In-situ Stress Rock Fracture Sensing with HD-FOS

Introduction

Luna's high-definition fiber optic sensing (HD-FOS) technology provides high spatial resolution strain measurements which allow users to obtain a distributed strain response over the length of a fiber sensor in a single measurement. With gauge lengths as small as 1.25-5mm, a single 1m sensor made of unaltered telecom-grade optical fiber provides hundreds of effective independent sensors. It is this spatial resolution that makes our technology ideal for direct measurement of fracture formation in underground rock. Through the use of a hydraulic sleeve sensor assembly, fiber optic distributed strain sensors are pressed against a borehole wall via hydraulic pressure in the sleeve. As the rock fractures due to sleeve pressurization, the HD-FOS sensor measures the localized strain, thereby identifying the direction and magnitude of the fracture with spatial resolution of 1.25 mm. This capability is useful for measuring the "in-situ stress" in the rock, i.e. the inherent stress that existed before the borehole was drilled. This is inferred from the relationship between the pressure at which the rock fractures and the minimum in-situ stress in the rock. The in-situ stress in the subsurface is of great interest to the oil & gas, geothermal, and geotechnical industries, as rock stress is a key driver in all underground phenomena. This new sensing technique will provide drastically increased amounts of data that can be leveraged to increase safety, production efficiency, and optimization of future subsurface engineered systems.

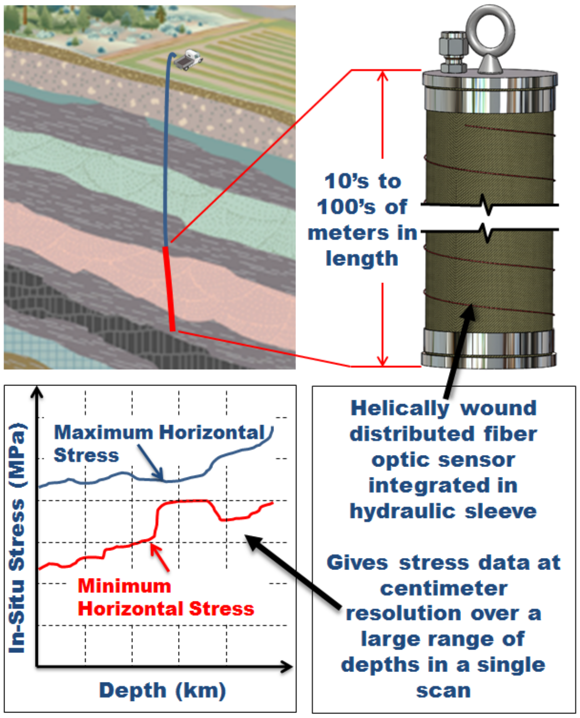

Figure 1: In-Situ Stress Measurement Sensor Using Distributed Fiber Optic Sensing

Background

The earth's subsurface possesses great potential for energy production, energy storage, and the safe disposal of hazardous materials. Presently, there is insufficient understanding of subsurface stress, human-induced seismicity, and their combined effects on permeability. Higher fidelity sensing of the subsurface is necessary to develop a geo-mechanical model that can guide geothermal and well design to minimize cost and maximize safety. A recent report by the JASON advisory group [1] emphasized the need for new ways to measure the *in-situ* stress state over a wide range of scales (10^{-6} to 10^{2} m) and at significant depth (up to 5 km). Acquiring this new data would be useful for underground structure stability, excavation design, rock support, rock burst prediction, rock behavior models, grout design, fluid flow, and fracturing (Ljunggren et al. [2]).

Numerous sectors within the energy industry will benefit from accurate *in-situ* stress measurements, including:

- Oil and gas – enabling risk-driven adaptive controls on injection rate, volumes, pressures, and well locations.
- Hydraulic fracturing – prediction and control of hydraulic induced fractures and the activation/reopening of faults.
- Geothermal – develop theoretical and experimental models relating stress and induced seismicity.
- Waste disposal – improved understanding of stresses that will act on deep disposal facilities for energy related waste products.

According to the DOE's SubTER group, in-situ stress measurement techniques are currently "woefully inadequate" [3]. Advances in stress sensing technology are critical to improving our understanding and mastery of the subsurface. The nation's energy security and environmental needs all hang in the balance.

