International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 09 Issue: 07 | July 2022 www.irjet.net p-ISSN: 2395-0072

Development of an End Platen to Integrate Fibre Bragg Grating Sensing Arrays in Triaxial Rock Test: A Technical Note

George Yabesh[1,3], Melissa Nogueira Kiewiet[1], Ausama Giwelli[1], Lionel Esteban[1], Leigh Kiewiet[1], Stephen Banks[2]

[1]CSIRO Energy, Kensington, WA 6151, Australia
[2]CSIRO Energy, Clayton, VIC 3168, Australia
[3]Currently at Action Drill & Blast, Belmont, WA 6104, Australia

---

Abstract - *Conventional radial strain measurements in triaxial testing are done using a small number of strain gauges or cantilever radial devices. The usual restricted number of these gauges and their location does not favour capturing a full picture of material heterogeneities. Fibre Bragg Grating (FBG) sensing technology could revolutionize conventional strain measurement. It offers higher-resolution measurements and allows more measuring points, enabling 3D shape sensing to capture localized rock mechanical changes and heterogeneities.*

To integrate FBG sensing to triaxial vessels, a new end platen was designed and engineered out of carbon fibre material reinforced with epoxy resin. The platen configuration allows using conventional strain measurement devices simultaneously with FBG sensors when required. There is a high correlation, or the assumption of radially symmetric deformation regardless of the orthogonal cantilever-type gauges measuring radial strain, whereas the FBG sensors measure circumferential strain.

Two hydrostatic tests were conducted on a standard aluminium plug of 76 mm in length and 38 mm in diameter. Six FBG sensors were attached to the surface of the sample. The aluminium plug, FBG wire and platen were positioned and secured inside the pressure chamber using a Viton sleeve. Additionally, two orthogonal cantilever-type gauges were placed on top of the test membrane.

The results show that FBG strain values are comparable to those obtained from the cantilever devices, which indicates the functionality of the platen design and opens possibilities of obtaining high-resolution 3D strain maps from rock samples, which is especially useful if there are heterogeneities or for reactive transport applications. The platen has so far been tested for FBG sensors only, but in principle, it would enable the integration of any fibre optic sensor.

Key Words: **FBG Sensors, Rock Mechanics Testing, Hydrostatic tests**

1. INTRODUCTION

A typical rock mechanics test involves the application of vertical load and lateral pressure onto a rock specimen (usually cylindrical) under well-controlled conditions in a laboratory while measuring the resulting vertical and lateral deformation using strain gauges [1, 2], cantilever-type gauges and Linear Variable Differential Transformers (LVDTs) [3], either individually or combined, and usually placed at the sample's mid-height. Although it is accepted that rock deformation can be reliably monitored with these techniques, those devices may offer only a limited view of the deformation field depending on the level of heterogeneity of a given material. The impact of such simplification could be particularly important, for example, for vuggy samples or if fractures or joints are present. Moreover, conventional electric gauges are susceptible to short-circuit, e.g., when exposed to brine for a prolonged period, thermal degradation, and electromagnetic interference [4, 5].

The Fibre Bragg Grating (FBG) sensing technique [6] has established itself as a strong candidate for strain and temperature measurements, following successful applications in medical sciences, telecommunication, magnetic field detection and the energy sector [7-10]. FBGs' real power lies in the sensor's high-sensitivity retention in adverse environments, multiplexing capabilities, and immunity to electromagnetic interferences, among others [5, 11, 12].

Recently, multiplexing FBG sensor arrays were successfully implemented to measure the deformation of rock samples subject to uniaxial compression under ambient conditions [12, 13]. However, using FBG sensors to measure strain when lateral confining pressure is present (as in triaxial or hydrostatic tests) is technically challenging, especially due to the FBG wire's fragility and limited minimum bending radius [14].

