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Measurement of small-strain stiffness of soil in a triaxial setup: Review of local instrumentation

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ABSTRACT

Accurate determination of soil stiffness at small strain (0.001 % - 0.1 % strain) is very important as it portrayed the stiffness of soil underneath geotechnical structures. To evaluate stiffness at small strain, it is important to achieve a minimum strain measurement accuracy of 10-4 %, this is attained using transducers, strain gauges and sensors which are attached on the specimen locally inside the triaxial cell. Several local strains measuring techniques have emerged with the intention of developing a seamless system which is easy, accurate and less expensive. This study epitomizes the existing types of small strain measuring instrumentation, their trend of development and technology. Those that can measure both axial and radial strain, axial strain alone and radial strain alone are distinguished and described. Also, the accuracy, features, merits, and demerits of each type of device have been discussed accordingly. This paper provides information that enables selection of a suitable device that will best fit a particular application. It is anticipated that the study will inspire further researches in the area.

1. Introduction

Stiffness of soil at small strain represents the actual soil stiffness under construction and typical service conditions of geotechnical structures like pavement, tunnelling, rails, embankments, retaining walls, foundations and deep excavation. It represents the region on the stiffness-strain curve where the strength of the soil is expected to reach its climax (Jardine et al., 1985a). The importance of soil laboratory characterization will never be over emphasized as it has contributed immensely towards a better understanding of behaviour of soil that surrounds geotechnical structures (Atkinson, 2000; Gasparre et al., 2014; Nishimura and Abdiel, 2017). Triaxial testing is one of the most popular and versatile apparatus for laboratory characterization of soil which is globally acceptable. The conventional triaxial system takes measurement of a soil specimen through transducers located outside the triaxial cell. Axial strain transducers are typically attached to the load ram, while the radial strain is determined either from the back-volume change or the axial strain readings. Even though the setup provide strain measurements with sufficient accuracy for routine triaxial tests, it does not measure soil deformation accurately at small strain level, where the peak strength and stiffness may likely to occur, or rather the shearing zone which is representative of in situ soil response (Xu et al., 2014). Error in conventional triaxial testing apparatus is attributed to the system's mechanism of operation whereby measured values are transferred through some elements such as load ram, top cap and top porous disc before finally reaching the transducers located exterior to the cell (Wu et al., 2014). This leads to the prediction of linear stress-strain relationship. In order to minimize the inevitable error related to conventional triaxial testing, many researchers contributed in advancing the triaxial setup by developing local transducers and sensors that can assess soil response over diverse engineering application. These transducers and sensors are normally placed on the specimen inside triaxial cell to evaluate soil parameters typically unattainable using the conventional triaxial apparatus for example (Nishimura, 2014; Wu et al., 2014; Ackerley et al., 2016; Shankar Kumar et al., 2016; Roshan et al., 2017). Measurement of strain on specimen is referred to as local measurement. The advent of these high resolution local sensors and transducers that can capture the soil behaviour more accurately at small strain has led to the discovery of the fact that soil behaviour is non-linear as against the previous researches that assumed linear stress-strain relationship (Hashash et al., 2010; Saffari et

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al., 2017). Non-linear stiffness characteristics have significant impression on the analysis and design of a broad range of geotechnical activities performed in soils (Atkinson, 2000; Hartzell et al., 2004; Gasparre et al., 2007; Figini et al., 2012; Kim and Roesset, 2004; Shih et al., 2017). Because of the importance of small strain zone, researchers have continued to develop keen interest in finding better ways to characterize soil behaviour within the region.

This paper intends to review the forms of local strain measuring instruments integrated in a triaxial testing apparatus for stiffness measurement at small strain in the laboratory. Works of previous researchers were consulted, and their contributions were accorded. This provides consolidated up-to-date information on the current state of the art of stiffness measurement at small strain in a triaxial testing apparatus using local devices, especially for new researchers interested in the area. There is no review work on this area after Scholey et al. (1995) and Yimsiri and Soga (2002). Nowadays there exist sophisticated ground movement assessment models that require more accurate small strain data (Zan et al., 2016). The paper will help in selecting the suitable instrumentation setup that will provide more reliable data for optimum performance and prediction of these models.

