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Damage monitoring using fiber optic sensors and by analysing electro-mechanical admittance signatures obtained from piezo sensor

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ABSTRACT

Damage monitoring is the need of the hour in this age of infrastructure. Many methods are being used for damage monitoring in different mechanical and civil structures. Some of them are strain based methods in which abruptly increased strain signifies the presence of damage in the structure. This article focuses on crack monitoring of a fixed-fixed beam using fiber optic sensors which can measure strain locally or globally. The two types of fiber optic sensors used in this research are fiber Bragg grating (FBG) and fiber optic polarimetric sensors (FOPS). FBG and FOPS are used for local strain monitoring (at one point only) and global strain monitoring (in the entire specimen) respectively. At the centre of the specimen, a piezoelectric wafer active sensor (PWAS) is also attached. PWAS is used to obtain electro-mechanical admittance (EMA) signatures. Further, these EMA signatures are analysed to access the damage state in the beam. These multiple smart materials together provide improved information on damages in the specimen which is very valuable for the structural health monitoring (SHM) of the specimen.

KEYWORDS

Fiber optic sensors, fibre optic polarimetric sensor (FOPS), fibre Bragg grating (FBG), piezoelectric wafer active sensor (PWAS), damage/crack monitoring, crack monitoring.

1. INTRODUCTION

Damage monitoring in different structures has been one of the most pressing issue in the field of structural health monitoring (SHM). Several smart materials have been proposed and researched for this purpose. Fiber optic sensors have been researched by many researchers around the world for possible damage monitoring in different mechanical and civil structures [1-4]. Fiber optic sensors offer a significant number of advantages which includes immunity to electromagnetic interference, electrically passive, long term stability, light weight, small size, multiplexing capabilities, ease of installation and durability. Also, complicated post processing is not required in case of fiber optic sensors; therefore, they facilitate real time structural health monitoring (SHM) [4]. Fiber Bragg gratings (FBGs) monitor a much localised area around them and therefore they are used for local strain measurement only [5]. Thus, FBGs can monitor damages only locally. FBG sensors are used for SHM of composite structures by embedding them into composite structures [6]. Recently, small diameter FBG was developed for the measurement of non-homogenous internal strain fields [7]. Fiber optic polarimetric sensors (FOPS) are used for global SHM i.e. FOPS indicate the presence of damage in the structure irrespective of the damage location in the structure however, finding location of damage using FOPS is very challenging [8, 9]. Recently, it was proved that FOPS can locate the damage in cantilever structures [10]. Overall, a single fiber optic sensor is not enough to get a promising picture of damage state in the structure.

Piezoelectric materials are very active smart materials as they actuate under electric field and also sense the reactions. Piezoelectric sensors can play a very important role in SHM industry. Piezoelectric wafer active sensors (PWASs) are either bonded on the surface or embedded in the host structure which is to be monitored. Electromagnetic admittance [EMA] signature is obtained using PWAS to access the health of the host structure [11, 12]. PWASs are used for the determination of pressure, acceleration, strain or force [13-16]. Again, PWAS alone cannot be used to provide sufficient information on damage in the structure.

Thus, it can be said that a single smart material cannot present the complete health assessment. Employment of multiple smart materials was suggested to get a clearer understanding of damage occurrence in different structures [17, 18]. This paper thus focuses on using multiple smart materials. In this study three types of smart materials; fiber Bragg grating (FBG), fiber optic polarimetric sensor (FOPS) and piezoelectric wafer active sensor (PWAS) are employed together for crack monitoring in a fixed-fixed beam. FBG monitors cracks in the central region of the beam by monitoring strain at the center. FOPS monitors cracks in a certain part of the specimen by monitoring strain in the same part of the specimen. The frequency peaks in the PWAS's EMA signatures change significantly due the cracks in the specimen. All these smart materials together present a much better health assessment of the beam.

