Monitoring Variation of Local Strain and Temperature in Fiber Reinforced Composites under High Strain Fatigue using Embedded FBG Sensors

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Abstract. This work focuses on the structural health monitoring (SHM) of biaxial glass fiber reinforced epoxy matrix composites under a constant, high strain uniaxial fatigue loading utilizing embedded Fiber Bragg Grating (FBG) optical sensors. Three consecutive FBG sensors with 40 mm distance in between which are written onto a same fiber optic cable are integrated along the gage length of a fatigue specimen in order to study the distribution and evolution of local strain during the cyclic loading. It is revealed that local strains measured by FBG sensors under the global constant strain fatigue imposed either using linear variable differential transformer (LVDT) or extensometer as control sensors can vary significantly and local strains measured by different FBG sensors along the optical cable can depart from each other as the loading progress, revealing the effect of local damage on the variation of local strains. Using thermocouples mounted on the location of the FBG sensors, autogeneous heating along the specimens are also examined and related to the FBG measured strains and damage progress.

Introduction

Fiber reinforced composites have found frequent applications in a variety of industries ranging from aeronautics, automotive to civil infrastructure as structural components thanks to their outstanding properties i.e. high specific stiffness and strength among others. They can be exposed the cyclic loads during their operation which may gradually damage their integrity. Strain monitoring can provide valuable insight on predicting the long-term behavior of composite structures. Strain-gages or strain-gage based extensometers are commonly used sensors for acquiring the strain data for composite structures during mechanical testing or in-service. Since a strain gage measures the strain of the object based on the change in the electric resistance of the metallic foil of the strain gage, it is rather sensitive to electromagnetic fields, and hence may require the usage of low pass filter to eliminate unwanted external noises. Additionally, due to their size, standard strain gages are not suitable for being embedded into composite structures, and instead are attached onto the object by a suitable adhesive such as cyanoacrylate after careful surface treatment of the object surface. Strain information becomes particularly important to monitor the long term behavior of structures under fatigue loading. However, surface mounted strain gages do have very low fatigue resistance and are not suitable for high cycle and high amplitude fatigue conditions. Mainly due to above elaborated reasons, alternative sensor technologies for strain measurement have been researched to find sensors which lack the limitations of strain gages. One of the recent and most prominent sensor technologies for strain and structural monitoring of structures is Fiber Bragg Grating (FBG) optical sensors. Being small and flexible, FBG sensors can be embedded discretely into composites at locations of interest thereby allowing for the investigation of local strain distribution and evolution without endangering the structural integrity of the host material [1]. Furthermore, based on the FBG collected strain data, structural health monitoring concept can be successfully implemented in composite structures, which can enable damage detection in real-time operating conditions and in turn allowing for significant reduction in the maintenance costs leading to substantial economic savings [2]. FBG sensors possess several other important attributes which are immunity to the magnetic interference, light weight, multiplexing and absolute measurement capability and high corrosion resistance that makes them particularly promising for strain and structural health monitoring applications.

Composite materials experience various damage mechanisms during fatigue unlike metals. As substantiated in the open literature, stiffness degradation of fiber reinforced polymer matrix composites in response to cyclic loads is characterized by three distinct stages. Namely, in the first stage comprising the first 15-25 % of fatigue life, the rapid formation and interconnection of matrix cracking causes a sharp, non-linear decrease in stiffness. The second stage accounts between 15-20 % to 90 % of the fatigue life where there is a gradual, and linear decrease in stiffness, which is attributed to crack propagations, fiber debonding and delamination. The final stage is differentiated by a sharp nonlinear decrease in stiffness due to the plurality of fiber breakages [3]. The number of studies on the usage of FBG sensors in fatigue monitoring is scarce and those available ones are limited to low cycle and low strain amplitude fatigue and to the best of author’s knowledge, there is no systematic study devoted to investigate the capabilities and limitations of FBGs for measuring strains in composite materials under high strain fatigue loading. Understanding FBG response under low-cycle fatigue conditions is important in terms of applicability of these sensors to monitor structures that are exposed to repetitive high strain amplitude dynamic loads. To this end, in this study, the performance and behavior of FBG sensors embedded inside glass reinforced composites under globally constant high strain, and low-cycle fatigue loading conditions is scrutinized referring to distribution and evolution of strain along the composite specimens. It is shown that strains from the FBG sensors located at different locations can decrease and significantly deviate from each other as low-cycle fatigue progress, notifying the distinction between the global and local response of the material. It is well documented in the open literature that when a specimen is subjected to cyclic loading, the portion of the mechanical energy is dissipated as heat (also referred to as autogenous heating) causing a rise in the temperature of the specimen. To be able to investigate the existence of relation between FBG measured local strains and corresponding temperature variations in fiber reinforced composite specimens composed of biaxial glass fibers and epoxy matrix during the fatigue tests, the autogenous heating of the specimens are monitored with three K-type thermocouples mounted on the specimens for the corresponding locations of FBG sensors.