Innovation

Reviewing the existing techniques for in-situ stress measurement has inspired Luna to take the established concept of sleeve fracturing [4] and add a revolutionary twist. By adding high spatial resolution strain-sensing capabilities to a sleeve fracturing assembly (Figure 1), Luna enables distributed sensing of subsurface stress that could be extended to unprecedented lengths (10's to 100's of meters) of borehole in a single operation. Luna's high definition distributed strain sensing instrument ODiSI-B is currently capable of millimeter-resolution, simultaneous strain measurements at thousands of individual points along a single 20 m optical fiber without the need for inscribing fiber Bragg gratings but rather analyzing the Rayleigh scatter inherent to the fiber.

Embedding this sensing fiber in a helical pattern within a rubber sleeve allows for precise measurement of radial and axial strain as the hydraulic pressure inside the sleeve is increased.

The continuous measurement of strain around the circumference and down the depth of the hole will provide new types of data that have previously been unavailable, spanning a large portion (10^{-3} to 10^{2} m) of the range of scales desired by the JASON report. The methodology for using this sensor to measure in-situ stress is depicted in Figure 2.

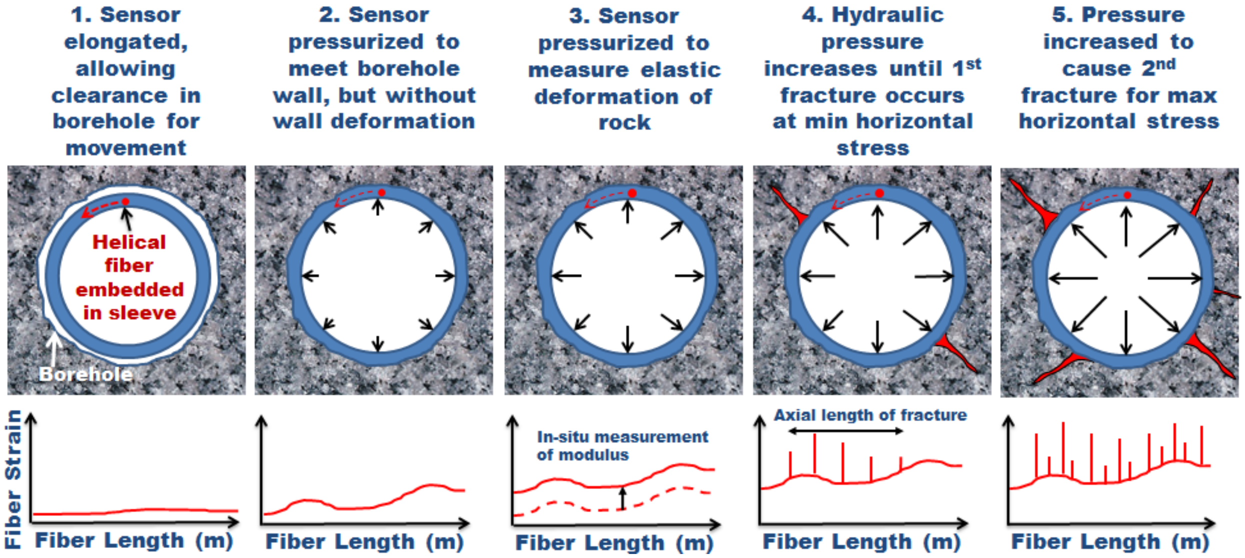

Figure 2: Methodology of Distributed Fiber Optic Sleeve Fracturing Concept

First, the diameter of the sensor sleeve is decreased, by elongating it and/or reducing volume of fluid, to give clearance for movement within the borehole so that it may be positioned at the desired location. Step 2 is to pressurize the sensor sleeve until it expands radially to conform to and interface with the contours of the borehole wall. A strain measurement is acquired and becomes the baseline signature against which measurements taken at higher pressures will be compared. The baseline measurement may also give information on the variation in shape of the borehole versus depth. Step 3 is to begin increasing the hydraulic pressure within the sensor sleeve to create elastic deformation of the rock wall such that measurements of the elastic modulus can be made. This measurement could identify variation in modulus (due to varying materials) as a function of depth as well as the porosity of the borehole wall identified by localized strain profiles. Step 4 involves increasing the hydraulic pressure to the point that the first fracture occurs. In theory, the direction of this fracture should be perpendicular to the minimum horizontal stress, S_h [4] The measured strain will exhibit a pattern of periodic peaks due to the helical configuration of the fiber in the sleeve; it will intersect the fracture on multiple windings. The distance of the first peak from the sensor origin will indicate at which angular orientation the first fracture occurred. The axial length of the fracture down the borehole can be determined