2. Soil stiffness and strain measurement using triaxial apparatus

According to Atkinson (1991) the variation of stiffness and strain of soil is categorized in to three regions; very small strain, small strain and large strain regions respectively on a stiffness-strain curve. The graph of Young's moduli (tangent and secant moduli) against strain demonstrated a constant stiffness within very small strain region, after which the stiffness declined drastically (Fig. 1). The region that marked the rapid decay of stiffness up to a point where strain is 0.1 % is referred to as small strain region. Large strain zone ranges from 0.1 % to 1% strain. Stiffness at 0.1% strain represent the characteristic strains of soils near structures, which is the minimum limit that can be obtained using the conventional triaxial apparatus. Findings from Atkinson (1991) were extended to in-cooperate the range of strain that can be obtained by the integrated and conventional triaxial system respectively (Likitlersuang et al., 2013). Basically, there are three ways to measure soil stiffness: dynamic methods, local devices and conventional approaches. From Fig. 1, soil stiffness at strain range less than 0.001 % is obtained using the dynamic approach which is typically triaxial apparatus integrated with bender element, local gauges are used to determine soil stiffness within the range 0 - 0.001 % strain while the conventional triaxial testing setup is only suitable for stiffness at strain range 0.1 % upward. Generally, there is a mark reduction in stiffness with the increase in the strain level. Soil strain beneath and around structures varies with the type of the structure. This is explained comprehensively by Likitlersuang et al. (2013). The ranges were based on soil stiffness and it gives reasonable design references for civil engineering structures such as retaining wall, tunnel and foundation. Soil strain range common to geotechnical structures such as tunnel deep excavation, foundation and retaining wall occurred over the region with greatest variation in stiffness on stiffness-strain curve. Across this region, it is essential to employ local gauges to acquire stiffness applicable to these geotechnical structures. The conventional measurement is not suitable for practical applications as it can only be used to obtain stiffness within strain larger than that of the geotechnical structures. Stiffness's measurement within the small strain region can be performed with reasonable accuracy using triaxial apparatus integrated with local measuring instruments (Shankar Kumar et al., 2016; Jardine et al., 1985a). Small strain measurements made with conventional apparatus are full of errors which are often more than even the values measured. Local transducers are required to work perfectly in water and oil under pressure and must be able to maintain level of accuracy and stability throughout the testing period.

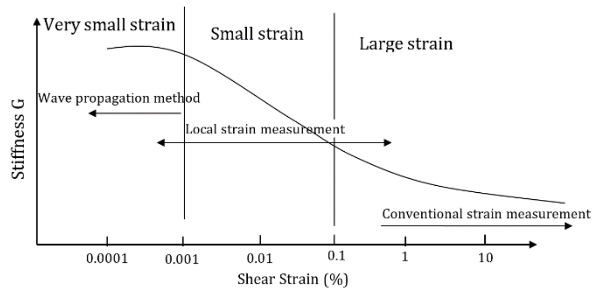


Fig. 1: Modulus degradation curve of soil stiffness from laboratory tests (Atkinson, 1991; Likitlersuang et al., 2013)

2.1. Sources and magnitude of error in small strain measurement in a conventional triaxial test

The analysis of sources of errors in conventional triaxial apparatus was presented by Jardine et al. (1985a) and Bald et al. (1988). Fig. 2 demonstrates the possible sources of error which are listed below:

- System compliance error which occur because of compression of porous paper, lubricant, deflection of internal load cell etc. External transducer readings are influenced by these factors.
- Bedding error which is as a result of unevenness of the specimen ends and imperfect fit between the specimen and porous stone.
- Seating error resulted when the gaps between the ram or internal load cell and /or platen and porous stones are closing.
- Error due to miss alignment of equipment and specimen resulted when the specimen is tilted, when the surface of the platens is not purely horizontal, when the ram is not purely vertical and

eccentrically loaded and when the thickness of the porous stone is not uniform.

