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Investigation of the dynamic strain responses of sandstone using multichannel fiber-optic sensor arrays

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ABSTRACT

In the process of rock mechanical experiments, strain-response measurement is a most fundamental and most essential procedure for geomechanical researchers. The main objective of this paper is to point out the feasibility and the superiority of the application of a novel multichannel fiber Bragg grating (FBG) sensor arrays for dynamic strain-response measurements of cylindrical specimen subjected to uniaxial compression. The principle, design, and embedment of multichannel FBG sensors used in the experiment are briefly described. To fully monitor the strain history of the sandstone cylinder in uniaxial compression, six circumferential FBG sensors, four lateral FBG sensors, linear variable differential transformers (LVDT) built-in machine have been utilized for spatially monitoring small radial and axial strains along the height of the specimen, respectively. The experimental results indicate that the proposed FBG sensors can successfully provide a full-field view of the surface strains, as well as detect the potential crack locations within the specimen, and strains measured by multichannel FBG sensors are in good agreement with the results of LVDT, especially in the axial strains. Hence, it could be inferred that multichannel FBG sensor arrays are capable of measuring dynamic strain responses of sandstone specimen in multistage compression, which would greatly strengthen experimental basis for further application and theoretic research of in-situ field monitoring.

1. Introduction

Dynamic strain monitoring plays an essential role in mechanical characterization analysis of sub-and core-scale specimens, health assessment of industry-scale geotechnical structures, etc. One of the basic and most used methods of testing which is performed on rock samples is determination of uniaxial compressive strength and deformability (Kuhinek et al., 2011; Ranjith et al., 2004; Xie et al., 2011; Xu et al., 2013; Yu et al., 2016). Over the past several decades, there have been various instrumentations and implementations for strain measurement such as linear variable differential transformers (LVDTs) (Ibraim and Di Benedetto, 2005; Yimsiri et al., 2005), electrical resistance strain gauge (ESG) (Kovačič et al., 2015; Montero et al., 2011; Motra et al., 2014; Raghuwanshi and Parey, 2016; Ramos et al., 2015), digital image correlation (DIC) (Lin and Labuz, 2013; Mehdikhani et al., 2016; Munoz et al., 2016; Walter, 2011), digital terrestrial photogrammetry (DTP) (Firpo et al., 2011; Sturzenegger and Stead, 2009) and extensometer (Feng et al., 2010; Jia et al., 2012; Perusek et al., 2001). Although it is generally agreed that these preexisting monitoring technologies can be comparatively accurate and reliable during the whole service life of the measurands respectively, intrinsic defects such as electromagnetic interference, signal loss, time-consumption and labor-intensity, uneasy acquisition, low resolution, and high cost remain intact, therefore they are deemed unsuitable for dynamic real-time and in-situ strain monitoring in field-scale engineering applications. Additionally, in terms of the sample heterogeneity and experimental complexity, it is important to note that these methods mentioned above can also barely implement high resolution and full-field simultaneous strain measurements with multiple sensors in harsh laboratory conditions (high temperatures, high pressures, corrosive acids, etc.).

Fiber Bragg grating (FBG) based sensing technology has been universally appreciated as the most promising candidate to effectively measure strain, temperature, pressure, vibration, ultrasound and other measurands (Sun et al., 2015). Owing to its outstanding advantages such as small size, flexibility, anti-corrosion, resistance to high pressures and high temperatures (HPHT), immunity to electromagnetic interference (EMI), large-scale multiplexing capability, wavelength-encoded characters, linearity, and so forth (Kou et al., 2012; Lai et al., 2013; Sun et al., 2013; Ye et al., 2014), it has a huge range of applications in aerospace (Davis et al., 2012), energy (Marques et al., 2015; Shivananju et al., 2013), and maritime (Prasad et al., 2009; Razali et al., 2015), oil and gas downhole (Nellen et al., 2003; Schmidt-Hattenberger et al.,

