Uniaxial compression test of rocks: Review of strain measuring instruments

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Abstract. The importance of uniaxial compression test (UCT) of rocks will never be overemphasized as it plays a vital role in understanding the mechanical properties of rocks for use in civil, mining, and petroleum engineering. Strain response of rocks to external loading is small; it requires a precise instrument to capture the strain with reasonable accuracy. The conventional method is associated with system compliance error, limited precision, and bedding error. Several methods were devised to alleviate these errors. This study embodies the existing strain measuring instruments during UCT of rocks, their principles, features, accuracy, merits, and demerits are correctly scrutinized. The paper serves as a powerful tool that enables the selection of a suitable instrument accordingly. It is hoped that the study will encourage more exploration in the area.

1. Introduction
The knowledge of mechanical behaviour of rocks is relevance and momentousness in rock mechanics, mainly when applied to petroleum industries, rock drilling, tunnel design, and design of waste depository. Laboratory testing has played an important role in strength characterization of rocks. Uniaxial compression test (UCT) on a cylindrical rock sample of length two or three times its diameter is the usual method of studying the mechanical properties of rocks in the laboratory. The test is propounded by the International Society for Rock Mechanics (ISRM) [1], after which more paperwork describing the pre-requisite and difficulty of UCT and how to overcome them was published [2]. Subsequently, a standard test method was developed by America Society of Testing and Materials (ASTM) [3], which was revised [4] and then extended to comprise confined testing and different state of stress and temperatures [5]. During the UCT test, the load is gradually applied to the rock core sample until it failed. The load-displacement data obtained can be used to determine the stress-strain curve of the rock sample, to establish parameters such as unconfined compressive strength, Young's modulus, poison's ratio from the curves. Other parameters that can be obtained include stress thresholds such as crack closure, crack initiation, and crack damage stress. These parameters are vital in the design of subsurface excavation, in-depth waste depository development of rock-physic model, wellbore stability analysis, and reservoir compaction survey, etc. [6]. Typically, strain response of a rock specimen is measured from a transducer, which is integrated with UCT machine; this method has proven to exaggerate the actual strain induced in the rock [7]. Also, the technique tends to neglect the small strain response of some rock types, especially the brittle rocks. These incur the need for a more precise method that can measure data in microstrain reliably. Over the years, many techniques and instrumentations for measuring strain response directly on the rock specimen have been developed by several researchers; strain gauge, linear variable differential transformer (LVDTs), extensometer, Acoustic emission, digital image correlation and FBG strain sensor [7]. Each of these methods has advantages and shortcomings.
This study intends to review the existing methods of strain measurement during UCT in the laboratory. Existing literature was referred to, contributions of researchers were harmonized, and their inputs are documented. It offers an integrated and current state of the art of local strain measuring devices during UCT. Also, the paper will provide first-hand information to new researches interested in the area. Additionally, UCT is a destructive test conducted on rocks; it is usually time-consuming and expensive; therefore, various UCT estimation models have been developed and calibrated using laboratory test results. Typically, the strain is measured in two ways; contact (strain gauge, extensometer, acoustic velocity, FBG sensor LVDT, and a non-contact method (DIC), photoelasticity, and coherent gradient sensor. The review focused on the contact method of strain measurement in UCT as most researchers adopt it; the non-contact technique is comparatively new and costly.

1.1. Error in strain measuring device during UCT testing
The conventional uniaxial machine measures strain through a transducer, which is attached to the machine Fig 1. This method does record not only the change in length of the specimen but also all other extending / elastic components of the testing machine and its drive systems, including any slipping of the sample in the grips and the unevenness of sample surfaces, thereby overestimating the strain values due to bedding and system compliance error. Quantities that are majorly affected by these errors are Young's modulus (E) and poison’s ratio (ν) and to some extent the stress thresholds (crack closure, crack initiation, and crack damage stress). Usually, the axial transducers are attached to the loading ram; this allows measurement of E. To measure ν, the system must be enhanced to enable radial strain measurement.

