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Research Article

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Structural Health Monitoring by Using Fiber Optic Sensors in Composite Materials

Kompozit Malzemelerde Fiber Optik Sensörler Kullanılarak Yapısal Sağlık İzlemesi

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ABSTRACT

In this study, design and application of a structural health monitoring (SHM) in composite materials with fiber bragg grating (FBG) sensors are investigated. The designed structure consists of laminated composite material that was produced by vacuum infusion method. The composite specimen was obtained by embedding a FBG sensor between the 12-layer glass layers. Moreover, SHM of the produced composite material was achieved by obtaining the strain data from the sensor embedded in the composite material. Application was carried out by making the composite plate fixed support on one side and applying different loads to the specimen. Strain ratios of these loads are obtained and the results graphics are shown.

Key Words
Fiber optic sensors, fiber bragg grating, structural health monitoring, composite materials.

ÖZ

Bu çalışmada, fiber bragg ızgaralı (FBG) sensörler ile kompozit malzemelerde yapısal sağlık izleme (SHM) tasarımı ve uygulaması yapılmıştır. Tasarlanan yapı, vakum infüzyon yöntemiyle üretilmiş tabakalı kompozit malzemeden oluşmaktadır. Kompozit numune, 12 katmanlı cam tabakalar arasına bir FBG sensörü yerleştirilerek elde edilmiştir. Ayrıca kompozit malzemeye gömülü sensörden şekil değiştirme verileri elde edilerek üretilen kompozit malzemenin SHM'si elde edilmiştir. Kompozit levhanın bir kenarı mesnetlenirken diğer tarafına farklı yükler uygulanarak uygulama yapılmıştır. Sonuçta bu yüklemeler için şekil değiştirme oranları elde edilmiş ve sonuç grafikler halinde gösterilmiştir.

Anahtar Kelimeler
Fiber optik sensörler, fiber bragg ızgara, yapısal sağlık izlemesi, kompozit malzemeler.

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INTRODUCTION

The need for the use of composite materials has increased in areas where traditional materials cannot fulfill the desired performance [1]. Composite materials are subjected to various loads depending on where they are used. The most common of these is fatigue behavior. Real-time structural health monitoring (SHM) is needed to monitor this [2]. All composite structures have a certain lifespan. Engineering science finds and applies the most suitable and economical solution according to the design parameters during the construction phase. The part will fail as a result of an overload or repeated application of the same load, fatigue or the end of its estimated operational life. To reach this conclusion, it is necessary to choose between one of three ways: Giving up on the part before it expires and without clear information, waiting for the part to fail on its own or monitoring the changes in the part to predict the breakdown time. The first method causes great economic loss, the second method can cause even greater economic loss and even loss of life, while the third method produces the most economical solution and prevents loss of life. This method is SHM. SHM in composites is not a very new technique. There are many examples in the 20th century around the engineering world that have been observed structural health. However, with the beginning of the 21st century, developments in related devices, sensors and computer technologies have led to a great improvement in both the content and the number of real-world applications related to SHM. This progress has allowed SHM in composites to move beyond the lab to the real world. Parallel to these developments, the emergence of many new devices, sensors, software possibilities and combinations has forced researchers and engineers to choose the most appropriate method among them. The aim of all these studies is to detect defects that may affect the life of the structure. Sensors such as resistive strain, fiber optic (FOS) and piezoelectric are widely used in SHM [3]. Conventional non-destructive testing methods such as ultrasonic testing, radioactive testing and acoustic-low frequency can be used for SHM. However, these methods are difficult to implement due to the size and mass of the system [4]. Whereas, FOSs similar to the human nervous system and they are ideal for SHM of composite materials. Due to its small size, it can be embedded in structures and the behavior of the structure can be monitored [5]. Previous studies have shown that the effect of temperature [6], curing process [7,8], impact [9], stress/strain [10] moisture, delamination and cracking [11,12] can be monitored with fiber optic sensors. According to Yilmaz et al. [13] reported using FOS that transverse cracking affects the Poisson ratio. Munoz et al. [14] developed a method for measuring strain using FOSs for SHM of composites. Antonucci et al. [15] used a bragg grating (FBG) sensor to monitor indentation-induced deformations in their study. Jung and Kang [16] studied the curing and stresses of three-dimensional knitted composites using FOS. Epaarachchi et al. [17] detailed the use of embedded FOSs in near infrared region (NIR) for the measurement of structural response of c in $0^{o}/90^{o}$ woven cloth/vinyl ester composite for static/fatigue loads.

In this study, a FBG sensor has been successfully embedded into the laminated composite material that produced by vacuum infusion method. The strain data of the composite plate having sensor were collected under transverse static loading unlike literature. The obtained results with respect to time are presented with graphs.

