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Investigation of Stud Bolt with Fiber Bragg Grating Sensor Under Different Bolt Tightening Torque

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ABSTRACT

This study presents an investigation of stud bolt with embedded Fiber Bragg Grating (FBG) sensor under different tightening torque. The use of FBG sensor enables the precise quantification of the actual strain caused by any loading acting on bolts, as well as the detection of potential harm arising from an excessive working load to the flange. The objective of this work is to monitor the axial strain of M18 stud bolts on a standard flange for pipe connections using multiplexed FBG sensors that are integrated into the bolts. A connection was established between two carbon steel pipes using a series of flanges secured by four bolts. The testing results demonstrated a clear and direct relationship between the tightening torque and the wavelength of the FBG sensor. The strain reading showed an acceptable level of linearity. It is revealed that, although bolts were tightened with the same torque, each bolt experienced a different level of tension. The methodology outlined in this research presents an alternative approach to monitoring the extension of bolted gaps and assessing the degree of bolt looseness.

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INTRODUCTION

The bolted connection is a widely utilized technique for mechanical joining. To guarantee the structural integrity and prevent loosening of bolt connections, it is imperative to apply pre-tightening throughout the assembly process. The investigation of the optimal pre-tightening torque represents a subject that necessitates scholarly examination. Achieving appropriate preload in a bolted connection might provide challenges. The research conducted by Ajaei & Soyoz [1] demonstrated that a decrease in bolt preload correlated with an expansion in the ranges of stress variations, thereby leading to an escalation in fatigue damage. Meanwhile, Feng et al. [2] demonstrated that an increased pretension force has the potential to reduce the occurrence of damaging events in the bolting system. Several other researchers have also discussed the correlation between preloading and the circumstances of the bolt [3-5]. Insufficient preload resulting from an imprecise tightening technique can be identified as a potential factor contributing to the failure of bolted joints.

From an engineering perspective, it can be stated that the design of all bolted joints aims to attain a precise level of tension, and the manner of tightening serves as the means to accomplish the desired tension. The impact of surface roughness on the correlation between torque and tension in threaded fasteners was examined by Nassar and Sun [6]. Their study aimed to improve the accuracy of estimating clamp load levels from tightening torque, thereby enhancing the safety and reliability of bolted assemblies, particularly in critical applications. In an earlier study, Kumakura and Saito (7) introduced a way for enhancing the integrity of bolted flange joints using multiple bolts. This method was subjected to experimental investigation and was determined to exhibit superior effectiveness when compared to the ASME approach. The study conducted by Liu et al. [8] revealed that the variation of bolt load distribution is significantly influenced by tightening torque conditions and bolt-hole clearances. However, the impact of other random parameters on the variation of bolt load distribution is minimal. Meanwhile, Zhu et al. [9] have devised a sophisticated apparatus for examining the early loss of tension in bolted joints with great precision. Their research reveals that the rate at which the bolts are tightened, and the frequency of repeated tightening exert significant effects on the initial loss of tension. A process criterion was proposed with the aim of minimizing it and improving the dependability and safety of critical applications.

When a bolt is subjected to preload, it can evenly distribute the applied working force throughout the plate near its head. According to the analysis conducted by Qiu et al. [10], the primary component that significantly influences the performance of bolt connections is the preload. The height of the bushes, although to a smaller extent, also contributes to this performance. In the absence of bolt preload, the structural integrity of the entire system would be solely dependent on the bolt's ability to support the applied load. From a mechanical standpoint, the bolt functions as a spring mechanism that is responsible for generating and maintaining preload within the joint. If the bolt is not appropriately stretched or elongated, it will not be possible to obtain and sustain the intended preload. The process of bolt tightening is more complex than it may appear, particularly for systems that experience significant working loads, such as those found in oil and gas distribution lines. In certain essential applications, the temperature and pressure loading often exhibit significant magnitudes. In order to maintain the structural integrity of industrial bolts under significant weight loads, engineers must possess a comprehensive understanding of the underlying principles of physics pertaining to bolting in industrial applications. If the preload torque exceeds the specified threshold, the connection will experience failure, whereas a preload torque below the designated threshold will result in non-compliance with the prescribed usage criteria. In their work, Liu et al. [11] determined that the application of suitable preload or interference fit could alter the contact status and stress distribution surrounding the fastener hole in loaded joints. Consequently, this modification leads to an enhancement in the load-carrying capability of the joints. Excessive preload or interference fit can lead to early joint failure and subsequently reduce the load capacity. Hence, the determination of the tightening torque of bolts has emerged as a crucial concern in the realm of assembly operations.

