Journal of Natural Gas Science and Engineering 36 (2016) 79–86

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Impact of laminations and natural fractures on rock failure in Brazilian experiments: A case study on Green River and Niobrara formations

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ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form
13 September 2016
Accepted 10 October 2016
Available online 13 October 2016

Keywords:
Tensile failure
Lamination
Natural fracture
Brazilian test

ABSTRACT

Natural fractures and laminations are common features in many unconventional resources which require hydraulic fracturing for economic production. To better understand the effect of such features on rock failure, we have conducted indirect tensile or Brazilian testing on several rock samples from Green River and Niobrara formations. Brazilian experiments were conducted at various orientations of laminations or natural fractures with respect to the loading direction. In contrast to isotropic rocks, we observed that rock failure can occur away from the vertical central line of rock parallel to lamination or natural fracture when the approaching angle between the lamination and loading direction is less than 30° in the tested samples. It was also determined that the tensile strength parallel to laminations or calcite-filled fractures is lower than the tensile strength perpendicular to lamination and/or the natural fractures; for instance the tensile strength of Niobara calcite-filled fractures were almost one third of the rock matrix.

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1. Introduction

Tensile failure mode is critical in the evaluation of the geologic processes, drilling and hydraulic fracturing operations for reservoir characterization and development plans. From a geological perspective, most of the joints, mineral veins and dykes are created when the fluid pressure is high enough to rupture the formation in tension (Gudmundsson, 2011). In drilling phase, lost circulation is a costly problem often due to unintentional excessive mud weight inducing tensile fractures. In hydraulic fracturing, a wellbore is intentionally pressurized to create tensile fractures for production stimulation from tight formations such as shale gas and oil reservoirs and the growth of hydraulic fracture is a function of the tensile strength (Laubach et al. 2004; Vejbaek et al. 2013).

In isotropic rocks, a planar fracture perpendicular to the minimum horizontal stress is expected as a result of the hydraulic fracturing operation. The minimum effective horizontal stress and the tensile strength of the formation is required to be exceeded to propagate the hydraulic fracture. However, this theory is valid only for isotropic rocks while most organic-rich shales do not show isotropic properties because laminations and natural fractures are common features in such reservoirs (e.g. Gale et al., 2007; Mokhtari and Tutuncu, 2015; Mokhtari, 2015).

Lamination is a result of the compositional layering due to the sedimentary processes (Schieber, 1998), clay mineral alignment (O'Brien and Slatt, 1990) and/or the lenticular distribution of kerogen (Vernik and Milovac, 2011). Moreover, the horizontal microfractures have been documented as a result of overpressurization in the course of oil and gas generation in organic-rich and mature shales (Berg and Gangi, 1999; Lash and Engelder, 2005; Lewan and Bridwell, 2013; Al Duhailan et al., 2013). Natural fractures can be also created as a result of tectonic forces. These fractures created in the geologic past are not necessarily oriented parallel to the present day maximum horizontal stress (Laubach et al., 2004).

Although tensile failure is a critical failure mode in various natural geologic processes or drilling and hydraulic fracturing operations, tensile strength is usually assumed unimportant throughout classical applications of petroleum geomechanics (Zoback, 2010; Fjaer et al., 2008) and in particular, there is very limited number of studies for measurements on the tensile strength of organic-rich shales (Gale and Holder 2008; Wang et al., 2013; Maldonado, 2011). One of the main reasons for this limitation is the significantly low value of the tensile strength of rocks compared to the compressive strength of the same formations. As discussed in detail by Fossen (2010), Griffith investigated the tensile failure in 1920s in terms of the energy required to break atomic bonds. He estimated the uniaxial tensile strength of a flawless rock to be around one tenth of its Young's modulus, i.e. a formation with 5×10^6 psi (5 Mpsi) of Young's Modulus could have a tensile

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http://dx.doi.org/10.1016/j.jngse.2016.10.015
1875-5100/Published by Elsevier B.V.

strength value of 0.5 Mpsi. Yet, the experimental studies show several orders of magnitude lower tensile strength in the range of 0–3650 psi (Gudmundsson, 2011). Griffith explained this discrepancy between the theoretical and experimental results as a result of the presence of microcracks, pores and grain boundaries within the rocks.