from the number of peaks observed and their relative distance down the fiber. An additional benefit of this as compared with traditional fracturing techniques is that the fractures are observed immediately during the pressurization process rather than using an impression packer or visual post-process [2]. During the optional Step 5, pressure is increased until a second fracture occurs, which ideally corresponds to the maximum horizontal stress, S_H. The relative clocking direction of this secondary fracture can be calculated from the phase between the first series of peaks and the new series of peaks. The measurement technique can accommodate additional unintended fractures or non-perpendicular fracture directions, because the high-resolution strain data will resolve these features. Variations in fracture magnitude and angular orientation, which corresponds to in-situ stress, may change along the depth of the borehole, and the proposed technique would allow those variations to be continuously observed. The resulting stress versus depth that is calculated from the technique would be plotted as seen in Figure 1. After executing a complete measurement at a single location, the pressure in the sensor sleeve is reduced. The fracture will close, and the sleeve is free to be positioned at the next location. During this process, all hydraulic fluid remains contained within the sensor. Because no fluid is lost and the outer diameter of the sensor sleeve can be as small as 50 mm, it is anticipated that all the equipment necessary to perform a measurement will fit on a utility truck (hydraulic pump, a spool of sensor/cable, reservoir of fluid, instrument electronics, and computer).

Luna's proposed technique could be used to evaluate new boreholes as well as those with existing fractures. It could be used for a one-time interrogation or recurring measurements over a longer period of time. Luna's strain sensing technology is based on the measurement of Rayleigh backscatter in optical fibers. The random and microscopic structures that give rise to Rayleigh backscatter are inherent, stable, and permanent features that exist in all optical fibers.

Experimental Results

Figure 3 shows the CAD design and several implementations of the in-situ stress sensor. The basic idea is to have a bladder with optical fiber applied to the outside surface (helically wound in this case, various coatings can be applied).

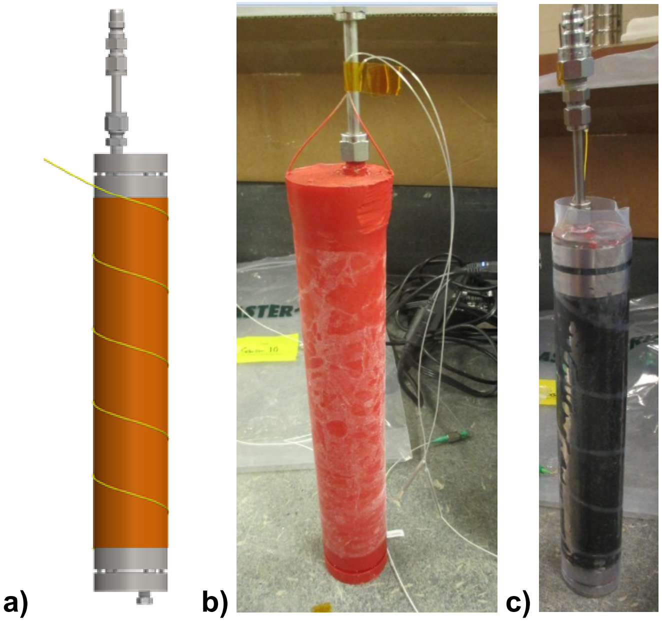

Figure 3: Example implementations of the sensor concept, a) CAD design, b) Rubber coating to hold fiber in place, c) Plastic coating to hold fiber in place.

Luna experiments have demonstrated the ability to fracture concrete blocks under known stress levels via hydraulic pressurization, with the distributed strain signals clearly showing the fracture forming and propagating. Figure 4 shows the experimental setup and a fractured concrete block as a result of the fiber-optic instrumented hydraulic sleeve.