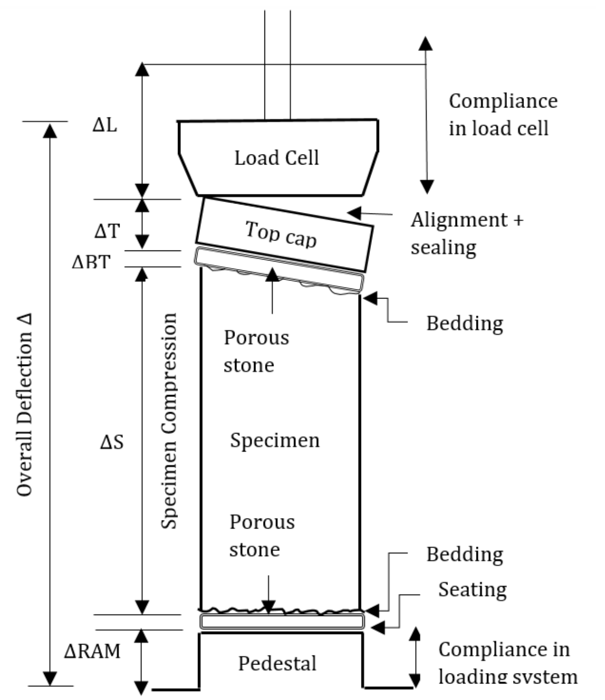


Fig. 2: Possible sources of error in conventional triaxial system after (Jardine et al., 1985c; Bald et al., 1988)

The conventional triaxial systems have proven to be incapable of measuring small strain with sufficient accuracy comparable with the in-situ measurement by many researchers even when correction of errors was applied. For instance the magnitude of errors in conventional triaxial system was assessed by Lo Presti et al., (1994) with a triaxial setup integrated with four separate gauges; two attached internal and two external to the cell in order to measure stress-strain of Ticino silty sand simultaneously. Considering linear variable differential transducer LVDT (with resolution of 0.3µm and accuracy of 1 µm) as a control, proximity transducer having the same specifications as the LVDT underestimated the soil stiffness by 10 to 15 %, external proximity transducer (having similar specifications with the control LVDT) by 20-30 %, while the external inductive displacement transducer values have shown to be unreliable at strain less than 0.1 %. Similarly, Yimsiri et al. (2005) observed that the performance of a cantilever linear deformation transducer known as Cantilever-LDT is more presentable than external linear variable differential (External LVDT).

Table 1 presents the stiffness response of external transducers compared to the respective internal transducers from previous literatures. It can be ascertained from Table 1 that the cantilever-LDT transducer measure small strain better than the external LVDT. Similar trend was observed by Kung (2007), Xu et al. (2014), Gasparre et al. (2014), Wu et al. (2014), Shankar Kumar et al. (2016), and Xu (2017). It is important to highlight that even though the importance of local measurement for more accurate assessment of stiffness at small strain is getting recognized day by day, the conventional triaxial testing is still the most frequently employed commercially. Perhaps because it is easier to conduct the conventional than the local measurement.

Table 1: Comparison of stiffness measured using internal and external transducers

Instrumentations	Stiffness at small strain by External compared to the Internal transducer	Reference
Cantilever-LDT and External LVDT	20-40% of that of Cantilever-LDT	Yimsiri et al. (2005)
Hall effect and external transducer	30-40% of that of the Hall effect	Wu et al. (2014)
Hall effect and external transducer	30-40% of that of the Hall effect	Kung (2007)
FBG-LDT and external LVDT	15-30% of the FBG-LDT	Xu et al. (2014)
SDT and external LVDT	30-45% of SDT	Xu (2017)
Internal and external LVDT	Readings unrealistic at small strain	Shankar Kumar et al., (2016)

2.2. Properties of small strain measuring devices

Based on studies conducted by Bonal et al. (2012), Wu et al. (2014), Nishimura and Abdiel (2017), Ackerley et al. (2016), Brosse et al. (2017), and etc. The following basic properties of small strain measuring device are extracted:

- The ability to capture strain of at least 10^{-4} accurately.
- The capacity to accommodate both radial and axial deformation measurement without sacrificing accuracy.
- The ability to operate on specimen of any dimension.
- It must be able to take measurement over central one-third of the specimen to avoid end restrained effects.
- It must operates in polar and non-polar fluid within the range of triaxial cell pressure.
- Non-interference with the soil behaviour.
- It must be able to operate under different stress path.
- Capability of providing stable stress-strain measurement over long period of time.
- It should not be affected by ambient temperature changes otherwise, it must be compensated.