The presence of such natural fractures and laminations can affect complex fracture propagation rather than the classical theories of planar fracturing in macro scale. To explain this concept, we present natural fractures in an outcrop of Niobrara formation in Fig. 1 and discuss the possible interactions of the induced fractures with natural fractures schematically. The propagation of hydraulic fracture toward natural fracture depends on the tensile strength of natural fracture compared to the matrix, in situ stress anisotropy, and the orientation of the natural fracture. Complex fracture behavior was evaluated by Blanton (1982), Olson et al. (2012), Bahorich et al. (2012), and Suarez-Rivera et al. (2013) in triaxial tests; by Warpinski and Teufel (1987) in mineback experiments; by Mayerhofer et al. (2010) on the analysis of microseismic and production data; and by Dahi-Taleghani and Olson (2011) with numerical modeling of the natural fracture interactions with the hydraulic fractures.

There are several methods to obtain tensile strength using laboratory and field data. In the field studies, one of the approaches is an extended leak off test in which two cycles of fluid pumping is conducted. In the first cycle, a fracture is induced but there is already a fracture in the formation in the second cycle; therefore, the difference between the breakdown pressures in the first cycle and the second cycle provides the tensile strength of the formation at the testing depth. The formation fails at the breakdown pressure (P_b) as fluid pressure exceeds the compressive stress and tensile strength of the formation. To decrease the uncertainty in the estimation of the tensile strength, a third cycle is suggested by Kunze and Steiger (1991).

In laboratory tests, tensile strength can be obtained utilizing either direct or indirect methods. In the direct tensile method, one end of a sample is attached to a surface and the other end is pulled until the sample breaks. The proper attachment of the rock sample to the loading surface is quite challenging. Therefore, direct measurement of tensile strength is not common. Instead, an indirect way of tensile testing is implemented that was originally proposed by a Brazilian engineer Fernando Carneiro in 1943 (e.g. Jaeger et al., 2007). This test is known as a Brazilian test, splitting test, or indirect tensile test in which a rock sample with specific dimensions is diametrically compressed until it fails in tension. Brazilian testing is an ASTM recommended method (ASTM D3967, 2008) for measurement of the tensile strength of rocks. Samples with thickness to diameter ratio of 0.2–0.7 are diametrically compressed in Brazilian tests. The objective of this paper is to conduct Brazilian testing on rock samples with lamination or natural fractures to explain the effect of these anisotropic features on tensile strength and fracture pattern under Brazilian testing.

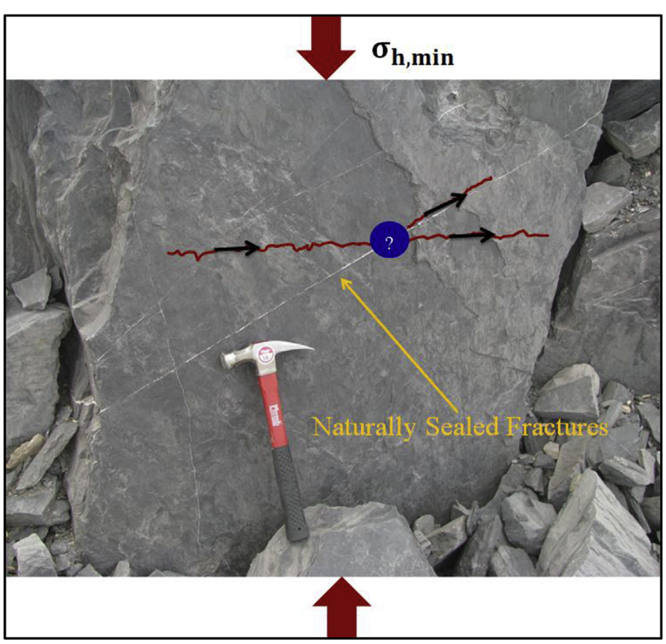

Fig. 1. This outcrop sample from Niobrara formation illustrates schematically the possible role of natural fractures in creating a complex fracture network rather than a planar fracture. The black arrow shows the possible directions of fracture propagation and the white bands presents the natural fractures.

2. Theory and description of Brazilian experiment

In our experiments, a servo-controlled load frame was used to apply the axial force at the displacement rate of 0.1 mm per minute. As recommended by ASTM, the displacement rate was such that the experiments were completed in 1–10 min depending on the core sample of interest. Displacement rate was preferred over loading rate to better capture the post-failure behavior of the samples.

