the concept and development of a strain sensing system for structural application based on the properties of photonic crystals. Photonic crystals are artificially created periodic structures, usually produced in the thin-film form, where optical properties are tailored by a periodicity in the refractive index. The idea of using the crystal as a sensor is based on the observation that a distortion in the crystal structure produces a change in the reflected bandwidth. When a photonic crystal is designed to operate in the visible part of the spectrum, a permanent distortion of the film results in a change in its apparent color. This property makes photonic crystals suitable for permanent monitoring of structural elements, as any critical changes in the strain field can be promptly and easily detected by visual inspection. A simple and low-cost example of photonic crystals consists of opals synthesized by vertical deposition. In this contribution we introduce a target application for the fatigue monitoring of wind turbines, and then provide the reader with some basic information concerning modeling of the crystal architecture and fabrication of these structures. Next we discuss their application to strain measurement, specifying how reflection and transmission properties of the opals have to be designed to satisfy the expected strain response of the sensor. Finally, we present the preliminary results of a laboratory validation carried out on thin films applied to a rubber support.

Keywords: Photonic crystals, Nanospheres, Strain sensors, Fatigue, Wind turbine, Monitoring, Visual inspection.

1. INTRODUCTION

The strong drive to exploit wind energy has recently led to new types of location for wind turbine installations being considered, including mountain regions and suburban sites. This stems from the realization that “conventional” types of site normally chosen are destined to be used up fairly quickly. Clearly, by comparison with conventional sites, such locations are bound to be more critical, because the more severe weather and wind conditions will have adverse effects on the functional capacity of the wind turbines (which will need to have particular structural features) and on the electricity generated. In fact, this resource is strongly influenced by the lay of the land, being characterized by lower air density, complex turbulence mechanisms and, in winter, very low temperatures and icing conditions. Nonetheless, considerable effort is currently being made to assess the technical and economic feasibility, and the community interest in exploiting wind energy resources in these environments\cite{1}. The installation of wind farms in complex terrains consequently demands in-depth analysis, in the design of such plant, of both the methods for assessing the resource and the more or less direct transfer of procedures and technologies developed for conventional sites. For the time being, the IEC standards\cite{2} (originally developed to provide a reference picture relating to conventional sites) fail to provide recommendations on this type of site, where the structure of the flow field is substantially more complex in terms of its effect on the stresses involved.

A major concern for wind farm installation in these sites is related to the reliability of the supporting structures in the life-long period. Generally, wind-induced vibration can severely damage light high-mast structures. Recent failures of lighting towers have raised questions as to the robustness and safety of the existing inventory of similar structures \cite{3}. Particularly for flexible steel towers, a combination of vortex shedding and natural wind gusts induce fatigue cracking, mainly at the base joint. Small cracks gradually develop due to wind-induced cyclic loads and eventually the cracks with

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highest stress concentration propagate, occasionally resulting in a catastrophic failure. The vulnerability of steel joints to fatigue is often coupled with the corrosion due to the aging of the structure: as corrosion reduces the thickness of metal connections, the likelihood of a failure grows dramatically with the age of the structure. Predicting the strength of these structures is difficult, for a number of reasons. First, because cracks can initiate at different points, including the base flange-to-column weld, the handhole detail and the anchor rods\cite{4}. Second, the response depends on the complex interaction between wind action and dynamic vibration. More specifically, in the steel mast supporting the turbine, the aerodynamic vibration directly induced by wind is always coupled with that produced by the rotor. The latter effect is even more critical when the rotor mass become eccentric as a result of the icing of the blades.