3. Overview of small strain measuring instruments

Early measurement of stiffness at small strain locally started way back since 1957 when Bishop and Henkel implemented lateral strain calliper, the concept which form the basis for most subsequent devices. This implies that local lateral strain measurement was first initiated before the axial strain measurement. Local axial measurements were established early 1970s when Atkinson employed submersible dial gauges which were attached on the platens. Next was a submersible linear variable differential transducer (LVDT) which is the most common type of local measuring device (Brown and Snaith, 1974). However, the use of this LVDT is accompanied by many limitations such as difficulties in mounting and alignment in the triaxial cell due to its large size and it was not suitable to work in water, hence many instruments have continued to evolve and mini-LVDTs were produced (Cuccovillo and Coop, 1997). An inclinometer known as electrolyte level was initiated by Burland and Symes (1982) which was subsequently modified and employed (Jardine et al., 1985a;b;c; 1986). Hall Effect transducer initiated by Clayton and Khatrush (1987) has also been used effectively, while the proximity transducer was implemented by Hird and Yung (1989) and has also gain acceptance. Goto et al. (1991) developed linear deformation transducer (LDT); it was redesign and improved by Yimsiri et al. (2005) and Xu et al. (2014). Another technique of using strain gauge was introduced by Gunasekaren and Robinson (2008). Recently, distributed fibre optic technology (DFOT) was introduced for stiffness measurement at small strain in the laboratory in a Conjuncture Helical Configuration (CHC) Pattern (Uchida et al., 2015). The method is being tested in the laboratory by conducting uniaxial compression test on acrylic glass specimen. Currently the authors are working on the application of the method in triaxial testing of soil specimen.

4. Review of local instrumentations

The review classifies the local small strain measuring instrumentation based on the technology applied and the ability of the same system to measure both axial and radial strain. Based on the technology applied, the instruments are classified into two in this paper, which are electrical and fibre optic base respectively. An electrical base instrumentation gives strain measurement in the form of electrical output; voltage, current or capacitance. The devices are attached locally on the specimen or placed in the triaxial cell leaving a gap between the device and the specimen. Fibre optics measures soil deformation by measuring changes in the wavelength properties of optical cables/ sensors attached within the soil specimen. Currently two types of this technology are popular; distributed fibre optics technology (DFOT) and fibre Bragg Grating popularly known as FBGs. The methods have gained acceptance in wide area of application. Classification based on the technology observed and the year of implementation is shown in Fig. 3.

These gauges are also classified based on ability of a single type of transducer to obtain axial and radial strain measurement. This classification will be discussed subsequently in next section. Local axial strain is normally determined using two transducers placed diametrically opposite to each other within the central one-third of the specimen for better accuracy (Jardine et al., 1985a;b;c; Yimsiri et al., 2005; Gasparre et al., 2007, 2014; Brosse et al., 2017; Shankar Kumar et al., 2016). It is believed that the strain measured by a pair of transducers will adequately represent the strain respond within the central on third of the specimen.

