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Optical visualization of strain development and fracture propagation in laminated rocks

Fatick Nath*, Mehdi Mokhtari

University of Louisiana at Lafayette, USA

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ABSTRACT

Shales are commonly anisotropic in nature due to layering and natural fractures which consequently impact the m0echanical behavior of shale in terms of stress-strain distribution, fracture initiation, propagation and fracture pattern. The classical method of strain measurement with strain gauges can not reveal the complex process of strain accumulation and fracture propagation in such anisotropic rocks. Therefore, we applied optical techniques along with image processing to measure strain on the surface of laminated Green River shale samples with various lamination angles under indirect tensile testing conditions. Full-field strain development was monitored over time and fracture patterns were identified utilizing digital image correlation (DIC) technique. A load-strain nature were established as a function of lamination angles incorporated with DIC generated horizontal, vertical and shear strain maps which results in better understanding of sequences in strain development and fracture pattern due to laminations. Variation in indirect tensile strengths are evaluated and reported with applied energy which shows that sample with higher tensile strength required higher applied energy to fail it. Fracture pattern obtained from DIC visualization are characterized which show that shear failure is dominant when failure occurred through laminations and tension for central failure samples. Finally, the measured axial strain from load frame is compared with DIC and achieved a considerable agreement in both measurement. The knowledge of this study can help in evaluating fracture behavior of laminated formations which can be important for energy-related activities including fracturing, fluid injection and extraction.

1. Introduction

Development of unconventional resources have been booming globally much faster than conventionals due to the availability of horizontal well drilling and hydraulic fracturing techniques (EIA, 2015). Shale formations show anisotropic behavior due to the laminations and natural fractures. In most hydraulic fracturing designs, it is assumed that the formations are homogeneous, and fractures are linear and symmetrical but in unconventional formations, anisotropy and heterogeneity are very common. So, investigating the parameters that impact the geomechanical behavior of laminated formations are in great importance in understanding the fracture behaviors and hydraulic fracture treatment design.

Fracture mechanism is complex due to laminations and organic richness due to varying contents of total organic contents (TOC) and clay structure (Sayers, 2013). The impact of kerogen volume on elastic properties have been investigated (Prasad et al., 2011; Zargari et al., 2013), however, the impact of these anisotropic features on local strain development and fracture pattern is not well understood.

The rock failure mechanism is a combination of complex process of damage accumulation, fracture initiation, propagation, interaction and subsequent failure (Amitrano, 2006). Accurate strain mapping is critical for understanding the mechanical behavior during entire failure process of rock. Conventional physical strain measurement systems (extensometer, Linear Vertical Differential Transformer (LVDT), strain gauges, etc.) for determining the mechanical behavior of rocks are not accurate enough due to the heterogeneous nature of shales. So, improving the study of material behavior, accurate strain measurement is crucial which involved in predicting important material properties (load-displacement nature, etc.).

Brazilian test set up commonly used to determine the indirect tensile strengths in which diametrically opposed compressive load is applied to determine tensile strength of the rock-like materials. Many researchers conducted experimental work on strength and failure of different formations (Wang et al., 2010; Zhou and Zhao, 2011; Frash et al. (2015); Mokhtari et al. (2014b); Li et al., 2017). Anisotropy and layer orientation also greatly influence the rock strength (Vernik and Nur, 1992; Vernik and Liu, 1997; Mokhtari et al., 2014a; Mokhtari and

* Corresponding author.
E-mail addresses: fatick102@gmail.com (F. Nath), mxm4487@louisiana.edu (M. Mokhtari).

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Tutuncu, 2016; Tavallali and Vervoort, 2010; Tan et al., 2015).

Most of the study explained the fracture pattern at the end of the experiment, as it was not possible to detect strain development in each time steps and to predict the fracture initiation point and propagation over time. To overcome these issues, optical method with digital image correlation (DIC) is utilized to create the map of full-field deformation over time throughout the entire fracturing process.

DIC is a powerful technique (Pan et al., 2009a; b) among other experimental methods for determining the displacement and strain fields across the surface of a specimen. DIC method offers full field, real-time, non-contact, and flexible (Sutton et al., 2009) measurement at any desired, exposed region of specimen. The theoretical fundamentals of the DIC technique was first introduced by Chu et al. (1985). It received a widespread application in many fields (Rue, 2015) of material testing. Nath et al. (2018) reported the dynamic visualization of strain development in cement-casing bonding using this optical method. Mokhtari et al. (2017) applied DIC technique on naturally-fractured rock samples under Brazilian testing conditions. They determined complex strain accumulation leading to fracture initiation and complex propagation. Therefore, this technique can be helpful in better fracture characterization required for the optimization of hydraulic fracturing (Parshall et al., 2017).

Nath et al. (2017) illustrated the DIC technique in characterizing the fracture growth and fracture behaviors of laminated sandstone and carbonate rock samples. Na et al. (2017) explained the effect of spatial heterogeneity and material anisotrophy on the fracture pattern of Mancos Shale using Brazilian testing and DIC. Zhang et al. (2012) reports the experimental investigation of deformation and failure mechanisms in rock under indentation by digital image correlation.