This explains why safe operation of a wind turbine normally requires an appropriate management program including routine inspection and non-destructive checks. Nonetheless, the reliability of the structures supporting the wind turbines can be enhanced via the adoption of permanent instrumented monitoring, as this provides useful information on their health and allows planning and implementation of rational management. In fact, an efficient sensing system provides the owner with a real-time damage estimate and allows maintenance in order to prevent failure. Specifically the system has to be sensitive to the micro and macro crack patterns induced by fatigue load. It is known that the stress intensity factor which controls crack propagation depends on the load applied and on the crack length\cite{5}. Hence instrumented systems measuring the magnitude of the local stress at the critical joints, and sensing techniques aiming to detect small cracks and to evaluate crack dimensions are crucial to improving the reliability of this type of structure. From an economic viewpoint, the installation of an instrumented system is of particular interest in wind farms that are not easily accessible for inspection, such as those in remote mountain areas. In fact, in such cases the high cost of routine management and inspection suggests the alternative adoption of automatic devices for both measuring and communication. In general, fatigue damage monitoring can be coupled with collection of environmental data (temperature, wind speed and direction), measurement of turbine performance, troubleshooting and active control of de-icing systems.

To improve protection of wind turbines against fatigue damage, this paper proposes the use of strain sensors to monitor the propagation of cracks. These sensors will be placed at key points in the structure, such as at the base joint. The strain sensors developed for this application are based on a novel optical technology: Photonic Crystals (PCs), sensitive to the strain field. Specifically, these PCs change their reflectance properties depending on the applied strain field, so that a permanent distortion of the film results in a change in its apparent color. In principle, this feature makes the sensor particularly suitable for the permanent monitoring of structural elements, as any critical changes in the strain field can be promptly and easily detected by visual inspection. Despite these devices still being in their infancy, and the applications limited to laboratory demonstration, this technology is very promising for fatigue damage detection. This as it allows a reconstruction of the strain field in critical zones, such as around the cracks. In a future scenario, this kind of sensor could be directly integrated in the construction of steel joints. In particular this sensing technology can produce a 2-dimensional image of the strain field, highlighting both the discontinuities induced by cracks and stress concentration at the crack tips. Many practical issues are still to be overcome to realize this possibility, but the research we present is a first step in this direction.

This paper is organized as follows: section 2 describes the wind turbine selected for the monitoring application, as well as the wind farm where it is located, and predicts the relation between fatigue-induced damage and strain response. Section 3 introduces the concept of Photonic Crystal (PC), its potentiality for strain sensing and then reports the procedure adopted for sensor production. Section 4 reports and comments the outcome the laboratory tests on prototypes of the PCs. Section 8 draws conclusions on the applicability of the proposed technology.

2. THE WIND TURBINE AND ITS STRAIN SENSITIVITY TO FATIGUE DAMAGE

The whole project targets the application of strain sensors to a wind turbine at the Trento Experimental Wind Farm\cite{6,7}. The objective of this farm is to create a reference in research on wind energy employment in Italy and Europe. It provides the necessary equipment for analysis and comparison of structural and functional characteristics of mini and micro wind turbines. In particular, the extensive use of such turbines, their technical and “economic” efficiencies, their environmental and acoustic impact and the problems during installation and removal are experimentally assessed in the farm. The wind turbines and the masts are set up with classical sensors, which acquire fluid-dynamic, functional and structural data. The data is recorded by an acquisition system at the wind farm and then sent to the Turbomachinery Laboratory of the University of Trento to be post-processed. To date there are two mini turbines, one three blade upwind turbine (rated power 20kW, tower height 18m, rotor diameter 8m), one two bladed downwind turbine, named GAIA, (rated power 11kW, tower height 18m, diameter of the rotor 13m) plus one three bladed upwind wind micro turbine...
(rated power 1kW, tower height 9m, diameter of the rotor 1.8m). Two dedicated wind measurement masts are placed according IEC standards near each of the larger wind turbines. These have sonic anemometers at two heights, 9m and 18m that allow wind turbulence to be fully characterized. This experimental setup is of paramount importance to investigate the dynamic behavior of the wind turbines.