The utilization of an FBG sensor for structural health monitoring (SHM) has attracted significant attention in recent times, owing to its notable advantages. The sensor's multiplexing capabilities, immunity to interferences, and ability to resist severe environments position it as a viable candidate for commercial development as a smart system for structural monitoring. Typically, FBG sensors employ light as its signal carrier, granting them immunity against electromagnetic and electrostatic sources [12-14]. Multiple studies have demonstrated the efficacy of FBG sensors in the real-time monitoring of bolts. Chen [15] devised a bolt monitoring system utilizing FBG sensors that can be conveniently affixed to the bolt's end. These sensors are reusable and offer a maintenance benefit by enabling real-time monitoring of bolts. In their study, Tu et al. [16] presented the application of metal-packaged fiber Bragg grating (RFBG) sensors. The development of the RFBG sensor involved a hybrid process that combined magnetron sputtering and electroplating techniques. Subsequently, the sensor was affixed to a bolt using spot-welding. To ensure accuracy and reliability, the sensor was calibrated using uniaxial tensile and thermal testing. The utilization of this technology presents a novel opportunity for the real-time monitoring of bolt clamping force and structural health assessment of bolt joint structures that operate in high-temperature environments. In a study conducted by Pran et al. [17], a long-term test was performed to observe the phenomenon of creep in bolted glass reinforced composite materials. To accurately measure the creep, an FBG sensor was strategically embedded at the central location of the bolt. The results of the test demonstrated the practicality of utilizing FBG sensors for field monitoring purposes. However, it is important to consider the influence adhesive material. The smart bolt concept described by Ren et al. [18] involved the utilization of four embedded FBG sensors for the direct measurement of axial and shear stresses. Subsequently, Duan et al. [19] conducted a comprehensive analysis of the previous method and introduced self-temperature compensated FBG smart bolts, aiming to enhance their suitability for a wider range of actual application scenarios.

The aim of this study is to observe the axial strain of modified stud bolts on a conventional flange for pipe connections using a set of multiplexed FBG sensors that were integrated into the bolts. The goal of this approach is to quantitatively assess the real-time stress encountered by individual bolts throughout the preloading process.

EXPERIMENTAL SET UP

A C-channel steel structure was constructed to support two 0.6-m long pipes, each of which was welded to an ANSI B16.5 steel flange on both ends (Figure 1a). The labelling for each bolt can be seen as in Figure 1(b).

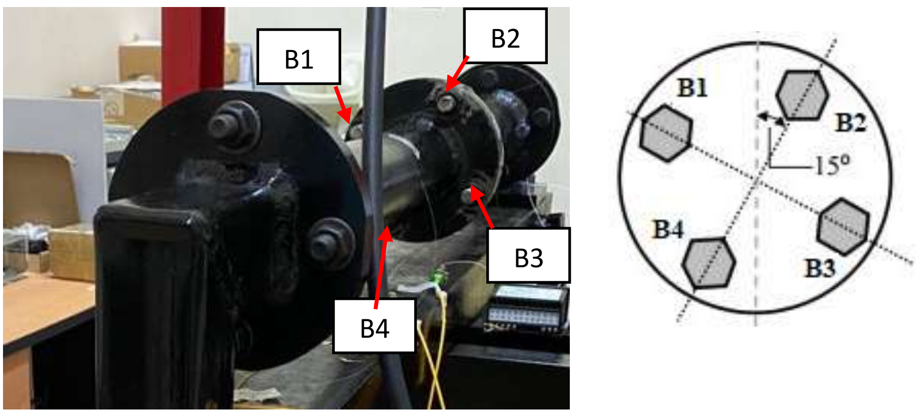


Figure 1. (a) The picture of the experimental setup (b) Position of bolts and its label

Four FBG sensors were utilized in this experiment to monitor the shift in the Bragg wavelength. The sensors have different wavelengths; 1544 nm, 1546 nm, 1551 nm, and 1550 nm, and were surface pasted on four stud bolts labeled as B1, B2, B3, and B4, respectively. Slight modifications have been made to each bolt in order to install FBG sensor, as shown in Figure 3. A super luminescent diode (SLD) light source with an output power of 600 mA was used in the FBG interrogation setup to monitor the FBG central wavelength. The SLD light source and FBG sensors were then connected using an optical circulator. All four FBG sensors were arranged in series, as illustrated in Figure 2. A high-speed FBG interrogator, or optical spectrum analyzer (OSA) with a minimum resolution of 1 pm and 1,000 Hz sampling frequency was utilized to acquire the FBG wavelength data.