2. THEORY

2.1 FBG

The fiber Bragg grating is a periodic structure of refractive index inscribed in the core of a photo sensitized fiber by exposing it to a high power excimer laser (248 nm) through a phase mask. The wavelength reflected by FBG is called Bragg wavelength and is given by

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

Where, n_{eff} is the effective refractive index of the mode propagating along the fiber and Λ is the grating period of the FBG. If FBG goes through any longitudinal strain, the grating period (Λ) of FBG will change resulting in the Bragg wavelength shift [19]. The strain is calculated by measuring the change in the Bragg wavelength as

$$\varepsilon = \frac{\Delta\lambda_B}{\alpha} \quad (2)$$

Where, $\Delta\lambda_B$ is the shift in the Bragg wavelength and α is the wavelength-strain sensitive factor and its value is $0.67 \mu\text{e}^{-1}$ for 850 nm.

2.2 FOPS

In FOPS, polarization maintaining (PM) fiber like, bow-tie fiber is used. In the high birefringent medium of PM fiber, the light travels in two mutually orthogonal modes of polarization; fast mode and slow mode. Fast mode travels faster than the slow mode in high birefringent medium. This difference in velocities introduces an additional phase between both the modes. This additional phase is given by

$$\Delta\phi = \Delta\beta L \quad (3)$$

Where, L is the length of the fiber and $\Delta\beta (= \beta_{fast} - \beta_{slow})$ is called the 'birefringence' of the fiber. Under the application of longitudinal strain, the length L of the core of PM fiber changes which means the phase ($\Delta\phi$) between both the fast and slow modes changes. As a result, the polarization of the light coming out of the fiber, changes. The polarization of light changes sinusoidally with increasing longitudinal strain. The light passes through an analyzer before it reaches the photodiode, therefore, the output intensity (or voltage V) of the light measured by photodiode also changes sinusoidally [9]. In the loading test conducted with FOPS, a normalized output parameter called state of polarization (SOP) is calculated as

$$SOP = \frac{V - V_{av}}{V_R} \quad (4)$$

Where $V_{av} = (V_{max} + V_{min})/2$ is the average photodiode voltage and $V_R = (V_{max} - V_{min})$ is the range of the variation of the photodiode voltage from first loading step to last loading step. Following photodiode voltage V , SOP also changes sinusoidally. The cycle of SOP variation depends on the beat length ($L_b = 2\pi/\Delta\beta$) of the PM fiber used. A phase change of 2π in SOP cycle means a change of L_b in the length of PM fiber used as FOPS. The SOP cycle is segmented to calculate total strain in the specimen [18].

2.3 PWAS

In PWAS, the damage is monitored by measuring the change in the electromagnetic admittance (EMA) signature of PWAS. The presence of damage in the host structure affects its admittance. The admittance of the PWAS can be measured by an electrical analyzer. An alternative voltage signal of 1 volt rms is applied to the bonded PWAS patch (Figure 1) over the user specified frequency range. The change in extracted admittance signature is an indication of structural loading or damage occurrence [20]. The admittance signature comprising of peaks, is a function of stiffness, mass and damping of the host structure.

The amplitudes of peaks obtained in the admittance signature of PWAS are proportional to the natural frequencies of the host structure. The occurrence of damages in the structure changes the natural frequencies of the structure and therefore, the peak amplitudes in the admittance signature change. This technique employs low-cost and low-power PWAS patches which can be non-intrusively bonded to the structure and can be interrogated without removal of finishes. One-dimensional approach to model PWAS-structure interaction has already been proposed [21]. The admittance of the PWAS sensor is expressed as

$$Y(\omega) = j\omega \frac{w_a l_a}{h_a} \left(\left(\bar{\epsilon}_{33}^T - d_{31}^2 \bar{Y}^E \right) + \left(\frac{Z(\omega)}{Z(\omega) + Z_a(\omega)} \right) d_{31}^2 \bar{Y}^E \left(\frac{\tan \kappa l_a}{\kappa l_a} \right) \right) \quad (5)$$

