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Test method

Monitoring Poisson's ratio of glass fiber reinforced composites as damage index using biaxial Fiber Bragg Grating sensors

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ABSTRACT

Damage accumulation in Glass Fiber Reinforced Polymer (GFRP) composites is monitored based on Poisson's ratio measurements for three different fiber stacking sequences subjected to both quasi-static and quasi-static cyclic tensile loadings. The sensor systems utilized include a dual-extensometer, a biaxial strain gage and a novel embedded-biaxial Fiber Bragg Grating (FBG) sensor. These sensors are used concurrently to measure biaxial strain whereby the evolution of Poisson's ratio as a function of the applied axial strain is evaluated. It is observed that each sensor system indicates a non-constant Poisson's ratio, which is a sign of damage accumulation under the applied tensile loading. As the number of off-axis plies increases, transverse strain indicates a notable deviation from linearity due to the formation of transverse cracking, thereby leading to a larger reduction in Poisson's ratio as a function of applied axial strain. Here, it is demonstrated that biaxially embedded FBG sensors are reliable to monitor the evolution of Poisson's ratio, unlike biaxial strain gages which record strain values that can be significantly influenced by the cracks formed on the surface of the specimen.

1. Introduction

Glass or carbon fiber reinforced polymeric composites have received a great deal of attention due to their high specific strength and stiffness for structural applications. The relatively high specific strength of composite materials makes them suitable for applications where the weight and operating costs are intimately coupled. In comparison to metallic materials, where the failure is usually triggered by a single crack during their service life, composite materials exhibit poorly characterized damage mechanisms due to the existence of multiple cracks, which makes the prediction of service life rather complex and difficult. Therefore, in literature, there are several approaches developed and investigated to understand the accumulation of damage and damage state of composite structures under static and dynamic loading conditions. For example, Highsmith and Reifsnider studied stiffness reduction as a damage indicator in composite materials [1]. Several researchers examined the reduction of Poisson's ratio as a damage indicator [2–5] since Poisson's ratio ($\nu_{xy} = -\varepsilon_y/\varepsilon_x$) embodies both axial and transversal strain (ε_x and ε_y, respectively) information and is affected by the transverse cracks formed as a result of applied longitudinal strain [6–8]. Paepegem et al. [6] investigated the evolution of Poisson's ratio of composite materials as a function of applied longitudinal strain, and showed that Poisson's ratio decreases with the applied strain. Smith et al. [8] modelled the evolution of Poisson's ratio using a shear-lag theory under static loading conditions, correlated their analytic model with experimental results, and indicated that Poisson's ratio decreases as the transverse crack density increases.

The measurement of Poisson's ratio of composites subjected to dynamic and static loading has mainly been performed using strain gages and extensometers. Due to their size, these sensors cannot be embedded in composite structures, and thus measure the strain from the surface. Additionally, surface mounted strain gages detach easily under cyclic loading, even at relatively few cycles. Moreover, strain gages and extensometers are sensitive to electromagnetic interference, and hence cannot be used in environments with high electromagnetic interference. To circumvent the drawbacks of strain measurements with surface mounted electrical strain sensor systems, one promising approach is the utilization of embedded Fiber Bragg Grating (FBG) based sensor systems [9]. FBG is a section

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of a single mode optical fiber which contains a periodic variation of refractive index formed holographically on the core of the optical fiber along the fiber direction, and acts like a stop-band filter [10–12]. An FBG sensor reflects a small portion of the incoming electromagnetic spectrum while enabling the passage of the others. The center wavelength of the reflected portion of the incident electromagnetic spectrum is referred to as the Bragg wavelength, $\lambda_B = 2n_{eff}\Lambda$ where Λ is grating period and n_{eff} is the effective refractive index of the FBG sensor. When subjected to strain or temperature variations, the grating period and the effective refractive index of the FBG sensor change, thereby causing a shift in the Bragg wavelength λ_B. The change in the Bragg wavelength can be coupled to external effects, namely, temperature and strain through the following equation $\Delta\lambda_B/\lambda_B = (\alpha+\xi)\Delta T + (1-\rho_e)\varepsilon$ where α and ξ are the thermal expansion and thermo-optic coefficients of the fiber core, respectively. Here, $\Delta\lambda_B$ is the shift in the Bragg wavelength, ΔT is the change in the temperature of the grating region and ρ_e denotes effective photo-elastic constant of the fiber core, which is taken as 0.22 in this work, and ε is the axial strain of the grating region. For a constant temperature, one can write the previous relation as $\Delta\lambda_B/\lambda_B = (1-\rho_e)\varepsilon$.