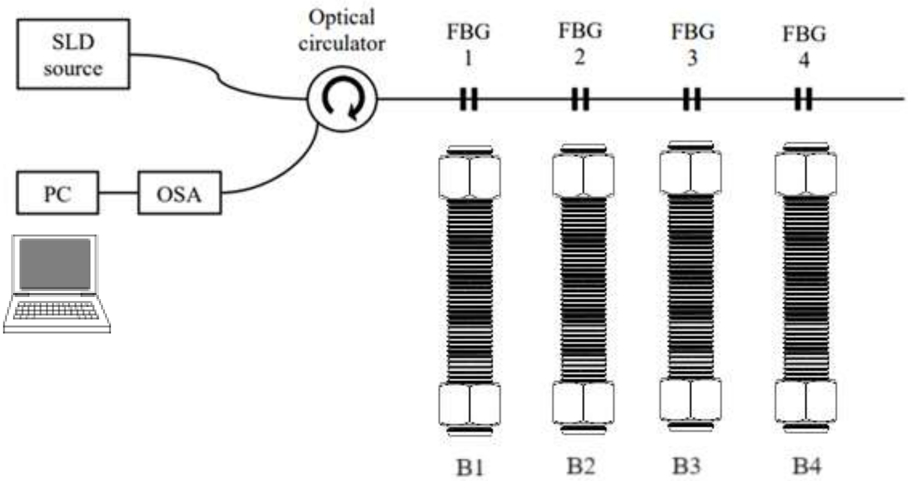


Figure 2. Schematic illustration of the FBG interrogation system

Figure 3. Location of FBG on bolt.

The experiment was conducted at a controlled room temperature of 27 °C with variances of ± 0.3 °C. A digital thermometer was employed, and its probe was located near the FBG sensor to monitor the surrounding temperature. At a controlled room temperature of 27 °C, the relationship between the shift of FBG central wavelength, λ_B and the strain parameter, ε can be expressed as,

$$\frac{\Delta\lambda_{\boldsymbol{B}}}{\lambda_B} = (1 - \rho_e)\varepsilon \qquad (1)$$

where ρ_e is an effective photo elastic coefficient and ε is the axial strain of the grating. Photoelasticity is defined as the change in reflected wavelength depending on the strain applied in axial direction. For FBG systems, the photo-elastic coefficient $\rho_e \approx 0.22$ can be found in the literature [20]. Therefore, the theoretical sensitivity of the grating to strain for a general FBG at the wavelength range of 1550 nm, is approximately $\Delta\lambda_{\boldsymbol{B}}/\varepsilon = 1.2\, pm/\mu\varepsilon$.

In order to examine the true strain experienced during bolt preloading, an experiment was conducted including the application of varying torque values ranging from 10 Nm to 70 Nm to individual bolts. It is important to note that no external load was applied to the flange during this investigation, therefore only axial force due to tightening was involved. The tightening of all bolts was performed manually with the aid of a torque wrench. To address the issue of flange misalignment and reduce the likelihood of associated difficulties, a transverse tightening approach was employed. This involved sequentially tightening the bolts in the following order: B3, B1, B2, and B4. The wavelength shift reading was taken after complete tightening set.

The primary objective of this measure is to uphold the integrity of a flange joint and proficiently manage the variability of stress experienced by the bolts. In order to assess the sensor's repeatability, the experiment was conducted on three separate occasions. In order to obtain more reliable data measurements, the wavelength readings obtained from the FBG interrogator were consistently maintained for a duration of 30 seconds during each stage of the experiment.

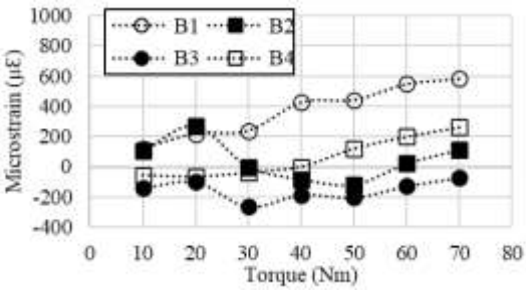
RESULTS AND DISCUSSION

Table 1 presents the strain measurements of the bolts following the tightening process. The presence of a negative sign indicates that the bolt is subjected to compressive stress, whereas a positive sign indicates that the bolt experiences tensile stress. The strain values were determined by applying the theoretical relationship between the wavelength shift, $\Delta\lambda_{\boldsymbol{B}}$, and the strain, ε, as derived from equation (1).