In this study, indirect tensile tests were conducted on Green River shale samples with varying TOC and evolution of strain field is obtained using digital image correlation. Programmable pyrolysis is utilized to determine the TOC content and maturity of the samples. Brazilian discs were prepared according to the ISRM and ASTM standards. The laminated anisotropic samples were tested at various loading angles (0°, 15°, 30°, 45°, 60°, 75°and 90°). Load-strain nature were established for all tested samples and tensile strengths were calculated using the peak load of the primary fracture of each sample. Then, fracture energy and trends in the fracture pattern were established based on anisotropy and angle of lamination. This combined approach is applied in shale samples with anisotropy due to layering and tested at different orientation to layering. The indirect tensile strength is measured as a function of lamination angle and finally full-field strain development is evaluated and compared.

2. Material and methods

2.1. Green River shale

Green River (GR) shale is an Eocene geologic formation that records the sedimentation of intermountain lakes covering large area of Utah, Colorado, and Wyoming (Donnell et al., 1967). To produce hydrocarbon from this immature organic-rich formation, artificial heating is required to convert kerogen to free hydrocarbon. The pyrolysis test reported that the tested samples have high amount of TOC (26.4–30.56 wt. %). The overall geochemical properties of GR shales tested in this study are listed in Table 1. Pyrolysis results of all tested samples are presented in Table 2. Tested samples are investigated as immature oil shale with type-I kerogen.

GR shale are typically laminated in nature (Fig. 1) and the laminated samples were examined for changes in fracture behavior due to the direction of lamination relative to the direction of the compressive force.

To begin preparing the samples, cylindrical cores with 2 inch diameter were drilled from larger irregular shaped rock blocks. It was maintained that the axis of the cores was parallel to the bedding planes.

Table 1
Green River shale properties.

Sample type	Outcorps
Kerogen Type	Type-I; immature, oil prone
Avg. Density (g/cc)	1.62–1.76
TOC (wt. %)	26.4–30.56
T_{max} (°C)	442–443

Table 2
Pyrolysis results of tested specimen.

Sample ID	S1 (mg/g)	S2 (mg/g)	S3 (mg/g)	Tmax (°C)	TOC (%)	HI	OI	PI
GR 1 (0°)	7.45	264.54	4.28	443	28.75	920	15	0.03
GR 2 (15°)	6.98	241.72	3.78	443	26.55	910	14	0.03
GR 3 (30°)	8.68	282.5	2.97	443	30.3	932	10	0.03
GR 4 (45°)	8.54	274.16	3.65	442	29.13	941	13	0.03
GR 5 (60°)	7.72	242.97	3.32	443	26.4	920	13	0.03
GR 6 (75°)	8.95	290.93	3.02	442	30.56	952	10	0.03
GR 7 (90°)	8.03	272.23	3.43	444	29.09	936	12	0.03

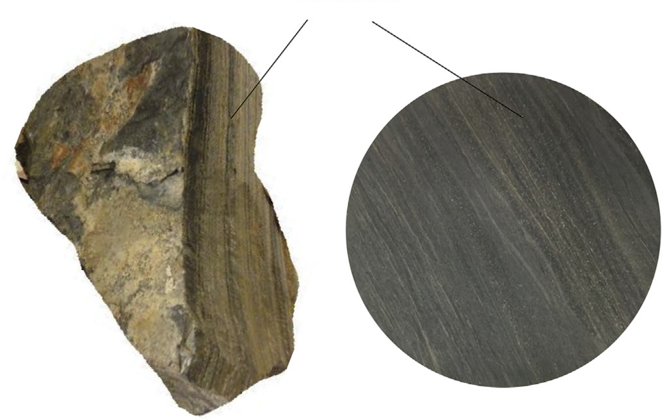

Fig. 1. Lamination in GR shale.

Then cores were cut into 1 inch length Brazilian discs to meet the dimension with the ISRM and ASTM standards (2″ Diameter × 1″ Thickness) to evaluate the tensile strength and fracture behavior. Then the samples were placed inside a stable temperature vacuum oven at 30 °C for two days to evaporate all fluids from the pores.

The samples were tested at loading angles (Fig. 2) of θ = 0°, 15°, 30°, 45°, 60°,75° and 90°. The angle θ = 0° and 90° representing the loading angle when lamination is parallel and perpendicular to the applied force respectively. The angles were labeled on the back side of the tested samples.

In this work, seven samples were taken with ~2″ diameter and ~1″ thickness for testing with seven different laminations. Generally, core samples are diametrically compressed (Fig. 3) in indirect tensile test and rock failure occurred due to tension as compressive strength is much larger than the tensile strength. The indirect tensile experiment is sometime called Brazilian or splitting tensile test. The samples were prepared and tested following the standard method, ASTM D3967-08. The length to diameter ratio (L/D) is suggested as 0.2 to 0.75 according to this standard. The sample diameter must be at least 10 times greater than largest mineral grain of the sample constituent (ASTM, 2008).

2.2. Theory of indirect tensile test

When a cylindrical sample disc with a diameter, D and thickness, t