Because of the wide use of this type of rotor in Europe, the two bladed GAIA wind turbine, shown in Fig. 1, has been chosen as a case study for this application. This turbine has more sophisticated instrumentation, partly because the machine layout was particularly suited for this purpose and partly because the rotor has been installed on a tubular tower, despite the original project having a lattice tower. We expect that the aerodynamic interaction of the blades with the upstream standing tower, will cause large fluid-dynamic effects and stress levels in these components, with increased fatigue on both. Another set of sensors is dedicated to energy measurements. The tubular GAIA tower is 18m tall, made in three pieces bolted together. An experimental modal identification of the structure was carried out by positioning 6 accelerometers along the tower and inducing impulse excitation. As an example of results, it is estimated that the first bending mode of the tower presents an Eigen-frequency of 1.26Hz and a damping ratio of 6.3%. These findings have been used to tune the numerical model employed in prediction of damage effects. One of the most critical parts of the tower is the base joint between the steel mast and the concrete foundation. This joint consists of a bolted ring flange, connected to the tubular mast by two welded joints, one above and one below the ring. This type of joint is particularly prone to fatigue damage because of the flexibility of the flange. Thus, research has been focused particularly at this point, investigating the local effects of fatigue damage.

Fig.1: Scheme (a) and (b) picture of one of the GAIA wind turbines at the Experimental Wind Farm in Trento.
The sensing principle selected for the monitoring system is based on local strain measurement at the critical joints. The reason for this choice is that the local response is much more sensitive to the crack patterns. In order to design a sensing system suitable for efficient strain monitoring in the application selected, we must investigate and quantify the effect of a crack induced by fatigue on the strain response of a wind mast. To this purpose, two Finite Element Models (FEMs) have been developed by using ANSYS software to predict the structural response of the steel tower to wind load, both in terms of crack propagation and of the strain field around the cracks. In particular, we assume that a horizontal crack can appear at the base joint, at the weld between ring and tube, due to fatigue.[8]

A global FEM has been developed using shell elements, to predict the response of the whole tower under various environmental conditions (Fig. 2a). The wind loads are derived from a static pressure related to a horizontal velocity of 60m/s, and are applied to the global model, taking into account the effects on the blades and rotor and on the tower itself. As an output of the global model, the displacement field at the border of a volume of about 1m³ around the crack location is computed. In turn, these displacements are employed as assigned inputs to a local FEM, developed using 3D elements (Fig. 2b). This second model aims to predict with high resolution the response near the tips of the crack. As an output, both the strain field and the intensity factors are derived by such a local model (Fig. 2c).[9]

These numerical simulations investigate the effects of different crack sizes, from 20mm up to 160mm, on the strain field. Particularly it is possible to follow the strain variation along whichever direction, as the crack grows. As an example of a result, a 120mm crack produces a variation of 0.6\(\varepsilon\) in the vertical strain just 50mm above the mid-point of the crack, under wind load. Hence a strain sensor capable of detecting such a variation will be able to identify the crack at that level of propagation.

In general, the strain field due to a crack is inhomogeneous (as Fig. 2c shows): it shows high concentrations around the crack tips and a specific pattern of stress increment and release. While the point measure is highly influenced by spurious thermal and wind loads, the strain pattern is a “fingerprint” of the specific fatigue damage. Hence, a sensor able to distinguish the effect of a crack should be able not only to provide a point measurement, but also to estimate the strain field over a relevant area. Obviously this can be done by installing a high number of mono-dimensional strain gauges, but it would surely be more economic to install a distributed 2-dimensional sensor. The technology presented in the next section addresses this requirement: despite being still at a research level, this solution can lead to a “spread sensor” able to actually show the strain field as a colored picture, as does FEMs software.
3. PRINCIPLE AND PRODUCTION OF PHOTONIC CRYSTALS

