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Mechanical strength of FBG sensor exposed to cyclic thermal load for structural health monitoring

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Abstract. Fiber Bragg grating (FBG) sensors are applied to structural health monitoring (SHM) in many areas due to their unique advantages such as ease of multiplexing and capability of absolute measurement. However, they are exposed to cyclic thermal load, generally in the temperature range of -20°C to 60°C, in railways during a long-term SHM and the cyclic thermal load can affect the mechanical strength of FBGs. In this paper, the effects of both cyclic thermal load and the reflectivity of FBGs on the mechanical strength are investigated though tension tests of FBG specimens after they are aged in a thermal chamber with temperature changes in a range from -20°C to 60°C for 300 cycles. Results from tension tests reveal that the mechanical strength of FBGs decreases about 8% as the thermal cycle increases to 100 cycles; the mechanical strength then remains steady until 300 cycles. Otherwise, the mechanical strength of FBGs with reflectivity of 6dB (70%) and 10dB (90%) exhibits degradation values of about 6% and 12%, respectively, compared to that with reflectivity of 3dB (50%) at 300 cycles. SEM photos of the Bragg grating parts also show defects that cause their strength degradation. Consequently, it should be considered that mechanical strength of FBGs can be degraded by both thermal cycles and the reflectivity if the FBGs are exposed to repetitive thermal load during a long-term SHM.

Keywords: structural health monitoring; fiber Bragg grating; thermal load; mechanical strength

1. Introduction

Various interrogation systems based on novel sensors like fiber optic sensors have led to an increase in research on smart structures (Chung and Kang 2008, Lee *et al*. 2014, Kwon *et al*. 2015). There are many kinds of sensors such as electric strain gages, piezoelectric transducers, magnetic sensors, etc. As conventional sensors, these devices have been frequently applied to studies in aerospace engineering, plants, heavy industry and civil infrastructures (Ihn and Chang 2008, Lee and Kim 2013, Kang *et al*. 2014). Currently, the applications of such sensor systems are gradually increasing as attempts are made to estimate the behavior of structures on site during operations for improved structural health monitoring (SHM). SHM has attracted much research, including real-time fundamental studies of sensors or sensor systems and field applications. Many of the studies on SHM have adopted fiber optic sensors due to the strong merits of these sensors compared to conventional electric sensors (Rao *et al*. 1997, Kim and Feng 2007, Grillet *et al*. 2008, Kim and Kim 2015).

Fiber optic sensors have many advantages such as long distance measurement with small power loss, corrosion resistance, and electromagnetic interference (EMI) immunity. The application of fiber optic sensors has been gradually expanded to primary structures as well as to sub structures and small modules. Among the applications, the suitability of fiber optic sensors has been assessed to apply them on civil engineering (Kesavan *et al*. 2005). And, in order to detect the lateral buckling of subsea pipelines, a methodology based on distributed fiber optic sensors is newly proposed and verified (Feng *et al*. 2015).

In particular, the fiber Bragg grating (FBG) sensor is the most prevalent sensor in use worldwide because, compared to other fiber optic sensors, it has merits such as ease of mass production, the possibility of absolute measurement, and multiplexing capability. These abilities of FBG sensors have led to a steep increase in long-term applications for real structures, allowing for structural health monitoring. An FBG accelerometer sensor is developed for structural health monitoring (Talebinejad *et al*. 2009). Recently, the applicability of FBG sensors is experimentally verified by measuring the steel strains in civil concrete structures through a fatigue test (Wang *et al*. 2014). In addition, a residual strain of non-prestressed reinforcement in partially prestressed concrete (PPC) beams is measured using the FBG sensors (Han *et al*. 2015). Moreover, optical properties related to sensitivity of FBG sensors are estimated to detect transverse cracks and delamination in carbon fiber reinforced plastics (CFRP) laminates with non-uniform

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strain fields (Okabe *et al*. 2000, Takeda *et al*. 2002).