When core samples are loaded in Brazilian test assembly, compressional stress is generated in axial direction and tension is generated in the horizontal direction. The state of stress for isotropic samples can be described using Equations 1 and 2 for the tension in x-direction, and compression in y-direction, respectively (e.g. Jianhong et al., 2009).

$$\sigma_x = \frac{2P}{\pi L}\left\{\frac{(R-y)x^2}{\left((R-y)^2+x^2\right)^2}+\frac{(R+y)x^2}{\left((R+y)^2+x^2\right)^2}-\frac{1}{D}\right\}, \tag{1}$$

$$\sigma_y = \frac{2P}{\pi DL}\left\{\frac{4D^2}{\left(4x^2+D^2\right)^2}-1\right\}, \tag{2}$$

where, P is the peak axial force, D is diameter, L is the length and R is the radius of the core sample. Maximum tensile stress occurs at the center, thus Equation (1) can be simplified to Equation (3) as recommended by ASTM to obtain tensile strength (T). In Equation (3), the unit of tensile strength is “psi” if the applied load has the unit of “lb_f”, diameter and length have the units of ‘inch”.

$$T = \frac{2P}{\pi DL}. \tag{3}$$

For an isotropic sandstone sample with D = 1.484 in and L = 0.840 in, the axial stress/axial strain curve is illustrated in Fig. 2. Stress increases until the sample breaks at 1046.51 lb_f representing “P” in Equation (3). The stress distribution along the horizontal axis is shown in Fig. 3. As the distance from the center of the sample increases, the tensile stress is decreased in the horizontal axis. Incorporating the stress in y-direction, the tensile failure should theoretically initiate at the center of a circular sample. However, there has been some controversy over the physics behind the Brazilian test arguing that an induced fracture might initiate at the contact point of the sample and the loading frame (Fairhurst, 1964). A high speed camera is required to precisely locate the fracture initiation point, however, the video record of the tensile failure of the sample with a conventional camera showed that the induced fracture initiation is not at the contact point of the sample (Fig. 4). In summary, Brazilian tests were utilized to determine tensile failure

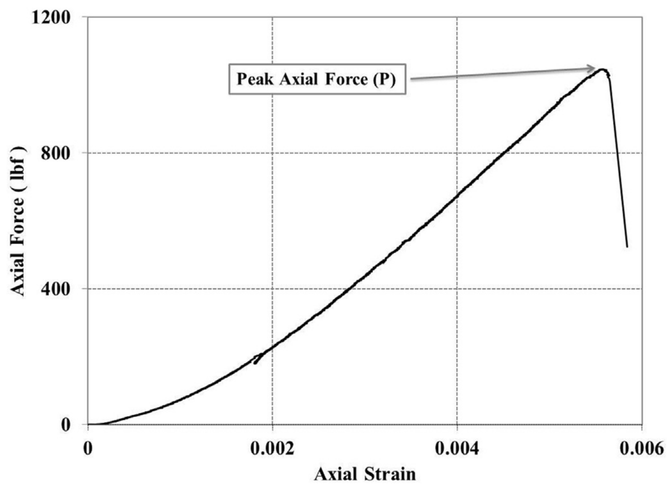

Fig. 2. Axial stress is increased until the sample is failed at force equal to "P" which is used to calculate the tensile strength.

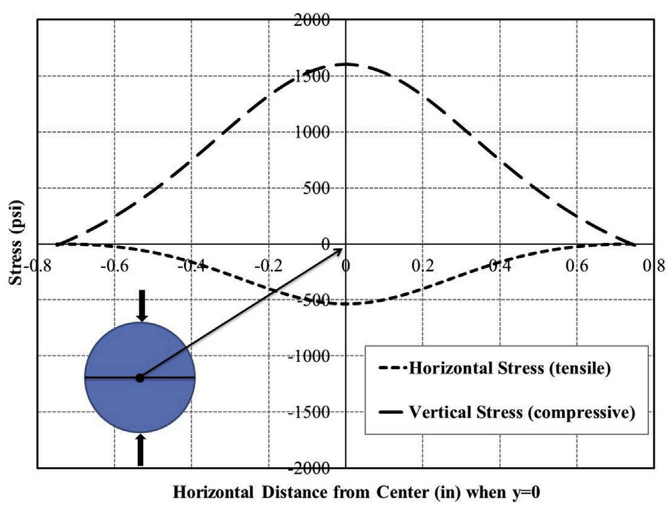

Fig. 3. Theoretical calculation of stress distribution in a Brazilian test at the point of the peak axial load is shown here. The sample is under maximum tensile stress (negative horizontal stress) at the center of the disk. As a result, the stress at the center at the failure is used to calculate the tensile strength.

due to practicability and ASTM standard of the Brazilian testing.

3. Description of rock samples

Full anisotropy can be simplified to transverse isotropy when there is an axis of rotational symmetry. To study the effect of lamination or natural fractures on tensile failure, several Green River core samples were drilled parallel to the lamination and tested based on transverse isotropic model. The schematic view of a laminated formation and corresponding samples for the Brazilian tests are shown in Fig. 5. These tests were conducted on Green River oil shale which is an immature hydrocarbon source rock and it has distinct lamination anisotropy. Green River is immature shale covering large area in Colorado, Utah, and Wyoming. To produce hydrocarbon from Green River shale, artificial heating is required to convert kerogen to oil and gas. Outcrop Green River shale samples with various total organic content (TOC) were donated by Enefit Company. The samples have high carbonate content with larger amount of dolomite content (30–40%).