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2004; Villnow et al., 2014; Zhou et al., 2012), biomedicine (Dziuda et al., 2013; Mishra et al., 2010; Roriz et al., 2013), acoustics (Silva et al., 2015; Takuma et al., 2014; Wu and Okabe, 2014), and especially for structural health monitoring (SHM) in various civil infrastructures (Ecke and Schmitt, 2013; Elshafey et al., 2016; Gage et al., 2014; Sanada et al., 2012; Torres et al., 2011; Weng et al., 2015; Xu et al., 2014; Zhu et al., 2015). However, it is worth noting that there are certain demerits of the FBG sensors. Because of more fragility of FBG sensor, some effective sensor package and protection methods are required. In addition, the FBG sensors and their interrogators are relatively expensive in comparison with conventional systems. And if high measurement resolution can be approached, FBG sensors are quasi-distributed fiber-optic monitoring technology and less powerful for the measurement of average strain or displacement than distributed optical sensors, such as Brillioun optical time domain analysis (BOTDA) or Brillouin Optical Time Domain Reflectometry (BOTDA).

Through these comparisons mentioned above, it could be found that in virtue of mechanical/electrical deformation of in-built components of conventional strain sensors, applied strains are deduced indirectly, so the measured strains are to a great extent dependent on properties of sensor components. The conventional strain measurements, such as ESGSs and LVDTs tend to be less stable over long periods of time due to decay and hence are suitable for short-term monitoring only. In addition, they can be easily deteriorated by water. In addition to these drawbacks, their each sensing unit needs many cables and wires for handling, which will suffer from electro-magnetic interference and electrical noise and it would further contaminate the measured strains. As for the conventional extensometer, it entails manual recording of data, which could be tedious, and for another, it will be obstructed by various installations in the in-situ applications. Besides, for the digital monitoring methods, the main limitation is that the devices frequently demand physical movement and could put the monitored structure out of service during the testing period (Yang et al., 2007). However, FBGs is an optical sensor made of thin fiber of glass and silica to transmit light signals, and external mechanical strain is calculated by the shifts of the reflected signals in the fiber (Yang et al., 2007). Therefore, it is tempting to conclude that the outstanding advantages make FBG stain sensors high-accuracy (one microstrain) to monitor permanently deep and ultra-deep subsurface environments.

Based on above-mentioned capabilities, it is concluded that FBG sensor can potentially serve as a viable alternative to ESG or LVDTs for real-time strain monitoring of core specimens in laboratory testing. To date, however, there are only a certain number of articles involved preliminarily in this field where FBG sensors have been tentatively bonded/embedded into core specimens for dynamic strain, crack propagation, and damage detections (Elshafey et al., 2016). Alvaro et al. (Castro-Caicedo et al., 2013) presented a packaging and calibration procedure for surface mounting of FBG sensors to measure longitudinal and transversal strains as occurs in gabbro specimens, as well as comparison and validation with ESG concurrently attached to the locations nearest the sensors. The final conclusion showed that response of FBG sensors was linear and reliable, the strain ranges in rocks were experimentally confirmed as a few tens of microstrain, and the influence of rock inhomogeneities could be diminished due to increased effective measurement area of the FBG sensor packaging. Chen et al. (Smith et al., 2014; Chen et al., 2014) conducted an initial experiment upon detecting the strain history of the cylindrical SCARC (simulated carbon ash retention cylinder) samples and fracture locations within the cylinder. Lee et al. (Lee et al., 2011) explored the development of a modified fiber optic sensored triaxial testing device coupled with a force transducer, linear displacement sensor, and a series of gauge/differential pressure transducers, as well as some soil tests carried out to practically evaluate and validate the effectiveness of the device based on the available test results by Xu et al. (Xu et al., 2014).