To guarantee the reliability of FBG sensors in long-term applications, it is very important to verify the sensors with regard to both signal characteristics and robustness. In detail, the demodulation principle of FBG sensors is based on wavelength change detection of a peak signal and requires stability of the signal characteristics. Moreover, it is required that FBG sensors should have high mechanical strength in order to survive when they are exposed to the harsh environments that can occur during long-term SHM. There are temperature changes of about 80 degrees (-20°C~60°C) in Korea over the course of a single whole year; this thermal loading can have severe effects on the mechanical strength of FBG sensors when they are exposed to it for many years. Therefore, the effects of long-term thermal loading on the mechanical strength of FBG sensors should be precisely investigated in advance, prior to SHM of structures on site. In response to these factors, it was revealed that the mechanical strength of a stripped FBG decreased about 55% regardless of grating length or reflectivity. When, to improve photosensitivity, an optical fiber is exposed to hydrogen at high temperature, the mechanical strength of the FBGs decreases to about 50% of the initial value (Wei *et al*. 2002, Kang *et al*. 2007).

In this paper, the mechanical strength of FBG sensors exposed to cyclic thermal load is investigated, including the effects of reflectivity of the Bragg grating on mechanical strength. Temperature range of cyclic thermal load is from -20°C to 60°C, which range is determined from a consideration of the climate in Korea during the course of one whole year. For overall effectiveness, the test is conducted using accelerated aging of the FBG sensors in a thermal chamber for 300 cycles. In addition, relations between the surface state and the mechanical strength of aged FBGs have been verified by scanning electron microscope (SEM) photos.

2. Demodulation principle of FBG sensor

The basic demodulation principle of fiber Bragg grating (FBG) sensors involves monitoring of the wavelength shift from their reflected spectra. A wavelength, which is determined by the Bragg condition as shown in Eq. (1), is reflected at the grating part of the FBG and the other wavelengths pass through it

$$\lambda_B = 2n_e\Lambda \tag{1}$$

If the FBG is exposed to external perturbations such as strain and temperature, the Bragg wavelength changes as shown in Eq. (2). It is possible to measure physical properties such as strain and temperature by measuring the wavelength change accurately from Eq. (2). There is a linear relationship between the shift of Bragg wavelength and strain as well as temperature. Moreover, FBG can be used as many other sensors for detecting displacement, acceleration, pressure and so on by designing a particular sensor head using various sensing mechanisms

$$\Delta\lambda_B = \lambda_B\left[(\alpha_f + \xi_f)\Delta T + (1 - p_e)\varepsilon\right] \tag{2}$$

where ε is the strain, ΔT is the temperature change, α_f is the coefficient of thermal expansion, ξ_f is the thermo-optic coefficient and p_e is the strain-optic coefficient of an optical fiber. Generally, it is known that α_f and ξ_f of silica fiber have constant values of 0.5×10^{-6}/°C and 6.9×10^{-6}/°C, respectively (Kang *et al*. 2005).

3. Experimental setup

3.1 Accelerated aging in a chamber

A schematic of the experimental setup is shown in Fig. 1. A total of 42 FBGs with 6 groups were tested in this study: each group is composed of 7 specimens. First, there are 4 groups of FBGs according to the change of the thermal cycle, namely 0 cycle (pristine), 100 cycles, 200 cycles, and 300 cycles. All FBGs in those groups have a reflectivity of 6dB (70%). Second, there are 3 groups of FBGs according to the change of reflectivity, namely 3dB (50%), 6dB (70%), and 10dB (90%). Using the phase mask method, all FBGs (FBG Korea Co.) are fabricated to have grating lengths of 10 mm. Photo-sensitive optical fibers, which are generally used to fabricate FBG sensors, are exposed to an intense UV laser for several minutes during the manufacturing process; this can cause the degradation of the mechanical strength of optical fibers. For this reason, in order to verify the effects of the reflectivity on the mechanical strength of the FBG sensors, FBGs with different levels of reflectivity (i.e., 3dB, 6dB, and 10dB) were also used.