The Lamination angle is defined as the angle between the applied force and the lamination (in two-dimensional view), i.e., T_{90} is the tensile strength of a sample perpendicular to lamination with 90° between the applied load and the lamination plane. Likewise, T_0 is the tensile strength when the bedding plane is parallel to the applied load. Thus, it is the tensile strength along the lamination plane. Equation (3) is derived with a isotropic mechanical property assumption. However, the failure of shales in a Brazilian test can be complicated when the core sample contains natural fractures. Thus, Equation (3) is solely used for quantitative comparison as discussed by Tavallali and Vervoort (2010a, 2010b, 2013). The fracture pattern, if present, is used to evaluate the effect of natural fractures and lamination on shale failure utilizing the Brazilian tests.

Similarly, the tests were conducted on Niobara samples with distinct natural fractures. Niobrara shale samples were donated by the CEMEX quarry in Lyons, Colorado. Niobrara is organic-rich shale originated 90 million years ago by the deposition of calcareous debris from algae and the remains of abundant marine life in an inland seaway extended from present-day Gulf of Mexico to Arctic Ocean (Eisinger 2011). The Niobrara formation is usually subdivided into the Fort Hays limestone member and the Smoky Hill member. Niobrara formation is sandwiched between the Pierre shale on top and Codell sandstone in the bottom. The samples come from the Fort Hays limestone and they are composed of matrix minerals and the naturally-sealed fracture. The matrix contains 86% calcite, 5% quartz and 5% illite. The natural fracture is calcite-filled as XRD study also confirms. To study the effect of natural

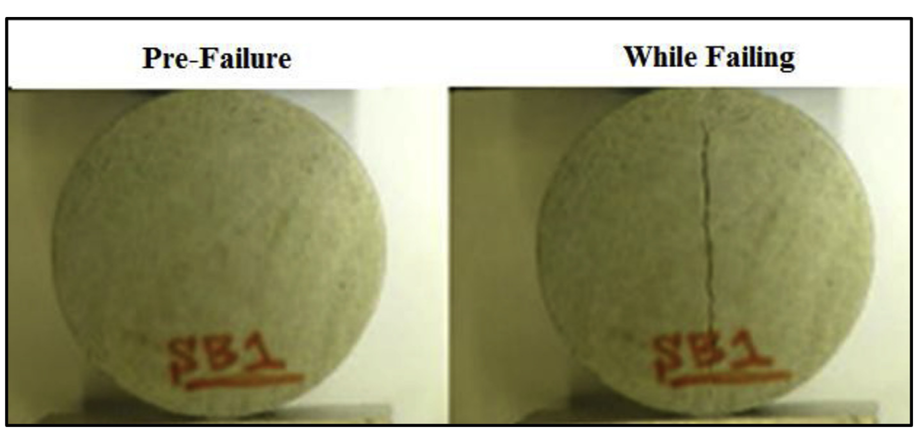

Fig. 4. Fracture initiation of a Berea sandstone core sample under Brazilian test was captured using a video camera recording.

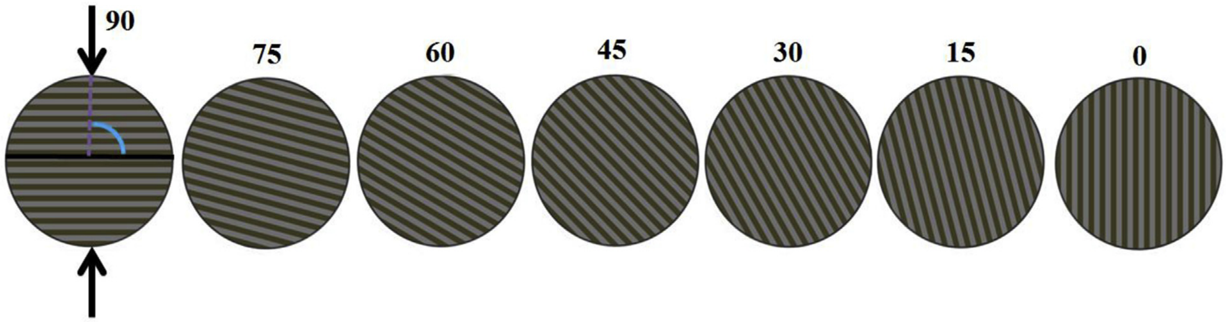

Fig. 5. Tensile strength anisotropy in transverse isotropic model and their corresponding Brazilian test configuration is defined.