MATERIALS and METHODS

The proposed structure consists of 1x1 m^2 0° woven fabrics consisting of 12 layers $[0°]_{12}$ glass fibers, and a fiber bragg sensor to embed. The system produced by vacuum infusion method consists of composite material and embedded sensor which can seem in Figure 1. Properties of the resin mixture used in the production of composite plates are shown in Table 1.

Epoxy resin F-1564 as matrix material and F-3487 hardener set were purchased from *Kompozitsan*, *Izmir*. Composite plates were produced by vacuum infusion method and then cured at 100 ^{o}C for 1 h. In the study, a single composite plate with 0 degree orientation angle with 12 layers was produced ($[0^{o}]_{12}$). Peel ply and flow mesh were used on both the top and bottom sides to facilitate resin flow during vacuum.

Before the resin is given, the dual FBG sensor is fixed by affixing it to the dry fabric. The location of FBG sensors are between the 6th and 7th layers in the composite plate. Dimension of the plate is 300x150x3 mm. FOS of the proposed structure was provided from EON Photocins Company, Bursa with 1515-1585 nm center wavelength range and fiber diameter (coating) of 150 µm within the core of a polyimide coated single mode fiber. It was used three FBG sensors throughout optic cable and collected strain data from these points. The distance between FBG sensors is ~ 50 mm. Also, the all tests were achieved at laboratory of EON Photocins Company. FBG is a section of a single-mode optical fiber [13].

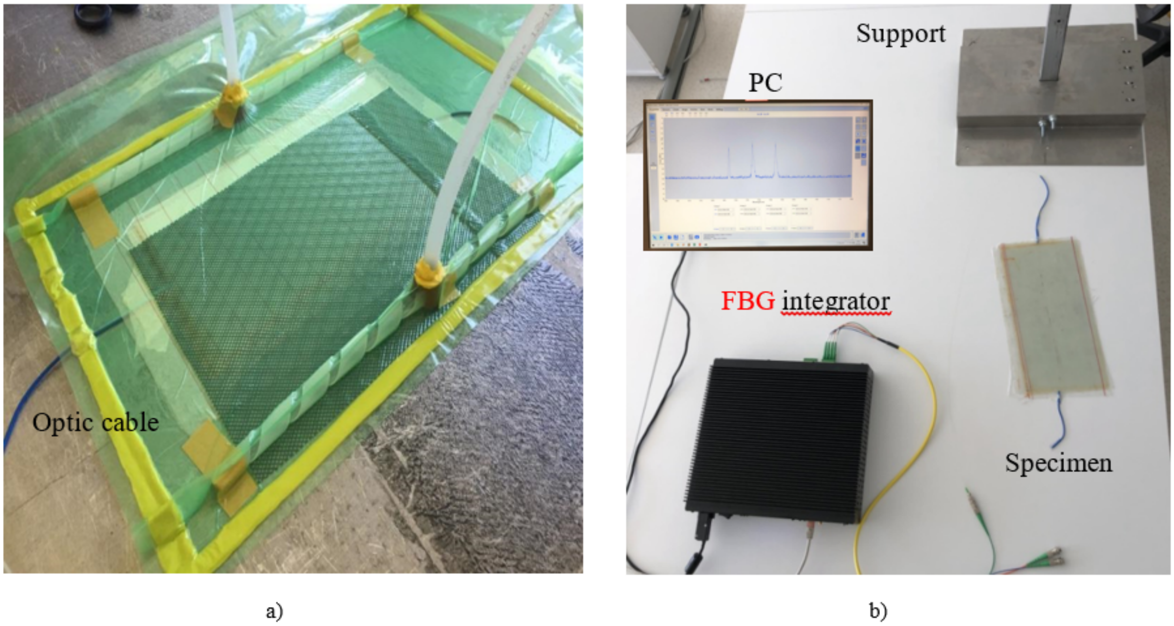


Figure 1. a) Production of composite material and b) experimental devices.

Table 1. Properties of the resin mixture used in the production of composite plates.

Epoxy material	F-1564 resin	F-3487 hardener
25 °C viscosity (MPa)	1250-1450	30-70
25 °C density (g/cm^3)	1.1-1.2	0.98-1.0
Mix ratio by weight	100	34