In this study, a new innovative end platen to integrate FBG sensor arrays into a triaxial system was designed and manufactured using carbon fibre reinforced with epoxy resin. A hydrostatic test was conducted to verify the platen functionality using a standard aluminium plug of 76 mm in length and 38 mm in diameter. For the test, an FBG wire containing six FBG sensors was inserted through the designed end platen to reach the plug radial surface. The FBG wire was then wrapped around the sample's surface and fixed using glue, and its free end was connected to an interrogator. The sample was finally placed inside a Viton sleeve. For the sake of benchmarking the strain measured from FBG technology, an additional standard technique for strain measurement was also added to the sample mounting: two orthogonal cantilever gauges were placed on the top of the Viton sleeve, adjacent to FBG sensors 3, 4 & 5, 6, to measure the sample's radial deformation. The test was done under hydrostatic pressure up to 20 MPa and in a temperature-controlled environment of approximately 23^0 C.

2. WORKING PRINCIPLES OF FBG OPTICAL

Fibre Bragg Grating (FBG) sensing has gained popularity and received increased attention in recent years. Laying inside the core of an optical fibre are FBG sensors of different wavelengths that are sensitive to external deformation and temperature. This possibility solidifies FBGs' multiplexing capabilities. In principle, FBG sensors work by partial reflection of broadband light that is transmitted into the system by equipment known as an interrogator (Fig-1). The reflected segment of light is of great importance and is defined by its wavelength, known as the Bragg wavelength, λ_B, which can be calculated using the equation:

$$\lambda_B = 2n\Lambda$$

where n is the effective refractive index of the FBG and Λ is the geometrical grating interval equal to the distance between two successive alterations of the refractive index.

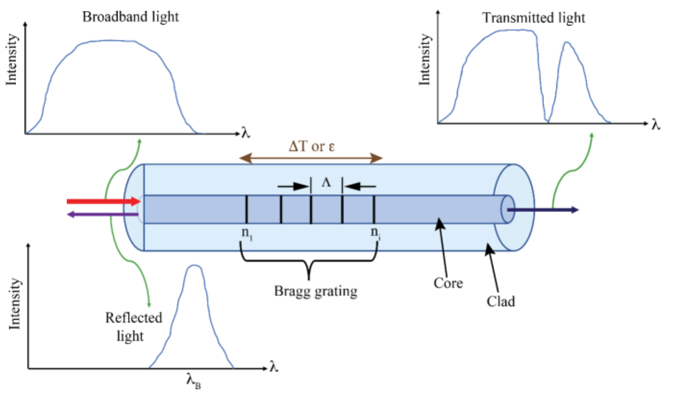

Fig -1: FBG sensor and the corresponding spectra [13]

All variations in physical characteristics within the Bragg grating zone are linked to alterations of either the geometrical grating interval (Λ), the core refractive index (n), or a combination of both. The relationship of the relative Bragg wavelength shift (λ_B) corresponding to the changes in the mechanical strain ($\Delta\varepsilon$) and the variation in the temperature (ΔT) is expressed as a first-order differential equation [6]:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 + \frac{1}{n}\frac{dn}{d\varepsilon}\right)\Delta\varepsilon + \left(\frac{1}{d\Lambda}\frac{d\Lambda}{dT} + \frac{1}{n}\frac{dn}{dT}\right)\Delta T$$

$$= (1+p)\Delta\varepsilon + (\alpha + \zeta)\Delta T = \mathrm{K}_\varepsilon \Delta\varepsilon + K_1 \Delta T + K_2 \Delta T^2$$

where $\Delta\varepsilon$ represents the strain on the FBG, ΔT is the temperature variation, p is the strain optic tensor related to the properties of the fibre, α is the thermal expansion coefficient of the fibre, and ζ is the thermo-optic coefficient.