Fig. 6. The white band on the left is a sealed vertical fracture in Niobrara formation and the open crack formed after the coring. On the right, the induced fracture occurred along the calcite-filled natural fracture after coring shows the low tensile strength of the calcite-filled natural fracture.

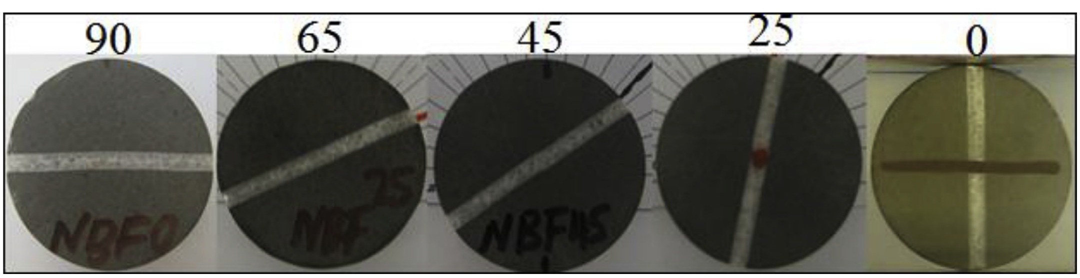

Fig. 7. The Niobrara core samples with the filled fractures were used in Brazilian tests. The orientations of samples for the Brazilian tests are noted on the top of each sample picture. The orientation is defined as the angle between the natural fracture and the applied axial load.

fractures on tensile failure of Niobrara formation, samples were drilled parallel to the sealed natural fractures (Fig. 6) and prepared according to the ASTM recommended Brazilian tensile test standards of a diameter to thickness ratio of two (ASTM D3967-08). The samples were tested at several orientations of natural fractures with respect to the applied axial load (Fig. 7).

4. Results and discussion

The results of Brazilian experiments on Green River and Niobrara samples will be presented. The effect of lamination or natural fracture angle on tensile strength and fracture pattern will be discussed.

4.1. Impact of lamination on tensile strength and fracture pattern of Green River shale

The effect of layering orientation on the tensile strength is shown in Fig. 8. The tensile strength along the lamination plane is lower than any other lamination directions. The tensile strength at

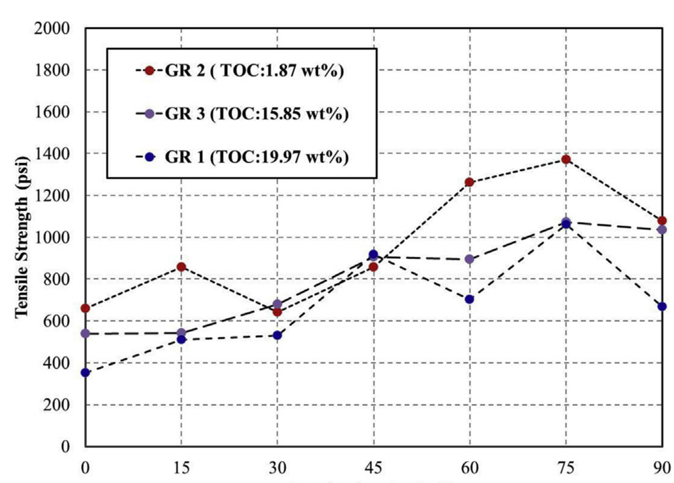

Fig. 8. Impact of the lamination and total organic content (TOC) on the tensile strength of Green River outcrop samples are illustrated.