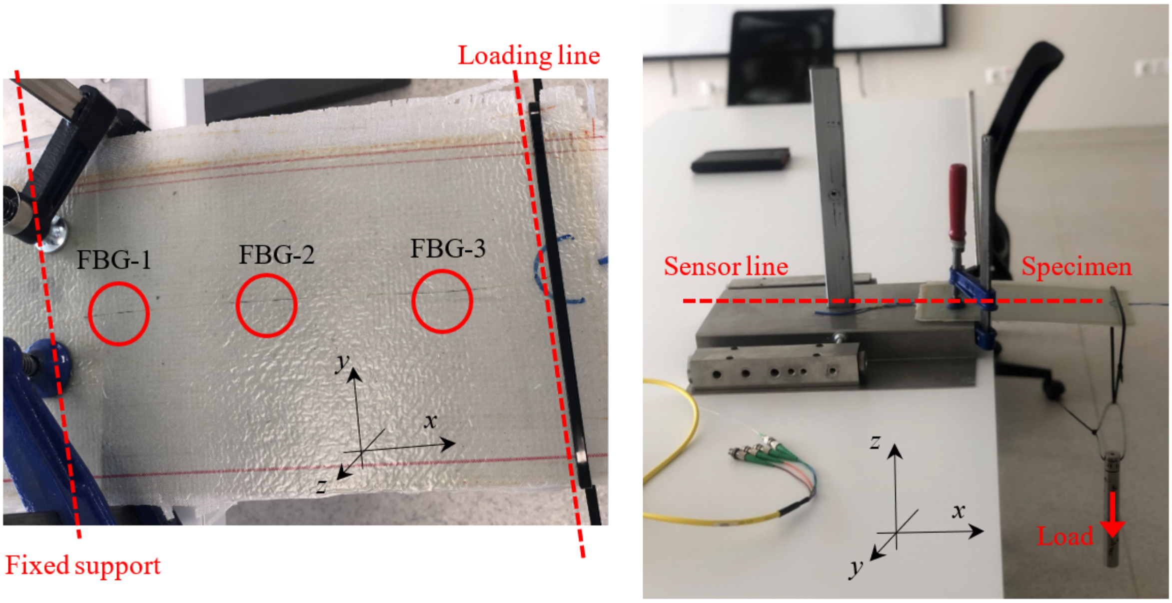


Figure 2. Boundary condition and experimental setup of the composite plate.

The Bragg wavelength shift due to stress is achieved through reflection and the spectrum of light. The Bragg reflection wavelength is

$$\lambda_B = 2\eta_{eff}\Lambda \tag{1}$$

In here
λ_B is the reflection wavelength,
η_{eff} effective reactive index
Λ is the grid spacing [18].

FBG is sensitive to stress, so when the grating is stretched or compressed, the grating loop will change and there will be a center wavelength shift. If it is taken differentiation of Equation 1

$$d\lambda_B = 2\Lambda d\eta_{eff} + 2\eta_{eff}\, \mathrm{d}\Lambda \tag{2}$$

is obtained. When dividing Equation 1 by Equation 2, Equation 3 can be written as

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\,\Lambda}{\Lambda} + \frac{\Delta\eta_{eff}}{\eta_{eff}} \tag{3}$$

in here
$\Delta\eta_{eff}$ is the change of reactive index
ΔΛ is the change of grid spacing [18].

Regardless of waveguide effects, which means without consideration the influence of fiber axial deformation on refractive index, the reactive index change in uniaxial elastic deformation

$$\frac{\Delta\eta_{eff}}{\eta_{eff}} = -\frac{1}{2}\eta_{eff}^2\left[(1-v)P_{12} - vP_{11}\right]\varepsilon = -P_e\varepsilon$$

(4)

where ε is strain. For the linear elastic range

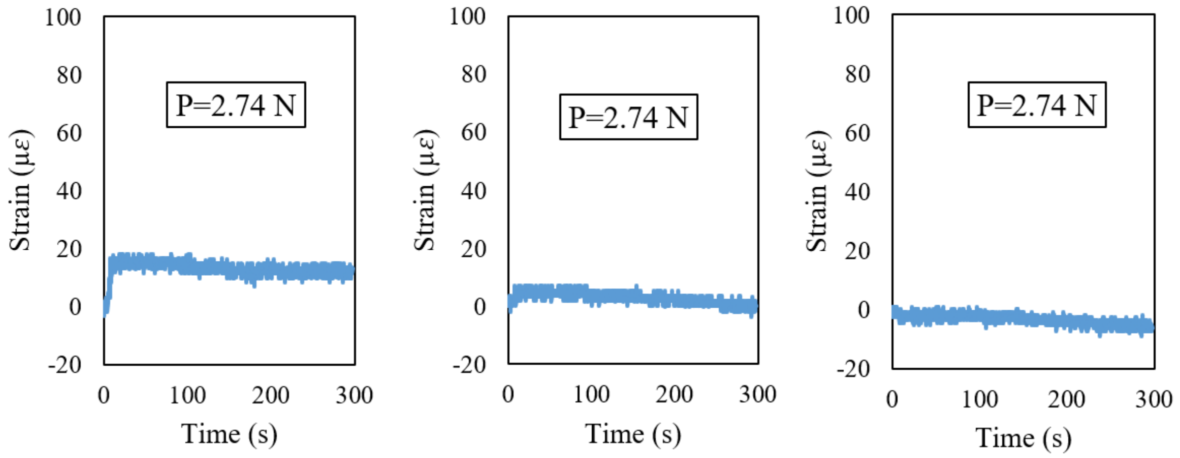
$$\varepsilon = \frac{\Delta\,\Lambda}{\Lambda} \tag{5}$$

v is Poisson ratio, P_{11} and P_{12} are elastic-optic constants, P_e is effective photo-elastic constant of the fiber core, which is taken as 0.22 in this study [13].