Results and Discussion

Figure 1a presents the evolutions of temperatures for three different thermocouples. As can be noted, the temperature evolution reveals three distinct stages: an initial increase called as first stage, followed by a second stage for which the rate of temperature increase smaller than the first stage, and finally notable increase prior to final failure, which is the third stage. Figure 1b shows the variations of maximum strains (i.e., peak strains in the sinusoidal strain form) that are recorded by LVDT and FBG sensors with 4mm apart one another where the middle FBG is positioned at the middle of the specimen gage length. Noting that the fatigue test on this specimen was conducted under globally constant displacement using the LVDT sensor, one may at first sight expect that FBG sensors should also give constant strain values. However, maximum strains gathered from the FBGs can be significantly distinct from the global behavior of the specimen. Different sections of the specimens can possess different strain variations during the loading process as inherent heterogeneity of the composite structure causes non-uniform strain distributions and elongations along the specimen gage length. As the fatigue experiment progresses, the local strains measured by FBG sensors drop down such that the trend has three distinct regions, that is to say, an initial sharp decrease followed by gradual and nearly linear decline and finally sharp drop. Note that these three stages are in agreement with the fatigue phases observed in temperature and mechanical energy (based on LVDT) plots as a function of cycle number in Figure 1a and Figure 1c, respectively. Another finding of this experiment is that the strain measured at different locations by the FBG sensors can significantly be different from each other as fatigue loading continues (i.e. between top and middle FBG sensors) thereby demonstrating reality of the non-uniform strain distribution due to the local difference in the damage form, density and evolution along the specimen gage length.

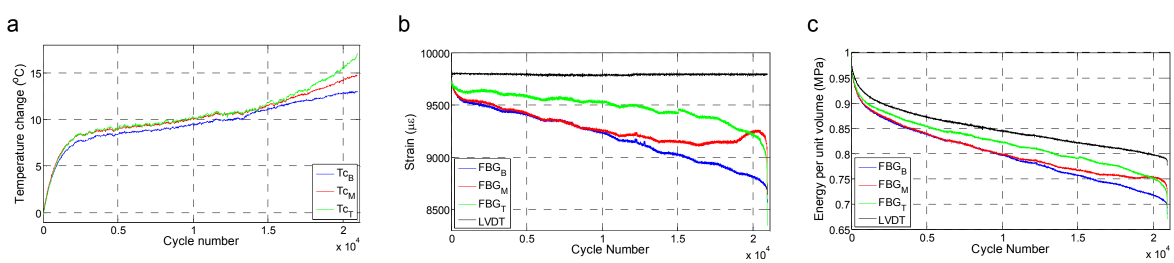

Figure 1: Evolution of temperature (a), strain (b) and mechanical energy (c) for all thermocouples and FBG sensors where the subcripts B, M, and T denote bottom, midle, and top locations along the gagelenght of the specimen.

Conclusion

Composite specimens containing three subsequent FBG sensors embedded along their gage length are exposed to constant, high strain fatigue loads. Considerable differences occur among individual sensors and LVDT in the course of the fatigue experiment implying the considerable difference between the local and global behavior of the material. It is found that fibers that are exposed to same global strain condition did not necessarily give rise to the same strains at the local level. It is demonstrated that such response from the FBG sensors can be attributed to the heterogeneous structure of the material causing nonlinear strain distribution and relaxation of the strain in the sensor vicinity due to the formation of various damage mechanisms such as matrix cracking and fiber-matrix debonding. This causes sensor strains to follow a trend similar to the stages in stiffness degradation or mechanical energy.

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