3. DESIGN OF NEW END PLATEN

A major challenge integrating FBG sensors into a triaxial system is to access the radial surface of the sample without compromising the confining and pore fluid(s) pressures and temperature, nor damaging the very fragile optical fibre. Considering such constraints, a prototype end platen was designed and engineered from carbon fibre reinforced with epoxy resin. It features (Fig-2): (i) a flat surface on the top side to allow standard core plugs to sit flush during testing; (ii) a stainless steel ring that prevents the fasteners from damaging the platen; (iii) one feedthrough network at the top centre of the platen and inclined at a 10° angle as it progresses out to the opposite end in the vertical orientation, to allow for thick wall cylinder (TWC) testing with integrated FBG; and (iv) another feedthrough network spiralling around the platen from the central position, next to the internal feedthrough at the bottom end of the platen and exiting out on the top side of the platen to facilitate FBG integration into the outer circumference of standard testing plugs.

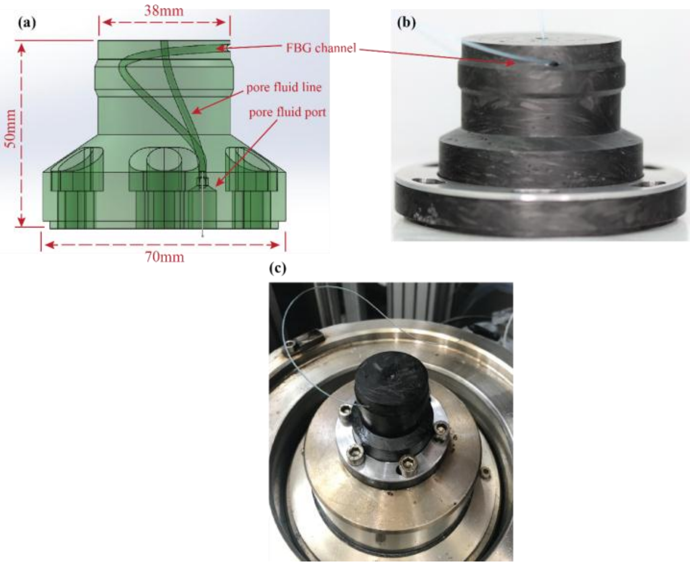

Fig -2: CSIRO's end platen used to integrate the FBG sensing technique into a triaxial rig. (a) 3D CAD of the end platen, (b) end-product of the molded platen with FBG wire out of the spiral channel, and (c) the platen installed inside the pressure chamber preparing for a mock test

The 2 mm feedthrough network design doubles as pore fluid lines for flow protocols. The outer feedthrough (iv) was designed to a maximum angle of 80° from the horizontal axis with gradual decrements of 10° as the feedthrough progresses spirally upwards to allow the minimum curvature possible. This transition is important as it allows for smooth entry of the FBG wire and prevents reflective losses while light travels through the FBG wire.

4. PILOT TEST

To ensure the end platen design does not impact FBG strain measurement under stress conditions, a hydrostatic compression test ($\sigma_1 = \sigma_2 = \sigma_3 = \sigma_0$) was conducted. The essence of this geomechanical test is to yield information about rock compressibility and the magnitude of the pore collapse pressure if such failure is achieved. For simplicity, a solid aluminium plug (known properties) of 76 mm in length and 38 mm in diameter was prepared for the test. A Fiber wire with six FBG sensors model DTG-LBL-1550-125, custom-made by FBGS Technologies GmbH, with 125 μm cladding diameter and Ormocer coating, was glued spirally along the plug length using Araldite epoxy adhesive with a curing time of 90 seconds (Fig-3a). The glueing was done so that FBG sensors numbered 1, 3, and 5 were positioned opposed to each other and at the same height as FBG sensors numbered 2, 4 and 6, respectively (Table 1). The range of Bragg wavelength of the six sensors is between 1530 to 1565 nm, with a 5 nm spacing to avoid overlaps. The manufactured wavelength sensitivity coefficients assigned at ambient conditions are 0.776 pm/με, 8.53 pm/K, and 0.0023 pm/K.