To excite a cyclic thermal load on the FBGs, a thermal chamber (TC-ME-025, JEIO-TECH Co.) with a temperature range of -20°C to 60°C was used for 300 periodic cycles. For the tension test of the FBGs according to cycle changes, FBG sensors were taken out of the chamber in 4 steps (i.e., pristine, 100, 200, and 300 cycles). For the tension test of the FBGs with reflectivity changes, only two cases, including the 0 cycle case and the 300 cycle case, were compared. Each thermal cycle is composed of 3 steps. That is, temperature was increased from RT to 60°C over a period of 10 minutes and was decreased to -20°C over a period of 70 minutes. After that, the temperature was re-increased to RT for 15 minutes. Details of the imposed thermal cycle are illustrated in Fig. 2.

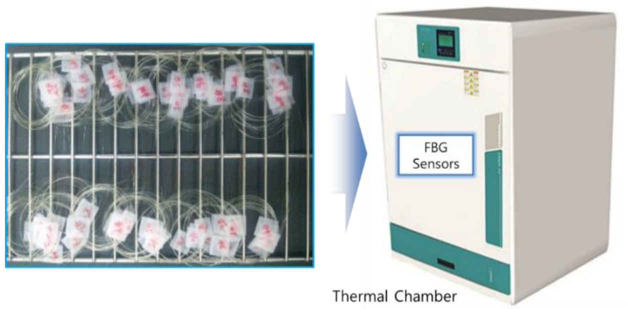


Fig. 1 Installation of FBGs in a thermal chamber

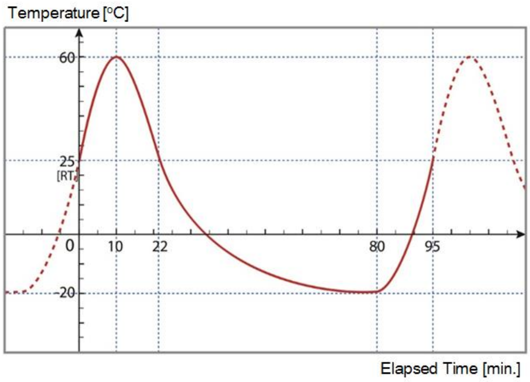


Fig. 2 Periodic thermal cycles imposed to FBGs

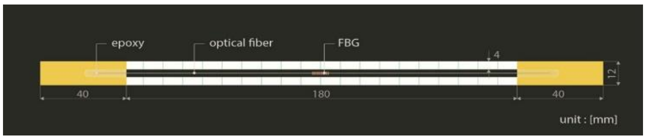


Fig. 3 Configuration of test specimens for mechanical strength

Fig. 4 Experimental setup for the tension test of FBG specimens

3.2 Tension test

As can be seen in Fig. 3, the test specimens were fabricated by bonding both ends to hardboard using epoxy adhesives. To prevent optical fibers from being damaged during handling, the specimens include paper based guide lines with lengths of 180 mm. The experimental setup for the tension test of the optical fibers is shown in Fig. 4. For the test, displacement control of 7 mm/min was applied according to IEC 60793-1-31; failure strength of the optical fiber was measured using a load cell of 100N in a tension tester (MicroTester 5484, Instron Co.).

In order to analyze the experimental results of the test, Weibull distribution model has been used with cycle change and reflectivity change of FBGs. The m of Weibull modulus is defined by Eq. (3) and it denotes the scale of each set of measured data

$$\ln\big(-\ln\big(1-F(\sigma)\big)\big) = m\ln\sigma - m\ln\sigma_0 \tag{3}$$

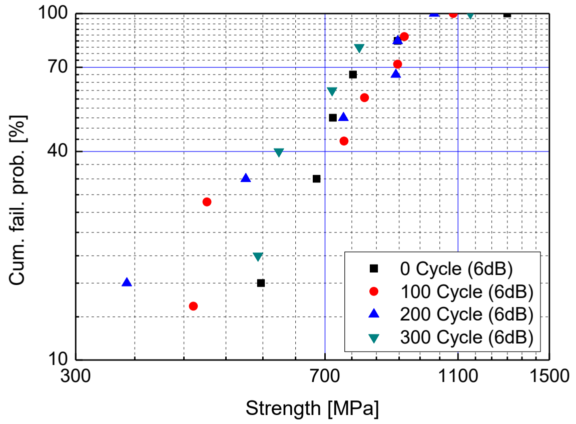
In the Eq. (3), $F(\sigma)$ is the cumulative failure probability at each stress level, σ is a stress at each data and σ_0 is a reference stress. Generally, the m value has a relation that is inverse proportion to the variance of mechanical strength.