In the past several decades, in virtue of the nature characteristics of maximal complexity, many uncertainties and little visibility (Baldwin, 2014; Kersey, 2000), it has been a crucial and challenging project to break through for geoscientists and reservoir engineers that how to realize high-accuracy, elaborative and permanent in-situ monitoring for the dynamic processes of unconventional energy exploitation and geological disposals in the deep subsurface formations, especially with the rapid expansion of CO_2 capture, utilization and storage (CCUS) (Xue et al., 2014), geothermal exploration, underground gas construction, shale gas development, enhanced oil recovery (EOR) (Sun et al., 2016). For these reasons, it is therefore evident to point out that FBG-based sensing technology will be aroused great interests and industrial demands in future due to its intrinsic superiority adapting for harsh environments (Braga, 2014; Nakstad and Kringlebotn, 2008). Undoubtedly, considerable efforts have been devoted to the field applications based FBG in the oil and gas industry (Hull et al., 2010; Koelman et al., 2012; Zhou et al., 2010). However, it has been realized that there are only few studies focusing on core-scale reservoir simulated experiments using FBG sensors (Bao et al., 2013), especially with explicit consideration of the dynamic strain responses of reservoir rocks.

In this paper, a new distributed monitoring method based on multichannel FBG sensor arrays is proposed and implemented to measure the axial and radial strain variations along the surface of cylindrical core specimen subjected to multistage uniaxial loads which has not been reported till date to the best of our knowledge. Ten FBG sensors (written in five arrays) and two built-in LVDTs are installed to characterize the full-field strain profiles and predict the potential micro/macrocrack propagation. By comparing the results from the multichannel FBG sensor arrays with built-in LVDTs, the applicability and workability of this idea and setup are confirmed.

2. Principle and methodology of multichannel FBG sensors

2.1. Operating principle of the FBG sensing technology

Traditionally, single mode fiber-optic (SMF) is made up of core and cladding as well as the core with a refractive index slightly higher than the cladding due to the presence of some dopants. An FBG consists of a short segment of SMF with periodic modulation in refractive index of the fiber core along the axis of the fiber, and is generally treated as a wavelength specific deflector or filter. When broadband light source (BLS) is launched into the FBG, each reflected light peak is centered on the called Bragg wavelength and light of other wavelengths without significant attenuation is transmitted, as shown in Fig. 1. The reflected wavelength of an FBG can be expresses as (Morey et al., 1990):

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

where λ_B is the Bragg wavelength, n_{eff} is the effective refractive index of the grating in the fiber core and Λ is the grating interval.

In practice, n_{eff} and Λ are both directly influenced by changes in strain and ambient temperature. When the grating is subjected to an axial strain to FBG orientation and/or an occurrence of temperature gradient closest to FBG, n_{eff} and Λ must be linearly modified through the thermo-optic and strain-optic effects, respectively. Hence, the relative Bragg wavelength shift $\Delta\lambda_B$ due to strain and temperature changes of the single fiber can be written as (Othonos and Kalli, 1999):

$$\begin{aligned}\Delta\lambda_B &= 2\left(\Lambda\frac{dn_{eff}}{d\varepsilon} + n_{eff}\frac{d\Lambda}{d\varepsilon}\right)\varepsilon + 2\left(\Lambda\frac{dn_{eff}}{dT} + n_{eff}\frac{d\Lambda}{dT}\right)\Delta T \\ &= \lambda_B(1-p_e)\varepsilon + \lambda_B(\alpha+\xi)\Delta T = S_\varepsilon\varepsilon + S_T\Delta T\end{aligned} \tag{2}$$

where ε is the longitudinal strain on the FBG, ΔT is the temperature variation, p_e is the effective photo-optic constant of the optical fiber core material; α is thermal coefficient for the fiber, and the quantity ξ denotes the thermo-optic coefficient of the grating. Moreover, the strain and temperature coefficients of relative Bragg wavelength shifts are $0.78\times10^{-6}\ \mu\varepsilon^{-1}$ and $6.67\times10^{-6}\ ^{\circ}\mathrm{C}^{-1}$. For a silica-based FBG with