In this study, we have investigated the effect of transverse cracking on the reduction of Poisson's ratio as a function of imposed axial strain. To this end, composite specimens with three different ply stacking sequences (i.e., uniaxial laminates, and laminates with two and four 90° off-axis plies) are instrumented with a biaxial extensometer and strain gage and then subjected to a quasi-static loading, thereby shedding light on the intimate relation between the reduction in Poisson's ratio and the off-axis/transverse ply cracking. Given that, in angle ply composites, the deformation in the lateral direction is enhanced, which can easily obscure the effect of transverse cracks on the lateral deformation, we limit our study to laminates with 0° and 90° stacking orientations. A novel approach for embedding biaxial FBG sensor into a composite laminate is proposed and utilized for multi-axis strain acquisition as well as for structural health monitoring of composites through referring to the reduction in Poisson's ratio. Specimens with extensometer, strain gage and embedded biaxial FBG sensor are subjected to quasi-static cyclic loading to study the reduction in Poisson's ratio under cyclic loading. It is shown that there can be notable variation in the values of lateral strain recorded by extensometer, strain gage and FBG sensor due to the difference in the gage length of these strain sensors. Referring to the reduction in Poisson's ratio, it is shown that composite specimens with a higher number of off-axis plies are more prone to the formation of transverse cracks. This study contributes to the state of the art in the field of composites materials testing and it is the first reported study on the measurement of decline in Poisson's ratio for composites with different fiber stacking sequences using embedded biaxial FBG sensors.

2. Methodology

The fiber reinforcement consists of 330gsm uni-directional (0°) E-glass stitched fabric (Metyx, Turkey) with the trade code of L300 E10B-0. The properties of the glass fibers used here are provided in Table 1. The matrix material is Araldite LY 564 epoxy and XB3403 hardener system purchased from Huntsman. Glass fibers were impregnated with resin by using vacuum infusion and then cured at 75 °C for 15 h. In this study, three composites laminates with the fiber stacking configurations of [90/90/0]s, [90/0/0]s, [0]6 were manufactured, which are respectively denoted by G6B1, G6B2, and G6U1 for convenience. Fig. 1(a) shows a composite specimen mounted on the wedge grips of the universal testing machine system with dual-extensometer system utilized in this study, while Fig. 1(c) presents the geometry of a test specimen with and without FBG sensors. In this study, we have used dual FBG sensors purchased from Technesa with λ_B = 1540 nm (transversal) and λ_B = 1550 nm (axial) and a gage length of 1 mm written holographically within the core of a polyimide coated single mode fiber such that the distance between both FBG sensors is nearly 21 cm. The optical cable with dual FBG sensors is fixed to the dry ply before composite manufacturing by interlacing it through stitching fibers of the ply in a configuration shown in Fig. 1(c). The ply with FBG sensors is stacked such that FBG sensors are embedded into the symmetry axis of laminates during the manufacturing stage. It can be seen from Fig. 1(b) that the section of the panel including the FBG sensor is cut into a L-shape so that the specimen can be clamped by the wedge grips of the universal machine without damaging the egress region of the FBG sensor. The egress/ingress of the optical cable into the composite was described in our previous study [12].

All static tensile tests were performed using a Zwick Z100 universal testing machine with a ±100 kN load cell. Static tensile tests on composite specimens with or without embedded biaxial FBG sensors were conducted under the displacement control of 2 mm/min according to ISO 527. A Micron Optics SM230 model interrogator was used to acquire the FBG signals with a sampling frequency of 1000 Hz during the experiments with Micron Optics Enlight Software. General purpose biaxial strain gages purchased from Micro-Measurements were used as axial and biaxial sensors with the code of C2A-06-062LW-350 and C2A-06-062LT-350, respectively. All the strain gages have a gage length of ~1.57 mm (0.062 inche) and a resistivity of 350 ohms. An Epsilon 3542 axial extensometer with a fixed gage length of 25 mm and an Epsilon 3575 transverse extensometer with a controllable gage length were utilized during tensile tests. Extensometer and strain gage data were collected concurrently by a National Instruments NI SCXI-1000 main chassis with a NI SCXI-1520 card at a sampling frequency of 1000 Hz. After tensile tests, small samples were cut from tested specimens with different stacking sequences using a water cooled diamond saw and then polished on their thickness side to visualize transverse cracking with an optic camera (Nikon ECLIPSE ME600).

3. Results and discussion

3.1. Quasi-static tensile tests

3.1.1. The effect of stacking sequence on the evolution of Poisson's ratio

In order to assess the evolution of Poisson's ratio of composite plates with different stacking sequences, test specimens were subjected to quasi-static tensile loading until failure, and all the data collected during the tests were processed and tabulated in Table 2 along with the fiber volume fractions. During the quasi-static tensile tests of all composite coupons, both axial and transversal strains were recorded by extensometers. Biaxial strain gages were attached only to a single coupon for each plate to investigate the effect of sensor type (i.e., gage length, measurement location) on the strain measurement. Fig. 2(a) yields stress-strain curves for

Table 1
Properties of fiber reinforcement.

	UD E-Glass fiber	
0	600 Tex	283 gr/m^2
90	68 Tex	37 gr/m^2
Stitch	76 DTex	10 gr/m^2