In addition, to investigate the main causes of the degradation of the mechanical strength of the FBG sensors during repetitive thermal cycles, SEM (9801A-1UPS-SN, Thermo Scientific Co.) photos of the surface of FBG sensors were taken at each measurement step (i.e., 0, 100, 200, and 300 cycles).

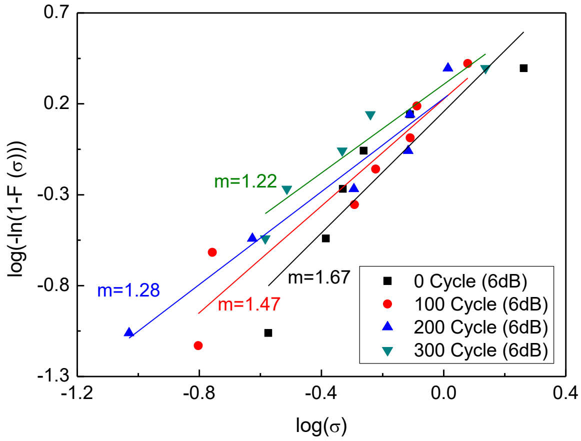
4. Test results and discussion

Tension tests for specimens with FBGs were performed to evaluate the mechanical strength as it is influenced by the repetitive thermal load. From Fig. 5, it can be seen that the mechanical strength of the FBGs at each cycle shows a Weibull distribution, which is commonly used to express the distribution of mechanical strength of specific materials. Seven specimens were tested per cycle; test results show that the mechanical strength of the FBGs decreased as the thermal cycle increased. The mechanical strength remained steady after 100 cycles. Specifically, the drop of mechanical strength is about 8% compared to that of the pristine FBGs; this drop is due to aging effects induced by thermal cycles, as shown Fig. 6. From the m value shown in Table 1, which is the Weibull coefficient, lower value shows higher variance as thermal cycle increases; that is to say, the increase of the thermal cycles induces higher variance in the mechanical strength. However, in future work, it will be necessary to survey the possibility of an additional drop in mechanical strength at much higher thermal cycles. Figs. 7 and 8 show results for the influences of the reflectivity on the mechanical strength. From the figures, which show the mechanical strength of the FBGs at 300 cycles, it can be seen that the mechanical strength values show a linear relationship with the reflectivity of the FBGs. That is, the mechanical strength is 811 MPa at 3dB (50%) reflectivity; this value then decreases to 761 MPa (-6%) and 714 MPa (-12%) at 6dB (70%) and 10dB (90%), respectively. These results reveal that higher reflectivity, and long exposure to UV light during fabrication, generate more of a strength drop when FBGs are exposed to cyclic thermal load, as can be seen in Table 2. Consequently, it is conclusively determined that appropriate reflectivity is better than too high of a reflectivity, although very high reflectivity might be better for higher signal sensitivity of FBGs because it can allow the generation of much more strength drop during a long-term SHM under thermal cyclic load conditions.

Meanwhile, SEM photos were taken of the surface of the optical fibers, the Bragg grating parts in particular, in order to analyze the causes of the strength degradation determined in this study. From Fig. 9, the size and frequencies of the damaged grains were found to gradually increase with the increase of the thermal cycle. However, as already mentioned in the previous paragraph, the mechanical strengths of the FBGs show steady values over the specific cycles, as shown in Fig. 6; the reason for this seems to be closely connected to the brittleness of the optical fiber, which is one of the characteristics of silica (SiO_2).