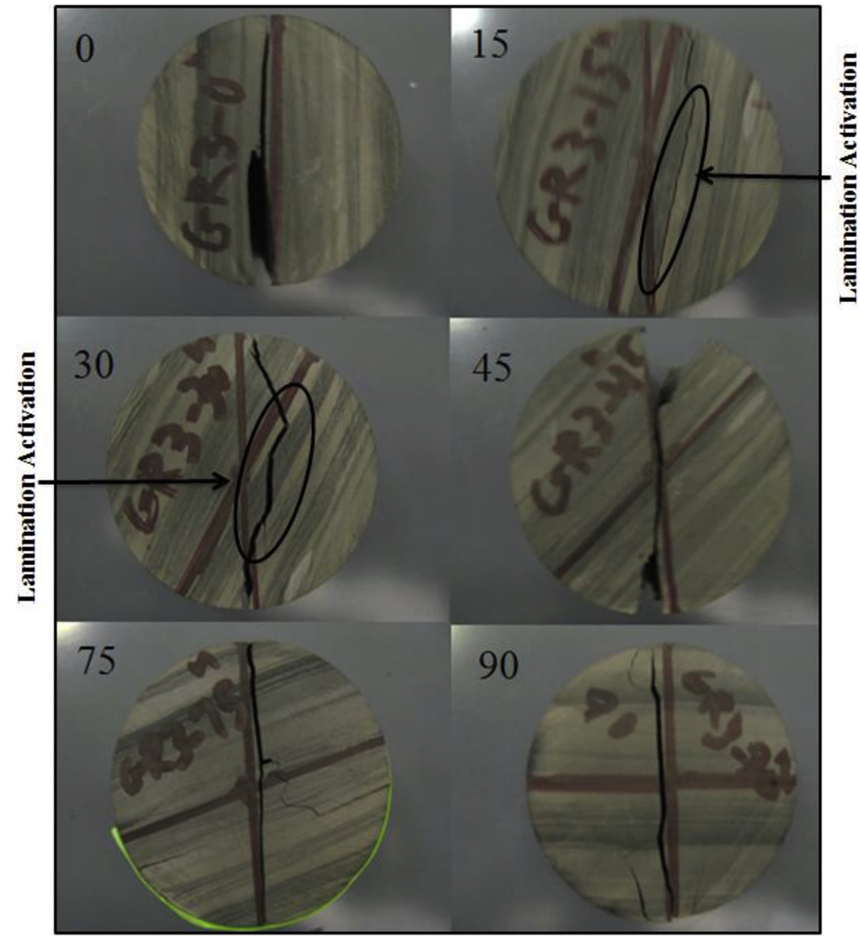

Fig. 9. Induced fracture pattern for Green River shale samples are depicted at various lamination angles. The numbers on the photos show the angle between the applied axial load and the lamination.

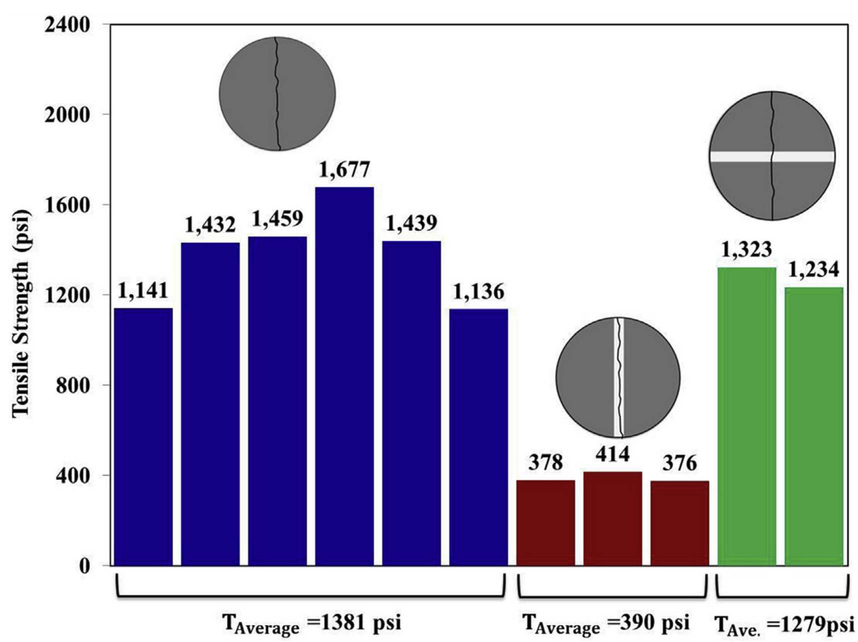

Fig. 10. The tensile strength of matrix containing no sealed natural fractures is compared with the samples containing horizontal or vertical calcite-filled natural fractures.

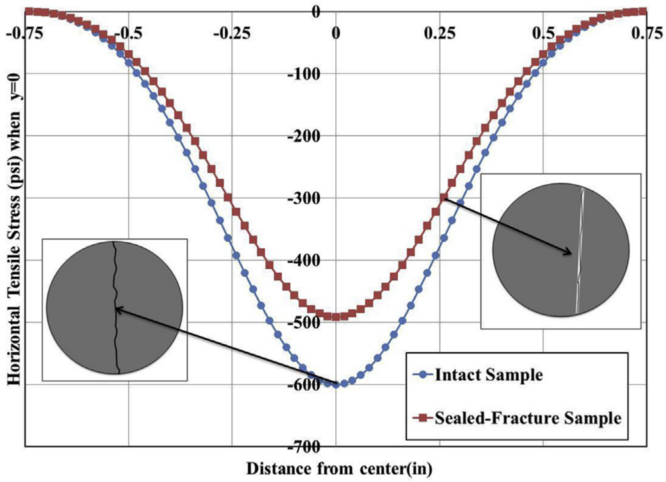

Fig. 11. Impact of a vertical natural fracture away from the vertical central-line on rock failure is shown. The natural fracture is one-third radius away from the center.