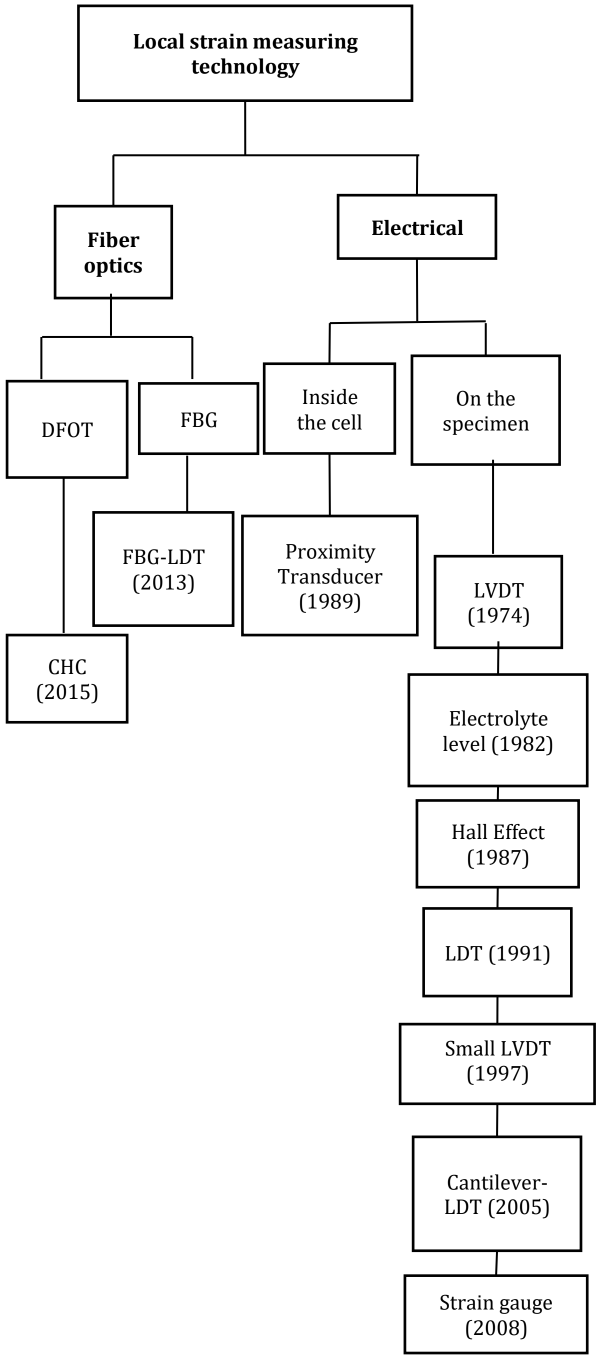


Fig. 3: Trends of development of local strain measuring devices based on the technology

Radial strain can be obtained by taking measurement directly from the specimen or derived from the axial strain. The accuracy of the derived radial strain is influenced by the accuracy of the measured axial strain and therefore susceptible to all the errors in the conventional system. Reliable radial strain is measured internally at the mid-height of the specimen. It is also assumed that measurements taking at two or more points will suffice to represent the entire radial strain along the mid-height of the specimen (Shankar Kumar et al., 2016). Nature of the device and its configurations, membrane penetration, specimens tilting, irregularity of the specimen's surface and bulging may affect the accuracy of the measured radial strain. The devices are itemized and discussed according to the trend of development in sections 4.1 to 4.8.

4.1. Linear differential variable transducer (LVDT)

LVDT is one of the most popular and old device for measuring stiffness at small strain. It was first developed by Brown and Snaith (1974). Nowadays it has obtained commercial values in the sense that even industries employ LVDT for soil strain analysis. Basically, there are two types of local LVDTs according to the nature of support; the floating type and the fixed type. The earlier floating type LVDT (Brown and Snaith, 1974) was supported by two circular split-sprung collars which are circumferentially mounted on the targets embedded in to the soil specimen at both ends of the gauge length (Fig. 4a). The setup allows the respective movement of the targets to be recorded by two LVDTs attached diametrically opposite to each other. However, the LVDT is big and its entire weight is supported by the soil which can cause failure apart from inability of the LVDT to work inside water. Costa Filho (1985) developed a fixed support type, whereby the LVDTs are mounted on a fixed support (Fig. 4b) which reduces the impact of the weight of LVDTs on the specimen. The fixed type of support causes jamming of the LVDT especially near failure of the specimen and the LVDTs are also non-submersible in water. Cuccovillo and Coop (1997) developed a small size, water submersible, easy to mount and align LVDTs (Fig. 4c) which has made remarkable improvement over the previously used LVDTs that were big and insensitive over certain linear distance. The previously developed non-submersible LVDT had many disadvantages and the focus of our subsequent discussion will be on the submersible LVDT as it is currently the type adopted for local strain measurement. Cuccovillo and Coop (1997) also developed radial strain LVDTs which allows measurement of both radial and axial strain using the same type of device simultaneously. LVDT was employed by Gasparre et al. (2007) in determining the stiffness of natural London clay. Other research conducted with LVDTs include; (Atkinson, 2000; Cabarkapa and Cuccovillo, 2006; Yimsiri et al., 2009; Jung et al., 2012; Surarak et al., 2012; Likitlersuan et al., 2013; Ratananikom et al., 2013; Gasparre et al., 2014; Nishimura, 2014; Shankar Kumar et al., 2016; Roshan et al., 2017; Wild et al., 2017).

The current most popular and widely accepted water submersible mini-LVDT has a resolution of <1μm using 16bit data acquisition, and the range can be ±2mm, ±5mm or ±7mm, working temperature range of -20°C to 60°C and can resist water pressure of up to 3500kPa. It can be used on 50mm, 70mm, 76mm, 100mm, 150mm or even customised specimen size. LVDT offer good resolution, high stability and linear calibration. However, it is costly and susceptible to jamming towards failure because of core tilting. Apart from that, it also requires great care during setting up of both the apparatus and the sample to ensure uniform and concentric loaded specimen for the instruments to perform accurately.