(a) Mechanical strength of FBGs with cycle changes



(b) Weibull distribution in log-log plot

Fig. 5 Distribution of mechanical strengths of FBGs with cycle changes

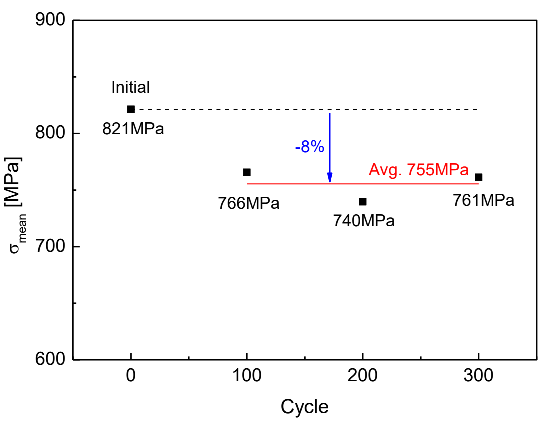


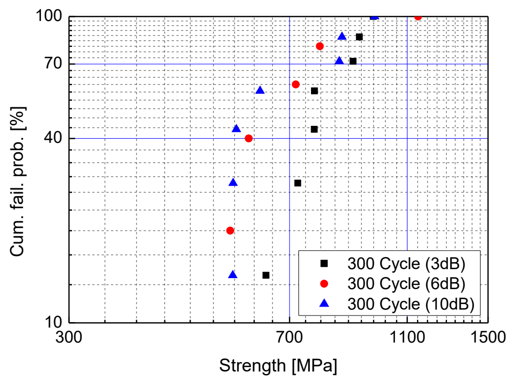
Fig. 6 Mechanical strengths of FBGs with cycle changes

Table 1 Mechanical strength with change of thermal cycles

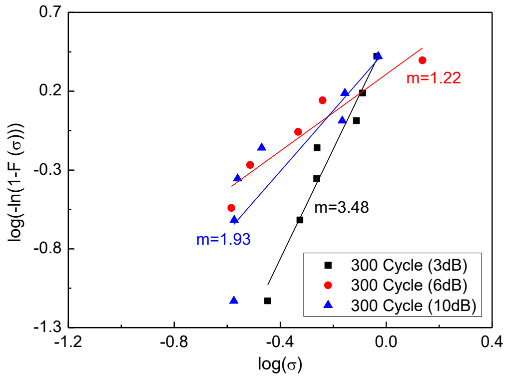
Property \ Cycles	0	100	200	300
σ_{mean} [MPa]	821	766	740	761
m	1.67	1.47	1.28	1.22

Table 2 Mechanical strength with reflectivity change of FBGs

Property \ Reflectivity	6dB (0 cycle)	3dB	6dB	10dB
		(300 cycles)		
σ_{mean} [MPa]	821	810	761	714
m	1.67	3.48	1.22	1.93