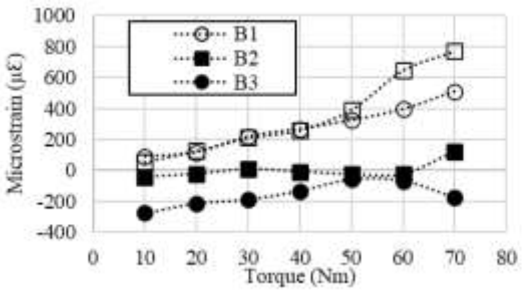
Table 1. Actual strain for all bolts in 3 trials.

Torque (Nm)			10	20	30	40	50	60	70
Microstrain (με)	B1	Trial 1	120.2	217.9	237.1	426.4	442.7	548.7	582.0
		Trial 2	88.0	115.3	218.4	267.6	323.4	395.0	509.7
		Trial 3	-5.1	-26.8	-61.8	-24.2	-10.2	14.5	50.7
	B2	Trial 1	108.9	270.9	-0.1	-82.3	-118.8	21.2	112.9
		Trial 2	-41.1	-21.6	7.8	-7.8	-24.8	-22.9	120.8
		Trial 3	-80.7	-0.8	18.8	39.7	85.4	135.6	174.7
	B3	Trial 1	-140.7	-100.6	-264.1	-184.8	-203.7	-128.3	-73.0
		Trial 2	-276.0	-212.8	-188.7	-133.3	-59.4	-69.3	-176.4

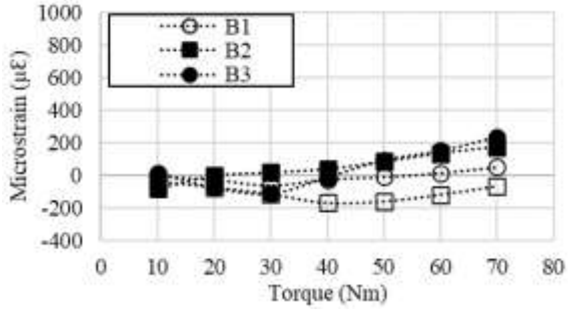
	Trial 3	14.4	-75.9	-112.7	-12.2	92.4	149.4	234.5
	Trial 1	-55.7	-67.3	-38.7	-0.6	120.3	199.2	260.5
B4	Trial 2	53.3	126.8	209.8	259.7	393.8	648.2	772.2
	Trial 3	-34.7	-71.3	-114.3	-168.5	-158.7	-117.0	-64.5



(a) Trial 1



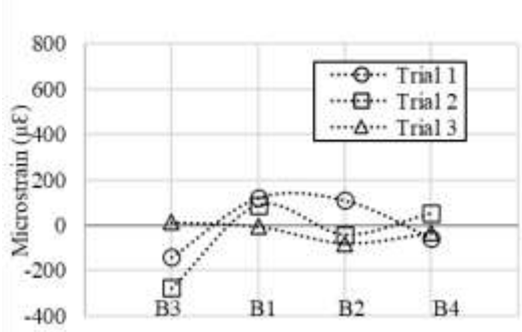
(b) Trial 2



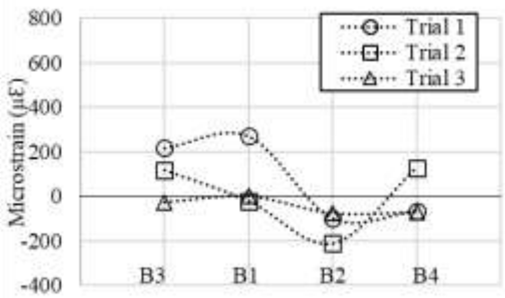
(c) Trial 3

Figure 4. Strain vs tightening torque.