This paper proposes creation of a distributed sensing system based on the application of special nano-structures called PCs. These consist of colloidal spheres in solution, organized into a 3-dimensional crystalline lattice. The size of the spheres and their polydispersivity are such that the crystal acts as a periodic photonic band-gap or as a narrow-band mirror. In other words it reflects or transmits only a specific wavelength range. These structures can be used in photonic devices such as switches, mirrors, filters and superprisms\textsuperscript{[10]}. This kind of PC can be fabricated as a soft film deposited on a flexible support. Spheres can be of silica or polystyrene, with diameters from 100 to 1000nm, and the opal PC can be infiltrated with various solutions, such as an elastomer. Following the idea originally suggested by Fudouzi\textsuperscript{[11],[12]}, these crystals can also be used as optical strain sensors, to monitor and display structural and environmental variations in terms of color change, which can be visualized by appropriate optical instruments or even by the naked eye.

The reflectance properties of the narrow-band mirror depend on the mechanical condition of the PC, and by an appropriate selection of the optical properties, the stop bands can be placed in the visible range. Generally, the overall reflecting behavior of the PC can be express by the modified form of Bragg's law\textsuperscript{[13]}:

\[
\lambda = 2 \cdot d \cdot \sqrt{(n_{\text{eff}})^2 - (\sin \theta)^2}
\]

where \(\lambda\) is the free-space wavelength of the light, \(d\) is the inter-planar spacing, \(n_{\text{eff}}\) is the effective refractive index and \(\theta\) is the angle measured from the normal to the planes\textsuperscript{[10]}.

When an axial strain is applied to the PC, the inter-planar spacing is modified by the transversal contraction, as illustrated in Fig.3. Hence the initial value \(d_0\) is reduced to value \(d(\varepsilon)\) depending on the applied strain value \(\varepsilon\). As a side effect, the refractive index \(n_{\text{eff}}\) is also linearly affected by the stress variation\textsuperscript{[14]}. The combination of these two effects renders the reflectance properties of the PC, and particularly the wavelength peak in reflection, sensitive to the applied strain. Once the relation is known, a measure of the color reflected by the PC can be used to estimate the strain inherited from the structure to which it is attached. It appears from Eq. 1 that for angles greater than zero the peak shifts to shorter wavelengths. This phenomenon induces a possible disturbance on the strain measure, as a variation in the incident angle can be wrongly understood as a strain variation. To overcome this problem, the interrogating system should be able to find the minimum value of \(\lambda\) by varying the incident angle: this is related to \(\theta=0\), and depends only on \(d(\varepsilon)\). As a final remark, we note that the transversal deformation encoded in \(\lambda\) is sensitive to the strain in both orthogonal directions on the plane on which the sensor is attached.

\[\varepsilon = \frac{\Delta l}{l}\]

Fig.3: Dependence of the inter-planar spacing from the applied strain. Comparison between the initial (upper figure) and strained (lower figure) configurations.
A variety of methods have been developed in the last decade to create colloidal crystals: such as vertical deposition\cite{15}, electrostatic repulsion\cite{16}, capillary force induced convective self-assembly\cite{17,18}, and electric field induced assembly\cite{19}; depending on the technique adopted, the production time ranges from days to weeks. Recently, some of the authors of this paper described a simple and effective method to obtain monosize polystyrene spheres and in turn, to realize colloidal photonic crystal structures from these spheres, based on spin coating technique\cite{20}. Despite the array of advanced techniques available, the PCs developed as strain sensors for the application presented in this paper have been produced by using the most classical technique, i.e. vertical deposition. This is the simplest and cheapest technique at the moment, while the main drawback is that it is time-consuming.

The crystal we produced was made with polystyrene spheres (PSs) embedded in a poly-dimethylsiloxane (PDMS) elastomer. We applied a three step technique: first the PSs which will form the opal structure are produced; then these are arranged in a lattice structure on the support; and last they are infiltrated with the elastomer. In the first step we mix styrene, water, a surfactant (SDS) and a polymerization initiator (K$_2$S$_2$O$_8$), while controlling temperature and stirring speed (Fig.4a). As to the parameters selected, the PSs were produced with a diameter of about 230nm. This value was chosen to obtain a suitable PC color; the size can be modified by applying a different fabrication protocol.