$$P_e = \frac{1}{2}\eta_{eff}^2\left[(1-v)P_{12} - vP_{11}\right] \tag{6}$$

A measured strain response at a constant temperature is found to be [19]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\varepsilon \tag{7}$$



a) b) c)

Figure 3. Variation of a)$\mu\Delta\varepsilon_1$, b)$\mu\Delta\varepsilon_2$ and c)$\mu\Delta\varepsilon_3$ with time for 2.74 N.

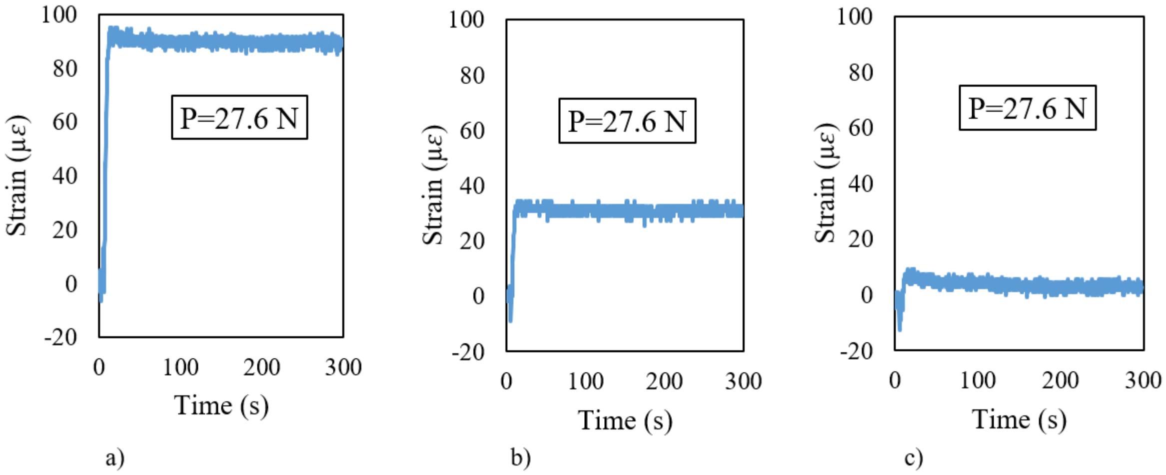


Figure 4. Variation of a)$\mu\Delta\varepsilon_1$, b)$\mu\Delta\varepsilon_2$ and c)$\mu\Delta\varepsilon_3$ with time for 27.6 N.

$$\frac{\Delta\lambda_B}{\lambda_B \varepsilon} = 0.78x10^{-6}\,\mu\Delta\varepsilon_i \qquad i = 1,2,3 \qquad (8)$$

where Δε is the change in applied strain [20], $\mu\Delta\varepsilon_1$, $\mu\Delta\varepsilon_2$ and $\mu\Delta\varepsilon_3$ are micro strain values of the sensor which a near the fixed support, middle of the plate and the near of the load, respectively. Figure 2 presents the geometry and boundary conditions of specimen with FBG sensors. In Figure 2, the experimental setup is shown so that the experiment can be performed without damaging the FBG sensor. Composite embedded FBG sensor was fixed at one end and loaded at the other side in the experiments.

RESULTS and DISCUSSION

Experiments were carried out according to the boundary conditions given in Figure 2. Starting from the minimum load of 2.74 N, the load has been increased. The maximum load value is 27.6 N. In Figures 3 and 4, the variation of micro strain with time is given for these two loading values. The maximum time is 300 s. The fluctuations at the beginning of the graphs are caused by human interaction with the weight for optimizing it. With the increase of the load, the deformations of FBGs-1 and -2 increased along the plate axis. However, there is no such change in FBG-3 due to its location and loading condition.

Yılmaz et al. [13] reported that the effect of transversely embedded FBG sensors on lateral strain was detected. In this study, unlike the literature, the deformations of the composite plate for out of plane loading were measured with FBG sensors. Thus, deformation-induced damage of laminated composites can be detected with fiber optic strain sensors [14]. This situation will provide great convenience to designers. The study can be extended for different loadings and composites.

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