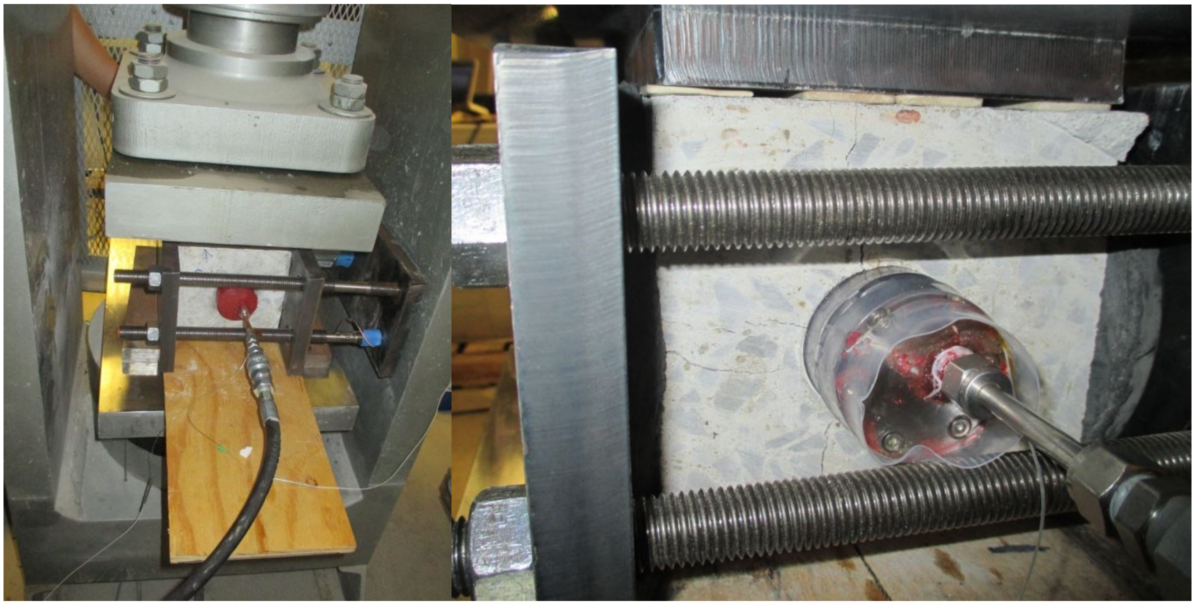

Figure 4: Luna in-situ stress sensor (left) Inserted in concrete block in vertical compression load frame and passive horizontal restraint frame (right) Example of fractured concrete block from hydraulic sleeve fracturing.

Figure 5 shows the real-time measurement of stress during a fracture event, illustrating the cyclic peaks in strain due to the helical winding of the fiber. Figure 6 shows the clear progression of strain measurements before the fracture, as the fracture is initiating, and after the fracture is complete. This data can be used to calculate the direction and magnitude of stresses being externally applied to the rock.

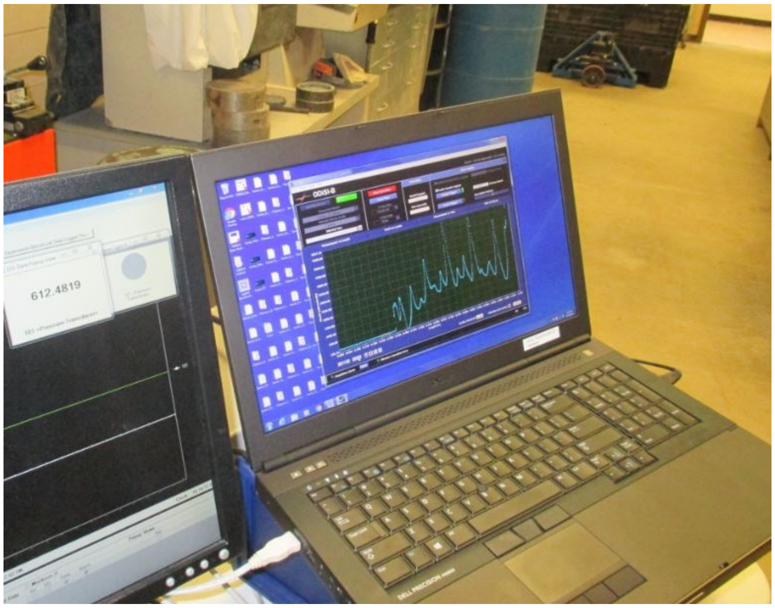

Figure 5: Periodic strain signal due to fracture of concrete.