![Figure 1. (a) Conventional Rock Uniaxial testing machine (b) Sources of error in UCT](image)

According to [8] the uncertainty in measuring E and μ relies heavily on the strain/displacement transducers, mounting transducers (that can read strain in microns) on the specimen will significantly reduce the errors in measuring E and ν. Fig 2. demonstrated an example of error calculations based on certain factors the influence E and measurement [8]. The result indicated the importance of having precise instrumentation with high resolution.
2. Review of strain measuring instruments

Majorly, electronic devices and sensors are used for strain measurement in UCT. Electrical appliances are indirect methods and give output in the form of voltage, capacitance, etc., which is converted to strain using a gauge factor. The measured strains depend significantly on the properties of the sensor components. Defective components cause uncertainties in the measured values. Although the pre-existing electrical sensors are generally agreed to be comparatively reliable, they possess inherent defects such as loss of signals, electromagnetic interference (EMI), electrical short-circuiting, some are labor-intensive, time-consuming, and costly. Fiber optics (FO) is another technology appreciated as the most promising suitor for measuring strain, given the exceptional advantages as flexibility, resistance to high pressure and temperature, anti-corrosion, multiplexing capability, small, immune to EMI, and so forth [7]. In general, strain measuring devices must possess the following qualities: Free from the effect of temperature variation; else temperature compensation must be applied; Rock strain is in few tens of microns; therefore, the sensor should be able to measure strain in microns; and stability throughout the measurement during UCT.

2.1. Linear Variable Differential Transformer (LVDT)

LVDT is a powerful displacement transducer that has an almost infinite life span when properly used. It is intrinsically frictionless and can be designed to operate at high temperature up to 650 °C. LVDT is among the most commonly used instrument since 1974. [9]. It has gained commercial values; even industries adopt the device for the analysis of rock strain. Nowadays, LVDT is produced in various sizes, making it suitable for all kinds of samples. Depending on the requirement, it can be optimized to withstand harsh environmental conditions. It has low hysteresis, excellent repeatability, linear calibration, immunity to external effect, measures strain even at the post-peak regime, high sensitivity, high range (1.25mm to 250 mm) of displacement, 0.25% full-scale linearity (0.003 mm dynamic response). Principally LVDT is an electromechanical device that can be used to converts linear displacement for a mechanical reference into a proportion of variable (electrical current, voltage, or electric signal and vice versa).

However, it is expensive, susceptible to EMI, and vulnerable to jamming towards failure because of core tilting. Moreover, extra care must be taken during the set up of both the apparatus and the sample to ensure uniform and concentrically loaded specimens for the instruments to perform accurately. Error due to electrical resistance can be eliminated by adopting short cables. When the sample is tested to breaking point, sudden shock may lead to damage of the LVDT. It measures the overall axial dimension of the sample, which might not reflect the correct strain induced within the sample. Researches conducted with LVDT include [10]–[12] among many others. Fig 3. Introduces LVDT and how it is mounted during UCT.
2.2. Compressometer
Compressometer enables the determination of E and v during UCT of rocks or concrete. It serves as a clamp where devices such as LVDTs and dial gauges are mounted on the specimen to enable direct axial and radial strain measurement. Nowadays, the use of dial gauge is diminishing as it entails manual recording of data, which is very tedious and time-consuming. It consists of two or three circular ring metals in which the distance between them can be adjusted to fit in on the sample. Depending on the size of the sample, the rings can be designed to fit efficiently. Usually, three devices (two for axial and one for radial) can be co-opted for measuring both axial and radial strain to determine E and v. Compressometer must be aligned vertically and accurately in a position to record data correctly. All the rings can be mounted on the specimens with the help of a needle-end screw, which pierces the specimen when tighten. Fig 4 illustrates an example of compressometer and how is it installed on the sample.

2.3. Strain gauge (SG)
SG was developed by Edward E. Simmons and Arthur C. Ruge in 1938. SG is one of the most commonly used gauges for the UCT test of rocks. It is attached to the rock using efficient adhesives such as epoxy resin or cyanoacrylate [15]. Strain-induced on a loaded sample is measured in terms of electrical resistance and converted using gauge factor GF. SG is made up of metallic strips of foil assembled in a grid pattern. SG is manufactured in various sizes. Based on the size of the specimen, a suitable SG is selected. SG measures strain in microns, it has good strain-sensitivity, and it is stable over short distance and duration of the measurement. It is sensitive to temperature, and its resistance changes with age. Nowadays, SG compensated against effect of temperature is available commercially. SG is packaged with cables soldered or unsoldered (soldered is recommended) Fig. 5 Shows SG attached to a specimen, and UCT was conducted.
Figure 5. SG on rock sample; (a) SG on specimen (b) Specimen with SG undergoing UCT[15]

SG is comparatively cheap, easy to get, and produced by many commercial industries. The set back of SG is that it doesn’t capture strain in the post-peak regime, mainly due to strain gauge damage caused by cracks in the rock. Moreover, adhesives for bonding SG must have; enough bonding capability to enable smooth transfer of strain; appropriate viscosity to facilitate the application of thin durable layer (thick layer affect strain transfer mechanism), and stability over operating temperature.