Then, in the second phase, a highly mono-dispersed PS suspension is deposited on a Viton substrate of size 50x15x1mm. This material is very flexible and therefore suited to a large deformation. The substrate was placed vertically in a beaker containing the water suspension and put in oven at constant temperature of 50°C. Two days were needed to deposit the PC on the support. During this time, crystallization is initially driven by strong attractive capillary forces acting between particles at the drying front when the liquid film reaches a thickness of the particle diameter (Fig.4b). This effect drives particles to aggregate in layers and creates a porous structure with high specific surface area. The large surface area facilitates solvent evaporation. The thickness of the PC is in the order of 10μm.

Then in the third step the lattice was infiltrated with (polydimethylsiloxane) PDMS (Sylgard 184, Dow Corning) (Fig.4c). The elastomer was supplied as a kit with two separate components: base and curing agent. We mixed base and curing agent in a 3:1 ratio. After infiltration the PDMS was cured for 4h at 65°C and then the excess elastomer was peeled-off from the crystal. Several infiltration cycles were necessary to completely fill the voids between the PS spheres, before any re-infiltration step the sample was swollen in a silicone fluid (Dow Corning 1cSt). The composite film obtained was a 3D lattice of PS spheres embedded in a PDMS matrix. The elastomer has the fundamental function of providing a flexible PC structure that can be handled. Furthermore this process affects the range of deformability of the PC. In fact, infiltration prevents direct contact between the PSs under transversal contraction, avoiding non-linear effects in the strain response.

![Fig.4: Production of the Photonic crystals: fabrication of the Polystyrene Spheres (a), vertical deposition (b), infiltration (c).](image-url)
Fig. 5a shows the Scanning Electron Microscopy (SEM) picture of a PC infiltrated with the elastomer. The PC appears red while it is not stressed, and turns green as a tensile strain is applied. The picture in Fig. 5b shows the effects of looking at the PC we fabricated at different angles $\theta$. Visual inspection shows that the value of the reflected peak wavelength $\lambda$ is of the order of 650nm (when $\varepsilon$ and $\theta$ are null). Now if we suppose that the PSs are in contact, than Eq. 1 predicts a value of reflected peak $\lambda=550$nm. Hence the actual color of the PC shows that the PSs are separated by the elastomer, and that $d$ is larger than their diameter. This observation highlights the relevance of phase three for definition of the optical properties of PC. This suggests we continue fabrication of the PC by adding a further step of “swelling”, in which the crystal is more and more infiltrated by additional elastomer.

4. EXPERIMENTAL VALIDATION OF PC PERFORMANCE

A prototype sample of PC, produced with the above technique, has been tested in the laboratory to identify the relationship between the applied strain and the wavelength of the reflected peak. The PC is a 10x10mm layer and, as described before, was deposited on a 50x15x1mm rubber support. As shown in Fig. 5b, the crystal looks red when observed perpendicularly, and turns green when seen from the side.

During the test, the strip is fastened to two micrometric linear stages, so that the centre of the PC is kept fixed, while symmetrically elongating the ends. Thus the applied field is basically a mono-axial strain, and the test is carried out by elongating the support. Fig. 6 shows the experimental set-up. The diffraction characteristic of the PC was recorded using a spectrometer. This is composed by a light source, a light receiver and a spectrometer analyzer. Both source and receiver are connected to a probe that allows easy inspection of the PC surface. During the test the probe was kept perpendicular to the strip. The output of this instrument is the full spectrum of the received light in the visible range (350-1050nm), with a wavelength resolution in the order of 0.1nm. The area of the PC inspected by the device is about 4mm$^2$: hence it is a local measure. The spectrum presents a single peak, due to its uniform color, depending on strain and on angle $\theta$, according to Eq. 1.