After curing, the aluminium plug with the six FBG sensors was carefully inserted into a Viton Sleeve. The assembled system was then placed inside the triaxial vessel on top of the new end platen to allow the FBG wire to come out of the triaxial system and be connected to an interrogator (Fig-3 a & b). A pair of cantilever-type radials (here called RC-1 and RC-2) was then placed on top of the Viton sleeve, as shown in Fig. 3 a & b. After that, the pressure cell was closed, filled with hydraulic oil, and hydrostatic loading commenced at 0.5 MPa/min in a temperature-controlled environment set to 23° C. Two hydrostatic loading-unloading cycles of 7.5 and 19.5 MPa (effective confining pressure) were conducted to ensure the repeatability of the FBG strain measurements. A high-accuracy, computer-controlled stepper motor pump was used. A LabVIEW application recorded pressure, deformation, and temperature data every second. FBG peaks data was obtained from FAZT I4 Femtosense software (Fig-3 c), with a measuring capability of 120 dB and a 0.1 pm precision.

To quantify the deformation of the membrane, which is inevitably captured in the strain measured by the radial cantilevers placed over the sleeve, and hence allowing a more realistic comparison of the FBG strain measurements with those from the cantilevers, an additional test was run in a different triaxial rig under similar temperature and pressure conditions, using an identical aluminium plug with one cantilever attached directly to the plug's surface.

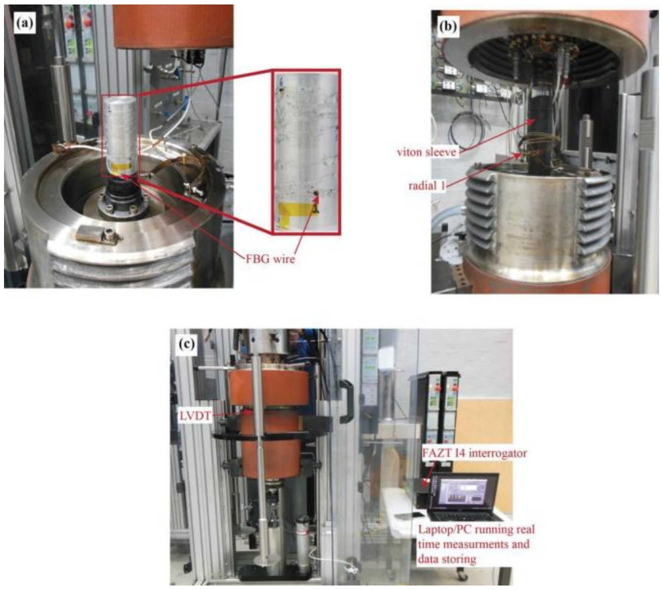

Fig -3: Sample set-up in triaxial stress test vessel: (a) aluminium plug with FBG wire glued to its surface, sitting on the newly designed end platen; (b) the same aluminium plug inserted into the Viton sleeve, and radial cantilevers attached to the sleeve; (c) the triaxial cell closed and interrogator communication on a PC laptop**Table -1:** FBG sensor locations on the aluminium plug

Sensor #	Distance from the bottom end of the sample (mm)
1 and 2	10.0
3 and 4	40.3
5 and 6	66.3

4. RESULTS AND DISCUSSION

Fig-4 a shows hydrostatic stress of both cycles vs time for the same loading rate. An example of wavelength shifts of FBGs during hydrostatic loading is in Fig-4 b. The results show that the wavelength shift increases linearly with the applied stress, consistent with the findings of Zhao et al. and Lei et al. [15, 16].