4.2. Electrolyte level transducer

This is an inclinometer made of electrolyte level sealed in a glass capsule, hosting three co-planer electrodes that are partially immersed in the electrolyte. The electrolyte is concealed in a thin-walled brass cylinder. The system operates basically by converting the axial deformation of triaxial specimen in to the tilt of the electrolyte level. Even though electrolyte level works reasonably, it responds to not only the axial deformation but also the rotation of the rigid body to which it is attached. It is also not suitable for a triaxial sample of size 38 mm diameters. Jardine et al. (1985a) simplified and improved the geometry of the electrolyte level by improving the hinge mechanism thereby reducing the effect of rotation of the rigid body to which it is attached and also making it workable on 38 mm diameter sample. Fig. 5 shows electrolyte levels transducers mounted on a 38 mm diameter sample. The improved electrolyte level has a resolution of up to 1μm and linearly calibrated. It is sensitive to temperature and vibration therefore it should be operated in a calm environment with temperature changes within ±3 °C.

The instrument is accurate, easy and quick to mount, has high resistance to water pressure in the cell, and remain undamaged even at high strain (Kuwano et al., 2000). Studies conducted using electrolyte level includes: Jardine et al. (1985a,b,c), Burland (1989), Jardine (1992), Kuwano et al. (2000), and Kuwano and Jardine (2002, 2007).

4.3. Hall effect transducer

The working principle of Hall Effect transducers is based on the fact that when a semiconductor plate is exposed to a magnetic field such that the flux lines are oriented perpendicular to the plate and flow of current, electromotive force (EMF) is produced across the plate normal to the flowing current. The instrument consists of two parts; the upper pad which is fixed on the specimen holding a suspended pendulum mounted on a spring that clutch the magnetic assembly. The lower part comprises of a metallic container which hold the semiconductor. This part is also fixed on the specimen. The Hall Effect transducer resolution is <0.1μm, and the accuracy is up to ±0.2% full range output (FRO) over 4mm range. Over 5 mm range, the accuracy is ±0.3% FRO while over 6 mm range is ±0.4% FRO. The device is suitable for variety of sample size ranging from 38 mm – 150 mm including customized specimens. The semiconductor chip most be compensated against temperature and changes in the DC voltage supply. Studies conducted with Hall Effect transducer includes: Clayton et al. (1989), Tatsuoka et al. (1990), Ng and Wang (2001), Ng et al. (2009), Clayton (2011), Muñoz-Castelblanco et al. (2012), and Wu et al. (2014).