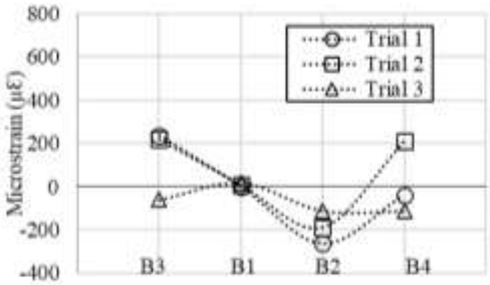
Figures 4 show the relation between strain measured by FBG sensor and the tightening torque. indicate that the distribution of strain on bolts does not exhibit a recognizable pattern especially at lower magnitude of torque. The increase in pattern becomes significant when the tightening torque reaches 40 Nm or higher. It is important to note that the maximum strain is not experienced by the same bolt in all three trials. In the initial trial, bolt B1 had the most elevated measurement of 582 $\mu\varepsilon$ when subjected to a torque of 70 Nm. In trials 2 and 3, it was observed that bolt B4 and bolt B3 had the maximum strain readings of 772.2 $\mu\varepsilon$ and 234.5 $\mu\varepsilon$, respectively, when subjected to a torque of 70 Nm. The findings also indicate that certain bolts will experience compression throughout each test, despite the intended purpose of tightening to induce tension stress in the bolts. Under low tightening torque, a significant number of bolts experience compression. However, as magnitude of the tightening escalates, most of the bolts experience tension, particularly beyond the threshold of 50 Nm.



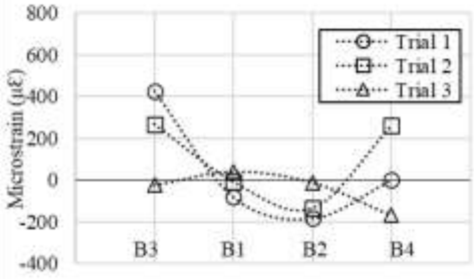
(a) 10 Nm



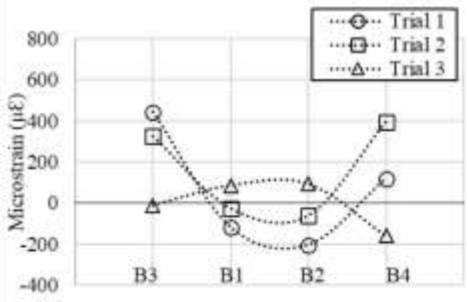
(b) 20 Nm



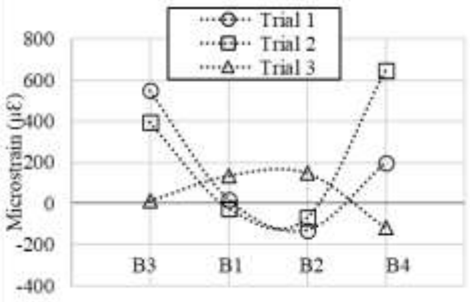
(c) 30 Nm



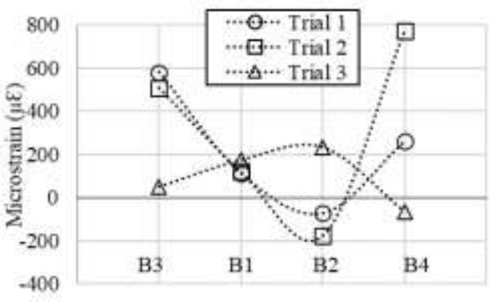
(d) 40 Nm



(e) 50 Nm



(f) 60 Nm



(g) 70 Nm

Figure 5. Strain measured by FBG sensor after tightening all bolts from torque 10 Nm to 70 Nm (a – g)

Figures 5 illustrate the strain values obtained from the Fiber Bragg Grating (FBG) sensor for each bolt, after the application of torque ranging from 10 Nm to 70 Nm. It is important to acknowledge that the strain measurement was conducted after each complete cycle of tightening, starting with B3, followed by B1, B2, and ending with B4. The bolts subjected to low torque values, specifically 10 Nm, 20 Nm, and 30 Nm, exhibited modest levels of stress. There is no discernible pattern of significance, and each bolt has the potential to undergo both compression and tension in every repeat. At this stage, a substantial amount of the stress experienced is attributed to the gravitational force acting on the flange. Nevertheless, when the torque applied to bolts reaches 40 Nm or more, they begin to undergo tensile stress due to the tightening process. Additionally, it is noted that the stress variation also increased significantly at each bolt for every trial.

CONCLUSIONS

This study introduced the utilization of a bolt fitted with an embedded FBG sensor to enable real-time strain monitoring of the bolt, particularly in response to varying levels of tightening torque. The experimental findings indicate that individual bolts will undergo varying stress conditions, such as tension or compression, despite the application of an equal amount of tightening force. The findings also indicate that the magnitude of strain encountered by each individual bolt differs across each repeat. Hence, the utilization of these FBG bolts provides engineers with valuable information for monitoring and predicting the lifespan of bolted joints, thereby facilitating maintenance activities.

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