90° is 1.6–1.9 times higher than the tensile strength at zero degree (parallel to lamination). The results of this study are in good agreement with the findings reported by Chenevert and Gatlin (1965) and McLamore and Gray (1967) emphasizing that the tensile strength along the lamination is lower than the tensile strength across the lamination plane in Green River shale. Tensile strength generally increased with the increase in the lamination angle although the relationship was not linear. The non-linear behavior may be due to complex fracture growth which will be discussed in the description of the fracture patterns. Tensile strength decreased as total organic content (TOC) increased similar to the observations made by Chong et al. (1984) on the Eastern US oil shales and by Closmann and Bradley (1979) and Youash (1969) on Green River shale.

The fracture patterns of Green River shale at various orientations are shown in Fig. 9. At zero orientation, the induced fracture occurred at the center of the core sample indicating the tensile strength along the lamination. The slippage caused the activation of lamination when the lamination angle is 15-degree. For the sample with 30° of lamination angle, the induced fracture changed its orientation between the matrix and the boundary of the laminations, perhaps causing a mixture of tensile and shear failures. The induced fracture crossed the lamination at the lamination angles above 30°. Therefore, 0–30° is the critical range of orientations between the loading direction and the lamination to activate the laminations in the Green River shale under Brazilian testing conditions implemented in our study.

5. Effect of natural fractures on tensile failure of niobrara limestone

The axial load was applied at the rate of 0.1 mm per minute using a servo-controlled loading frame. The axial force and axial displacement was recorded. Subsequently, the tensile strength (or the peak strength) was calculated and the fracture pattern was analyzed.

The horizontal and vertical fractures are compared to an intact core sample obtained from the same interval. The tensile strength of the host rock and samples with calcite fractures parallel to loading and calcite fractures perpendicular to loading are presented in Fig. 10. Using the six indirect tensile tests on the core samples without natural fractures, an average tensile strength of 1381 psi with a central fracture was observed. When the natural fractured samples are aligned parallel to the direction of the applied load, the natural fracture and the maximum stress are in the same direction. Thus, the sample fails along the natural fracture, already present weakness plane, with a lower stress. These vertical naturally fractured samples had an average of 390 psi tensile strength which is almost one-third of the strength of samples without the natural fractures. When the natural fracture was horizontal, the sample failed vertically at the center crossing the natural fracture. In this case, the mean tensile strength of the rock was 1279 psi, which is almost identical to the tensile strength of the samples with no natural fractures.

A second set of samples contained vertical fractures at a location one-third the radius away from the central line (Fig. 11). Based on the linear elastic theory with the isotropy assumption, the fracture was expected to occur along the central vertical axis. However, the rock failed along the small vertical natural fracture due to the impact of the natural fracture. The analysis of the stress in this sample was compared with the intact sample using linear elastic assumption. The sample without the natural fracture failed at 1012 lb_f (491 psi). Therefore, a quarter inch away from the center where the natural fracture approximately presented, the tensile stress is about 300 psi. This indicates that the tensile strength of the natural fracture is almost 300 psi which is similar to the tensile strength obtained for a core sample with a natural fracture located at the center.

The failure pattern for the sample with 15-degree, 45-degree and 65-degree deviation of the natural fracture from the direction of the applied load are shown in Fig. 12. At 15-degree, induced fracture changed its orientation, failing both in the host rock and along the calcite-filled natural fracture. When the natural fracture is 45° from the horizontal axis, the core sample failed at the center, crossing the calcite-filled natural fracture. Similar behavior occurred when the angle was greater than 45° similar to our observation for the 90° sample. At 65°, a complex fracture behavior occurred. The major large fracture was at high angle with respect to the applied load. As a result, the induced fracture crossed this sealed fracture. However, the induced fracture re-oriented toward a small sealed fracture at the low angle existed naturally in the bottom of the sample.