The PC underwent a deformation cycle, from an original length of 14.0mm up to 17.0mm, corresponding to a maximum elongation of 3mm and a strain 21.4%, and then down to 0.5mm absolute elongation. As reported in Table I, the whole cycle included 10 steps: at each step, the reflectance spectrum was measured. In the same table, $\lambda$ indicates the wavelength of the diffraction peak. The results are reported in Fig. 7a: the shape and the width of the band are almost constant during the test, while the peak wavelength and amplitude change. The attenuation depending on the strain is a well known phenomenon[11]. Each spectrum presents a clear bell-shape, with a width of about 30nm. The wavelength shift of the peak occurs in the range 637-651nm.
Fig. 6: Scheme (a) and (b) picture of the set-up for the laboratory test on the photonic crystal.

TABLE I: Test protocol and results

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<th>4</th>
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<tr>
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Fig. 7: Reflectance spectra of the infiltrated PC recorded during the elongation test (a) and Experimental relationship between the peak positions and the strain as a result of the elongation tests (b).
Fig. 7b shows the experimental relationship between the peak wavelength and the applied strain, recorded during the load cycle. As expected from Eq. 1 and Fig. 3, the wavelength decreases as the strain increased, and the average slope is estimated at about $\Delta \lambda_p/\Delta \epsilon = -63 \text{pm/m} \epsilon$. The hysteresis between the loading and the unloading phases is probably due to irreversible deformation on the Viton support. Comparing with prediction of Eq. 1, this finding is compatible with a low Poisson ratio, of the order of 0.2.

Considering the wavelength resolution of the instrument we used, the corresponding strain resolution is about 1.5m\(\epsilon\). This is not fully satisfactory for the target application, if we compare this result with the response analysis presented in section 2. Moreover the main drawback of the PC we obtained is that a variation of strain up about 20% does not induce a color variation visible to naked eye. This is because the strain-free reflectance wavelength (650nm) is too far from any color transition. If that value was about 600nm, the same 20nm wavelength variation would induce a transition between red and yellow. Work is in progress in order to optimize the system looking for new substrates as well as for a free strain photonic resonance in visible light.

5. SUMMARY

The laboratory results show that a strain sensor based on a PC can be made: the reflected color is sensitive to the applied strain and hence a measure of the reflected peak wavelength can lead to an estimate of the deformation of the structure to which the sensor is attached. The sensitivity to strain is today too low, and the color is not appropriate for visual inspection. Nonetheless, both features will be improved by further research on the fabrication of PCs. The strain-free color depends on the diameter of the PSs and on the number of swelling processes: appropriate tuning of these parameters can change the reflected wavelength so that the color appearance will be more sensitive to the applied strain.

At the current state of the art, comparison with optical strain sensors available off-the-shelf, such as those based on the Fiber Bragg Grating\(^{[14]}\), shows that the performance of PCs is much lower. In fact, the resolution of these sensors is of the order of 1\(\mu\)\epsilon\. This due to 3 facts: the width of the reflected peak is of the order of 20pm (as the grating is about 20mm long), the precision of the spectrum analyzer is about 1pm, and the grating is deformed directly by the structural strain to be measured and not by the transversal strain. Even though we do not expect to reach similar performance with the PCs, we point out that in order to recognize fatigue damage it is essential to reconstruct the planar strain field around cracks.

This paper reports the first results of an ongoing research project aimed at investigating the use of Photonic Crystals for health monitoring of wind turbines. This technology seems very promising for measuring the strain variation induced by fatigue cracks. In a future scenario, the whole steel joint could be covered by a continuous PC layer, and the optical properties calibrated so that the cracks would induce an apparent color variation, visible at least near the stress concentrations. The next step of the project will develop new PCs that will improve the performance seen so far.

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