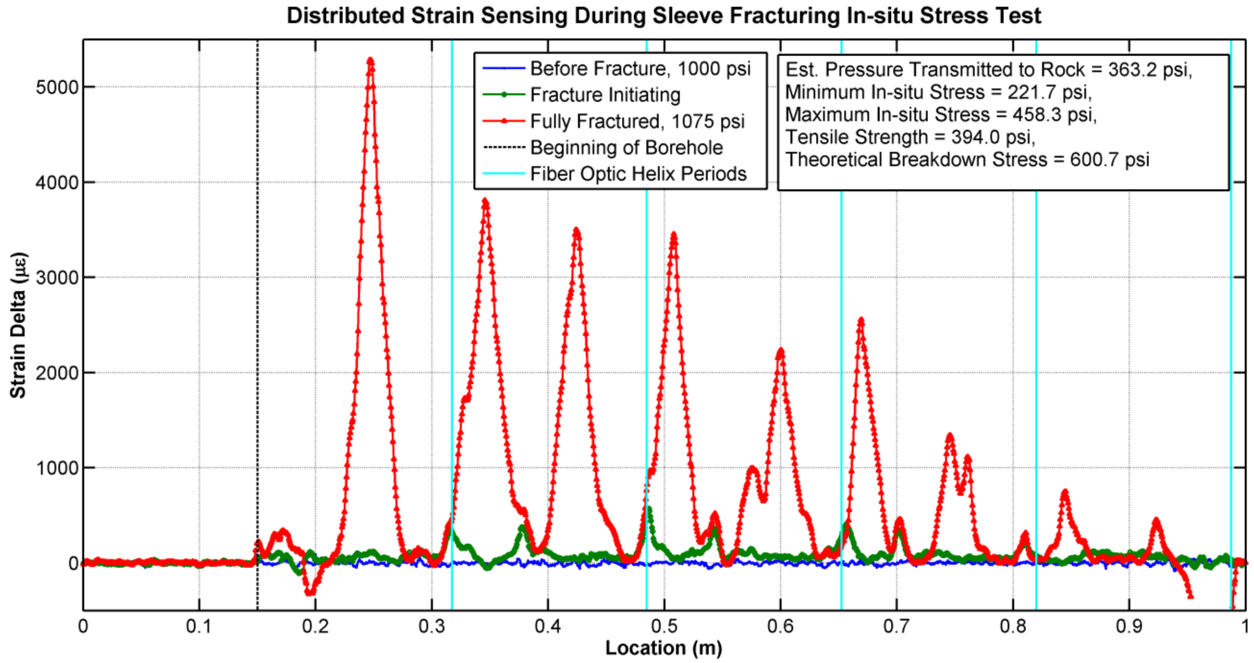

Figure 6: Luna in-situ stress sensor output before, during, and after fracturing process, clearly showing two strain peaks per helical period for a vertical fracture that split the block in half. The smaller green peaks arose first before the major fracture propagation, potentially giving insight into fracture mechanics and formation.

Conclusion

To the authors' best knowledge, this is the first published successful direct high resolution strain measurement of hydraulic fracture formation and propagation in rock. The high spatial resolution of Luna's HD-FOS allows for visualization of continuous strain profiles with more detail than ever before for downhole environments. Work is ongoing to translate the fracture detection of the HD-FOS sensors into in-situ stress calculations. It is envisioned that field operations using a ruggedized sensor could yield immediate in-situ stress measurements for unprecedented lengths of boreholes, and in less time required than traditional hydro-fracturing techniques.

Acknowledgements

Luna would like to thank the Department of Energy for funding this research.

References:

[1] JASON (2014). *Subsurface Characterization Letter Report, JSR-14-Task-013*, The MITRE Corporation, McLean, VA, 16 pp.

[2] Ljunggren, C., Chang, Y., Janson, T., and Christiansson, R. (2003). "An overview of rock stress measurement methods." *International Journal of Rock Mechanics & Mining Sciences*, 40, 975-989.

[3] U.S. Department of Energy (2014). “Subsurface Control for a Safe and Effective Energy Future”, SubTER Crosscut White Paper.

[4] Sano, O., Ito, H., Hirata, A., and Mizuta, Y. (2005). “Review of methods of measuring stress and its variations.” *Bulletin of the Earthquake Research Institute*, University of Tokyo, 80, 87-103.

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