6. Conclusions

To investigate the possible contribution of the tensile strength anisotropy (impact of the lamination and the natural fractures) and consequent fracture patterns, Brazilian tests were conducted on Green River and Niobrara core samples. Green River is an immature shale with distinct laminated structure. Tensile strength perpendicular to lamination was 1.6–1.9 higher than the tensile strength parallel to lamination. Below the lamination angle of 30°, lamination was activated during the Brazilian testing. Above the lamination angle of 30°, induced fracturing occurred across the lamination. Moreover, tensile strength decreased as the total organic content increased in Green River shale. Brazilian testings were also conducted on Niobrara samples with natural calcite-filled fractures. Calcite-filled natural fractures had almost one third of the tensile strength of the intact samples of Niobrara outcrop formation. When the natural fracture angle was less than 30°, the natural fracture was activated. Therefore, natural fracture or lamination could be activated in both cases of Green River shale and Niobrara limestone samples when the angle between the applied load and the lamination/natural fracture was less than 30-degree in Brazilian testing.

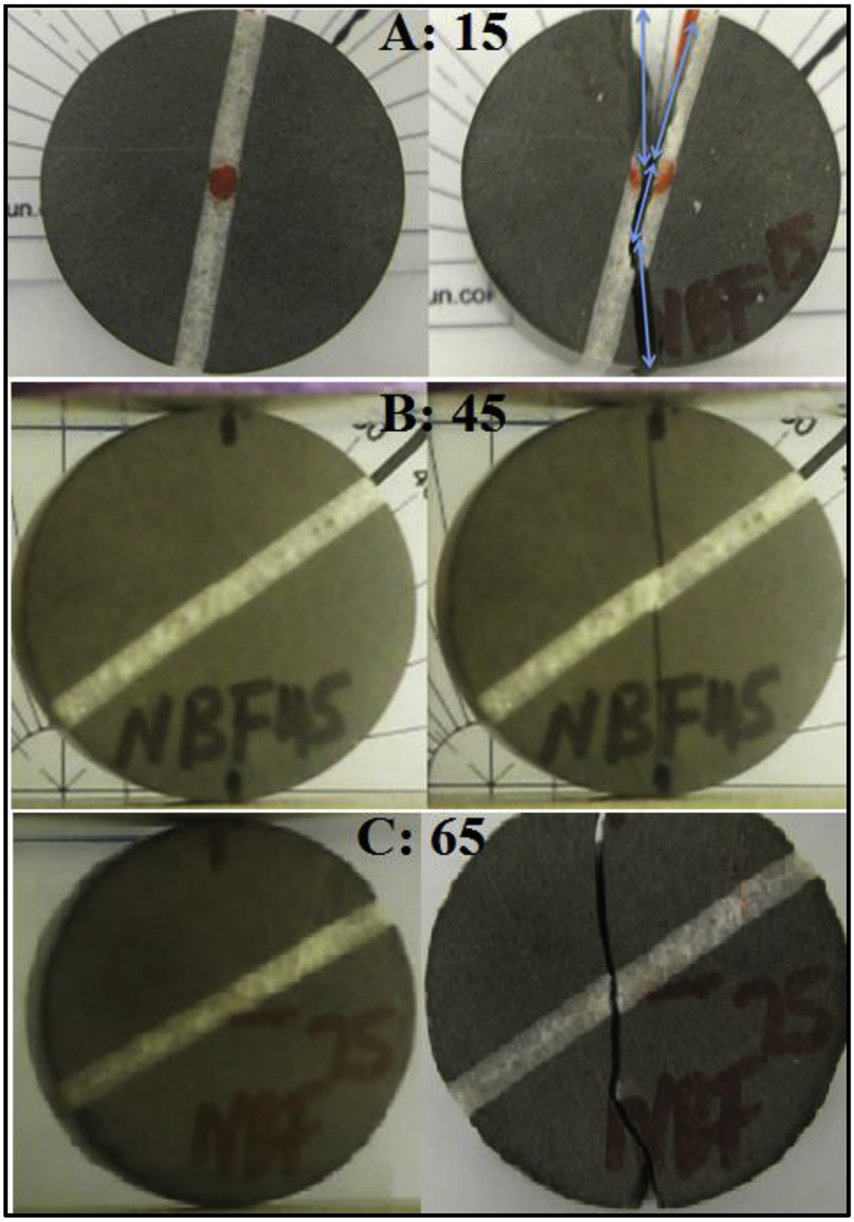

Fig. 12. a: Tensile failure of Niobrara core sample with 15°, 45° and 65° calcite-filled natural fracture is shown (left: prior to test, right: post failure).

Acknowledgement

The financial support from the sponsors of the Unconventional Natural Gas and Oil Institute (UNGI) Coupled Integrated Multiscale Measurements and Modeling (CIMMM) consortium at Colorado School of Mines is highly appreciated. We thank the CEMEX quarry for providing the Niobrara samples and Enefit Company for the Green River shale samples.

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