$$Y(\omega) = G + jB \quad (6)$$

Where, Z_a and Z are the mechanical impedances of the PWAS patch and the host structure, respectively; j is the imaginary unit; ω is the angular frequency of the driving voltage; w_a , l_a and h_a are the width, length and thickness of the PWAS patch, respectively; $\bar{Y}^E = Y^E(1 + j\eta)$ is the complex Young's modulus of the PWAS material at zero electric field; d_{31} is the piezoelectric constant; $\bar{\epsilon}_{33}^T = \epsilon_{33}^T(1 - j\delta)$ is the complex dielectric constant; η and δ denote the mechanical loss factor and the dielectric loss factor of the PWAS material, respectively; κ is the wave number which is related to the angular frequency of excitation ω by $\kappa = \omega \sqrt{\rho / \bar{Y}^E}$; and ρ is the material density of the structure. G is real component of admittance, i.e. conductance and B is imaginary component of admittance, i.e. susceptance. Equation (5) indicates that the admittance of PWAS patch is directly related to the mechanical impedance (inverse of admittance) of the host structure. Therefore, any change in the admittance signatures is an indication of a change in the structural integrity. The signature comprises of both the conductance and susceptance.

3. EXPERIMENTS AND RESULTS

In this research, three smart materials; FBG, FOPS and PWAS are bonded with an aluminum beam of dimensions 800 x 50 x 2.67 mm³. The schematic of specimen beam with all the three smart materials is shown in the Figure 1. The instrumentations of FBG, FOPS and PWAS are also depicted in the Figure 1. The FBG was bonded at the center of the beam to monitor strain at the center point. FBG uses a light source and an interrogation system. FOPS was bonded in the length of 45 cm of the beam as shown in Figure 1, therefore, it measures the total strain within that length of 45 cm. FOPS uses a light source and a DAQ system to record the data. PWAS was also bonded at the center of the beam. PWAS uses LCR meter to acquire the EMA signature.

Figure 1. Schematic of specimen with multiple smart materials.

Figure 2. Schematic of experimental setup with cracks at locations 1, 2, 3, 4 and 5.

The specimen beam was fixed at both of its ends and then it was loaded at its center through a hanger (130 gms) as shown in Figure 2. The beam was loaded incrementally in the steps of 200 gms and the data were recorded by FBG interrogator, FOPS's DAQ system and PWAS's LCR meter. After the first set of data recording, all the weights were removed from the hanger and a crack was made at location 1 as shown in the Figure 2. Further, the beam was loaded incrementally with the same loading steps and the second set of data was recorded. Similarly, additional cracks were made at locations 2, 3, 4 & 5 and third, fourth, fifth and sixth data sets were recorded accordingly.

3.1 Measurement by FBG

The strain measured at the center of beam by FBG with increasing load is shown in the Figure 3. The strain is plotted against load for every crack scenario from 'No crack' to 'Cracks 1,2,3,4 and 5'. The load versus strain lines are almost overlapping for every crack scenario except 'Cracks 1,2,3,4 and 5' where a crack is made close to FBG. In this case, the slope of the load versus strain line changes significantly. Clearly, FBG can monitor damages in its vicinity only.

Figure 3. Strain measured by FBG for different crack scenarios.