Stress-strain curves are shown in Fig-4 c & Fig-4 d. Data recorded by FBG sensor #2 and radial cantilever #2 were disregarded due to low quality, hence are not shown in the figure. The variation in the readings from the five valid FBG sensors could be attributed to: (i) nonuniformities in the glueing process, which was done manually and whose effect is yet to be investigated; and (ii) the inability to manually reduce the reflected optical power. The latter can be solved by adding an attenuator in the FBG system to deal with any round-trip insertion losses, although the fluctuations in the strain measurements are quite small – in the order of 0.05 and 0.07 millistrain for the 7.5 MPa and 19.5 MPa, respectively. Nevertheless, it can be observed that strain data derived from the FBG sensors show a similar trend to the ones derived from the readings of the radial cantilever #3 (RC-3) (measured straight on the plug's surface), and they are also of the same order of magnitude.

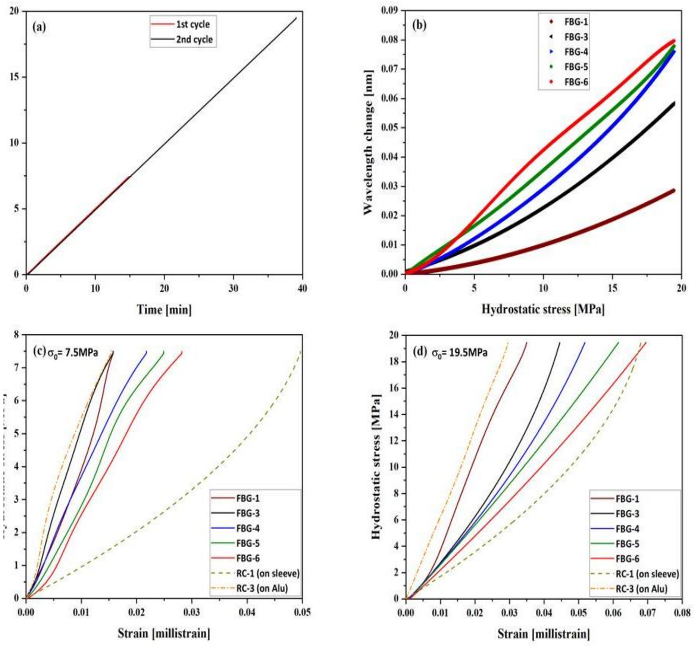

Fig -4: Summarized graphical representation of results obtained from this protocol: (a) stress vs time curves for both loading cycles, i.e. 7.5 MPa and 19.5 MPa; (b) FBG sensors wavelength change with the increase in hydrostatic stress for the 19.5 MPa loading cycle; (c) and (d) stress-strain curves for the loading cycles 7.5 MPa and 19.5 MPa, respectively, as measured by FBG sensors, RC-1 (reading on top of the Viton Sleeve) and RC-3 (reading on Aluminium surface)

3. CONCLUSIONS

In this work, we investigated the possibility of integrating Fibre Bragg Grating (FBG) multiplex sensors into an axisymmetric triaxial stress vessel using the newly designed end platen. Cyclic hydrostatic stress was applied on an aluminium plug prepared with 6 FBG sensors. Simultaneously, radial cantilever gauges were also used to monitor the radial deformation of the tested plug. Results show that FBG strain values were comparable to the ones from the radial strain cantilevers, which indicates that the implemented FBG sensing protocol using the newly designed platen achieved its purpose and can be used in future triaxial testing campaigns. Moreover, it opens possibilities of distributing more FBG sensors throughout the circumference of the rock samples to measure 3D strain variation orthogonally along the radial direction of samples.

The results encouraged the design of another FBG-end platen, which is currently being engineered using 3D printed titanium technology (instead of carbon fiber reinforced with epoxy resin). The material choice aims at exploring the ability of FBG sensors to function at elevated temperatures, allowing the performance of geomechanical tests at high temperatures (above 100° C).

ACKNOWLEDGEMENT

The authors would like to thank Bruce Maney and Yevhen Kovalyshen of CSIRO Energy for their assistance in designing the platen. Also, many thanks to Andrey Prusenko for finalizing the design, selecting the material, and manufacturing the FBG platen. This work could not be possible without the financial support from CSIRO Energy.