2.4. Extensometer
It is a mechanical strain device produced in various gauge length and clip/clamp system to suit the shape of the specimen, configuration, measuring range, operating temperature, and pressure. Extensometer was first developed by Charles Huston, 1879, and the ownership was transferred to Fairbanks & Ewing (a dominant manufacturer of testing machines and scales). It is usually attached to the specimen and connected to a controller that has the software installed on a PC to aid data acquisition. Extensometer has gained values due to its accuracy, high resolution: <0.2 µm RMS typical at 1 Hz; <0.5 µm at 10 Hz; <1 µm at 100 Hz; <5 nm in low strain rate as it responds to a minute strain. The device is durable, which is why it is employed for UCT of rocks. There are three types of extensometer: Cambridge (Cam), Ewing’s (Ew), and Huggenberger (Hug) type. The fundamental difference between the three is the magnification of the small extension during measurement. Cam and Hug have mechanical magnification while the Ew possess optical magnification. Though extensometer has considerable cost and easy to use, it is challenging to capture strain at post-peak regime due to misalignment caused by progressive cracks on the surface of the rocks. It can also be challenging to use on small and delicate specimens. Pictorial view of an extensometer fixed on the specimen is shown in fig 6. the extensometer must be set up for each sample and tends to restrict access to it. If the sample is tested to breaking point, the sudden shock can damage the transducer.

Figure 6 Extensometer mounted on rock specimen during UCT (a) radial extensometer (b) axial and radial extensometer [21]
2.5. *Acoustic emission (AE)*

AE involves radiating acoustic (elastic) waves through rocks during UCT, which is translated into displacement or strain in rocks. AE rate is also used to measure damage accumulation occurring in rock specimens during UCT. Usually, AE signals acquired from piezometers attached to the sample are analyzed with the aid of AE acquisition and analysis system. Fig 7 demonstrates AE transducer attached to rock specimen during UCT. AE is used to identify, reveal, and characterized damage in rocks with high precision, which is why the method is commonly applied to detect stress thresholds of rock during UCT. AE can be detected within frequency ranges between 1KHz to 1 MHz. In rapid stress-release events, spectrums of stress waves starting from zero and typically falling under MHz can be generated. AE has gained popularity for use in determining the mechanical performances of materials such as rocks.

![AE transducer](image)

**Figure 7.** AE on rock specimen during UCT[16]

2.6. *Fibre Bragg Grating Sensor (FBGs)*

FBGs are sensing portion inscribed on an optical fiber made up of glass or silica that transmits light signals, any strain caused by external mechanical influence is calculated by the shift in the reflected signals of the fibre [7]. FBG grating is imprinted on a short segment of single-mode optical fibre (SMOF) by creating a periodic adjustment in the refractive index of the fibre core along the SMOF length. Each grating behaves as wavelength with specific filter making it possible to have many gratings along single SMOF. When a broad spectrum of light source passes through SMOF with FBG grating imprinted, all the light will get transmitted except for those having similar wavelength as the Bragg wavelength. Fig 8 demonstrates the working principle of FBGs.

![FBG working principle](image)

**Figure 8.** Schematic diagram of the FBG working principle [17]

FBGs are influenced by changes in strain and temperature when measuring strain; the effect of temperature must be linearly modified or instead compensated. The compensation can be done through experiment [18]. To date, there are only a few numbers of articles that include preliminary in this field where FBG sensors were tentatively bonded to core specimens. It was experimentally confirmed that the strain ranges of rocks are in few tens of microstrain, and the influence of rock inhomogeneity could be diminished as a result of an efficient measurement. FBGs are known for their inherent superiority in adaption to harsh weather environment, high resolution, high sensitivity, multiplexing, and quasi-distributed measurement capability. Indubitably significant researches have been devoted to
the field of application-based FBG sensor in the oil and gas industries [19]. It can be ascertained that there will be a high demand for FBGs by the industry in the future. Until today only a few works of literature focused on core-scale simulation experiments using FBGs, especially considering dynamic sensing [7]. Combining the right knowledge and equipment, one can be able to inscribe FBGs on SMOF, making it cheaper and convenient to use.

3. Conclusion
The state-of-the-art review of contact – techniques of strain measurement during UCT was presented. The accuracy, technology, installation technique, operation principle, advantages, and disadvantages were discussed. The methods were divided into two; those that are bonded on the specimen using adhesives (SG and FBGs) and those that are mounted with the aid of clamp or clip mechanism (LVDTs, Extensometer, and AE). It can be highlighted that SG and FBGs got destroyed when the specimen failed, while LVDT, AE, and extensometer can be used several times when handled with care though they are more expensive comparatively. Except for FBGs, all other methods are vulnerable to EMI and electrical short-circuiting.

Generally, the selection of a technique is dependent on availability, budget, application, and requirements. This article served as a guide for the proper choice of the method of strain measurement in UCT.

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