3.2 Measurement by FOPS

In FOPS, the intensity of light coming out of fiber is measured by a photodiode, which is recorded by the DAQ system. This intensity changes sinusoidally with increasing load and therefore, the SOP (equation 4) value changes sinusoidally as shown in Figure 4. The period of SOP cycle reduced with increasing damage in the beam. This reduction in SOP cycle is subtle therefore; it is not so visible in Figure 4. The total length of the FOPS used in this experiment is 45 cm. Since the beat length of the PM fiber used in this experiment is 2.8 mm, one complete cycle of SOP variation corresponds to 2.8 mm increment in the fiber length or the specimen length. Similarly, a quarter SOP cycle will correspond to 0.7 mm increment in fiber length. Following this, each SOP cycle is segmented to calculate the total longitudinal strain in 45 cm length of the beam at various points. Thus, FOPS can be used to calculate the total strain over a certain length. The total strain in 45 cm length is plotted against increasing load in Figure 5. The load versus strain lines corresponding to 'No crack', 'Crack 1' and 'Cracks 1 and 2' are almost overlapping. Such is the situation because in these cases the cracks are outside the 45 cm length of FOPS (see Figure 2 for crack locations). When additional cracks are induced in the part of specimen where FOPS is present (Crack locations 3, 4 and 5), the slope of the load versus strain line increases significantly which is apparent in Figure 6. Thus, FOPS measures strain in its entire length leading to crack monitoring in certain length of specimen.

Figure 4. SOP cycles of FOPS for different crack scenarios.

Figure 5. Total strain measured by FOPS in 45 cm length of specimen for different crack scenarios.

3.3 Measurement by PWAS

EMA signatures of the specimen were obtained for every crack scenario (from 'No crack' to 'Cracks 1,2,3,4,5') for the frequency range from 10 KHz to 150 KHz at a sweep step of 0.25 KHz. The EMA signatures with increasing number of cracks (from 'No crack' to 'Cracks 1,2,3,4,5') for No load condition are shown in Figure 6. From these EMA signatures, it is difficult to make any observation as such. To study the effect of cracks on EMA signature, the Root Mean Square Deviation (RMSD) index is calculated for different crack scenarios. The effect of cracks is reflected in the pattern of Root Mean Square Deviation (RMSD) index [22, 23]. RMSD is used to compare the EMA signatures of two different states. It is defined as

$$RMSD-k (\%) = \sqrt{\left[\frac{\sum_{i=1}^N (y_i^k - x_i^1)^2}{\sum_{i=1}^N (x_i^1)^2} \right]} \times 100 \quad (7)$$

Where, i ($= 1, 2, 3 \dots N$) represents the peak number in the signature and k ($= 2, 3, 4 \dots N$) represents the crack scenario. x_i^1 is the amplitude of i^{th} peak in base condition signature which is the ‘No crack’ signature in this case and y_i^k is the amplitude of the same i^{th} peak at k^{th} crack scenario. In this study, the RMSD essentially compares the base condition signature (or the ‘No crack’ signature) with the later signature with k^{th} crack scenario. The crack scenarios from ‘Crack 1’ to ‘Cracks 1,2,3,4,5’ were taken with $k = 2$ to $k = 6$, respectively. Hence, the RMSD indices were calculated with respect to ‘No crack’ signature. The RMSD indices with increasing cracks are given in Table 1. Clearly, the RMSD index increases drastically with increasing damage in the specimen.

Figure 6. EMA signatures with increasing cracks for ‘No load’ condition.

Crack scenarios	RMSD (w. r. t. ‘No crack’ signature)
No crack (base step)	
Crack 1 ($k = 2$)	13.23
Cracks 1,2 ($k = 3$)	17.30
Cracks 1,2,3 ($k = 4$)	20.51
Cracks 1,2,3,4 ($k = 5$)	24.08
Cracks 1,2,3,4,5 ($k = 6$)	25.81

Table 1. RMSD indices with increasing cracks and at ‘No load’ condition.

4. CONCLUSIONS

One smart material or sensing technology is not sufficient for damage monitoring in a structure. Improved information on damage in any structure can be obtained by using multiple smart materials. In this research, three smart materials; FBG, FOPS and PWAS are used for damage monitoring in an aluminum beam. FBG monitors damages in the central region of the beam. On the other hand, FOPS can monitor damages in a pre-decided length (45 cm in this case) of specimen through total strain monitoring. In case of PWAS, EMA signature varies substantially due to occurrence of damages in the specimen. The higher the damage in the structure the greater is the change in the RMSD value. Thus, RMSD quantifies the severity of damage in the specimen. Multiple smart materials employment has a great scope for further investigation.

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