REFERENCES

[1] Clayton C. R. I. and Khatrush S. A. A New device for measuring local axial strains on triaxial specimens. Geotechnique. 1986; 36:593-7.

[2] ISRM. Suggested methods for determining the uniaxial compressive strength of rock materials. 1972.

[3] Ibraim E. and Di Benedetto H. New local system of measurement of axial strains for triaxial apparatus using LVDT. Geotech Test J. 2005; 28:436-44.

[4] Uchida S, Levenberg E, Klar A. On-specimen strain measurement with fiber optic distributed sensing. Measurement. 2015; 60:104-13.

[5] Kovalyshen Y., S. Banks, Giwelli A. Measurement of rock strain using Fiber Bragg Grating sensors. In proceedings of: The 52nd US Rock Mechanics/Geomechanics Symposium, Seattle, Washington, USA; 17–20 June 2018.

[6] Othonos A and Kalli K. Fiber Bragg Gratings: Fundamentals and applications in telecommunications and sensing1999.

[7] Yi XH, Chen XY, Fan HC, Shi F, Cheng XM, Qian JW. Separation method of bending and torsion in shape sensing based on FBG sensors array. Opt Express. 2020; 28:9367-83.

[8] Roriz P, Silva S, Frazao O, Novais S. Optical fiber temperature sensors and their biomedical applications. Sensors-Basel. 2020;20.

[9] Schukar V, Köppe E, Hofmann D, Westphal A, Sahre M, Gong X, Bartholmai M, Beck U. Magnetic field detection with an advanced FBG-based sensor device. In

proceedings of: 30th Eurosensors Conference, Berlin, Germany; 2016.

[10] Marques RD, Prado AR, Antunes PFD, Andre PSD, Ribeiro MRN, Frizera-Neto A, Pontes MJ. Corrosion resistant FBG-based quasi-distributed sensor for crude oil tank dynamic temperature profile monitoring. Sensors-Basel. 2015; 15:30693-703.

[11] da Silva Falcão B, Esteban L, Giwelli A, Kovalyshen Y , Banks S, Al-Yaseri AZ , Keshavarz A, Iglauer S. Monitoring fluid migration using in-situ nuclear magnetic resonance core flooding system integrated with fiber optic sensors: A proof of concept. In proceedings of: The 35th International Symposium of the Society of Core Analysts (SCA Annual Symposium), Online Event; 13-16 September 2021.

[12] Sun YK, Li Q, Yang DX, Fan CK, Sun A. Investigation of the dynamic strain responses of sandstone using multichannel fiber-optic sensor arrays. Engineering Geology. 2016; 213:1-10.

[13] da Silva Falcão B, Giwelli A, Nogueira Kiewiet M, Banks S, Yabesh G, Esteban L, Kiewiet L, Kovalyshen Y, Monmusson L, Al-Yaseri A, Keshavarz A, Iglauer S Strain responses of outcrop limestone rock using multiplexed FBG sensor arrays: An experimental investigation. Manuscript submitted 2021.

[14] Yabesh G, Giwelli A, Nogueira Kiewiet M, Kiewiet L, Esteban L., da Silva Falcão B, Banks S, Al-Yaseri A. Can FBG sensors measure rock deformation under hydrostatic pressure? In proceedings of: ARMA/DGS/SEG International Geomechanics Symposium, Dhahran, Saudi Arabia; 2021.

[15] Zhao WS, Zhong K, Chen WZ. A Fiber Bragg Grating borehole deformation sensor for stress measurement in coal mine rock. Sensors-Basel. 2020;20.

[16] Lei WL, Chai J, Zhang DD, Ouyang YB, Ma Z, Du WG, Liu YL. Experimental study on overburden deformation evolution under mining effect based on Fiber Bragg Grating sensing technology. J Sensors. 2020;2020.