(a) Mechanical strength of FBGs with reflectivity changes



(b) Weibull distribution in log-log plot

Fig. 7 Distribution of mechanical strengths of FBGs with reflectivity changes

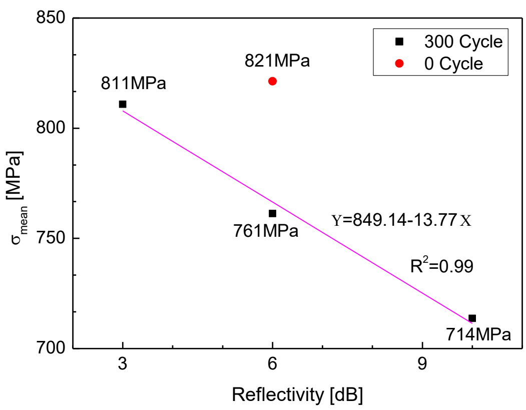


Fig. 8 Mechanical strengths of FBGs with reflectivity changes

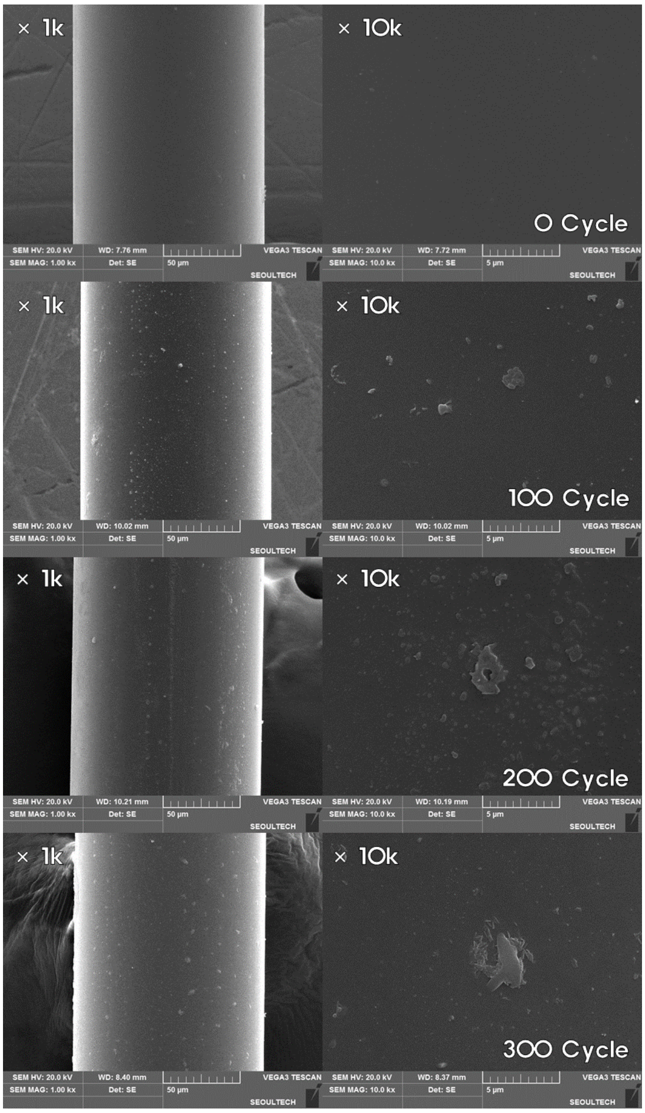


Fig. 9 SEM photos on the surface of FBGs with cycle changes

5. Conclusions

The main purpose of this study is to investigate the change of the mechanical strength of FBGs exposed to long-term repetitive thermal load. For this purpose, an accelerated aging test with FBGs is conducted in a thermal chamber at temperatures ranging from -20ºC to 60ºC for 300 cycles. The influence of repetitive thermal load on the mechanical strength values of FBGs is examined through tension testing. Conclusions achieved from the test are as follows.

- The mechanical strength of FBGs with 6dB reflectivity decreases as thermal cycle increases; the mechanical strength then remains steady until 300 cycles. Due to aging effects induced by the thermal cycles, the degradation of the mechanical strength is about 8% compared to that of pristine FBGs.
- The mechanical strength shows a linear relationship with the reflectivity of the FBGs. As the initial reflectivity of the FBGs, 3dB, increases to 6dB and 10dB, the mechanical strength of the FBGs at 300 cycles decreases to about 6% and 12%, respectively.
- From SEM photos of the surface of the grating parts in a single optical fiber, a gradual increase of damage, in terms of size and frequency in particular, is observed as the thermal cycle increases. However, due to the brittleness of silica (SiO_2) fiber, the mechanical strength does not show the same tendency as the SEM results.

Consequently, it is determined that appropriate reflectivity is better than too high reflectivity, although very high reflectivity might be better for higher signal sensitivity of FBGs, because it can allow the generation of much more strength drop during a long-term SHM under thermal cyclic load conditions. For the long-term behavior longer than 300 cycles, FBG sensors seem to show the similar tendency until their sudden failure at an arbitrary cycle, that is a general characteristic of brittle materials.

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