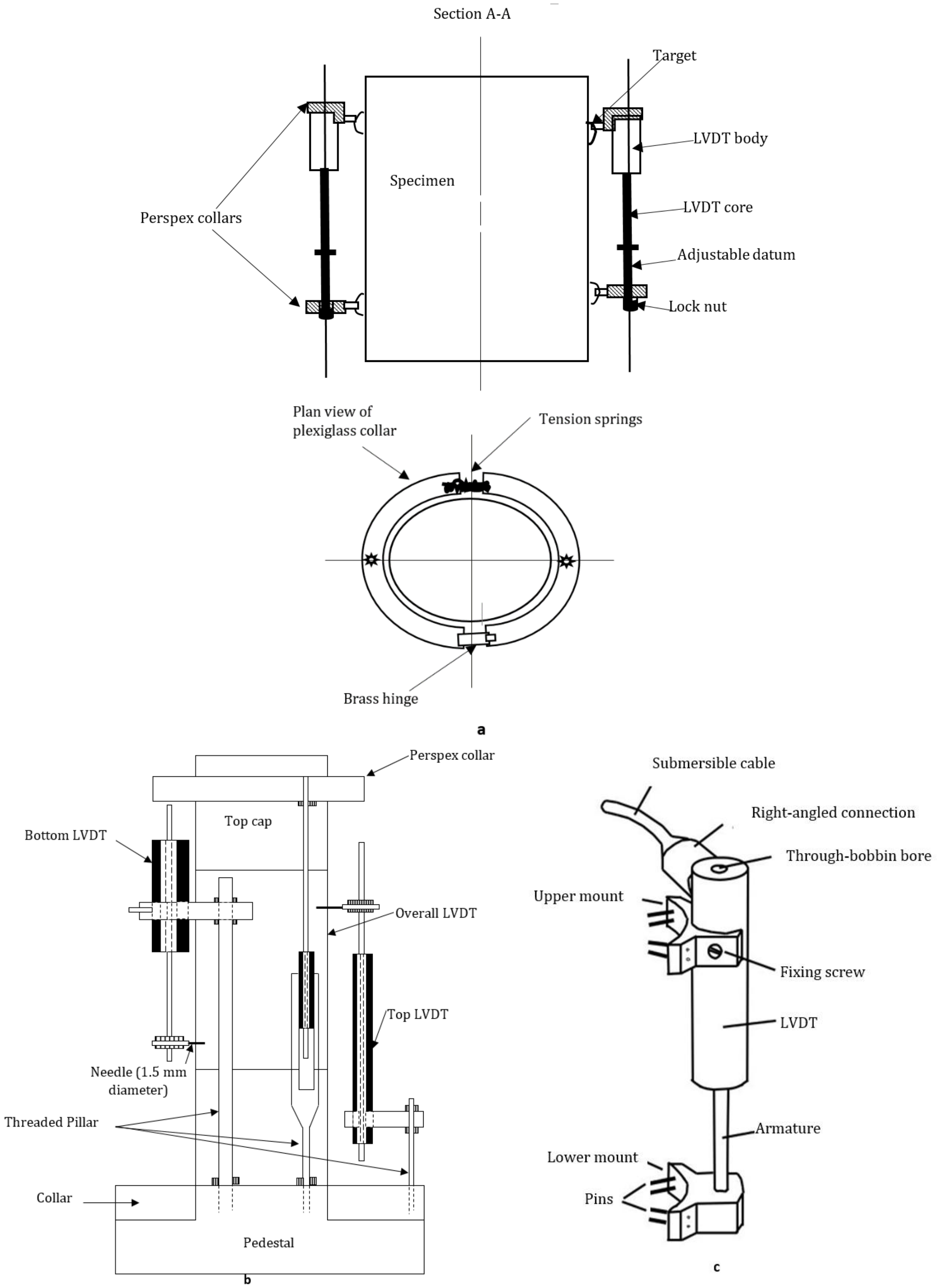


Fig. 4: Diagrammatic representation of LVDT; (a) Floating type LVDT (Brown and Snaith, 1974); (b) Fixed support type (Costa Filho, 1985); (c) Water submersible LVDT (Cuccovillo and Coop, 1997)

Difficulties in alignment of Hall Effect transducers on a triaxial soil specimen, rotation of lower pad in some cases while conducting triaxial test, are the limitations of Hall Effect transducer. Fig. 6 describes the schematic view of Hall Effect transducers on a soil sample.

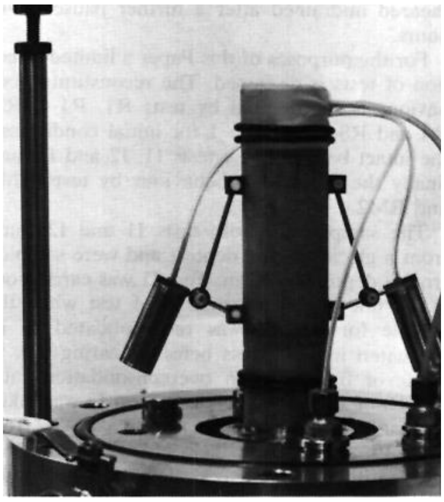


Fig. 5: Electrolyte levels transducers mounted on soil specimen after (Jardine et al., 1985a)

4.4. Proximity transducer

Proximity transducer operates based on the principle that when eddy current is circulated within a metallic target, there is going to be a loss of magnetic field. The loss of the magnetic field varies with the distance between the probe and the target. Eddy current is induced in the target by the coil in the transducer which changes with the distance between the transducer and the target. Changes in the eddy current cause a corresponding change in the impedance which can be measured by connecting the transducer to a Wheatstone bridge circuit. Proximity transducer can be a fixed type (Fig. 7a) or a floating type (Fig. 7b).

Normally the fixed type is employed as the floating type is difficult to mount and arrange on a specimen. This transducer possesses linear calibration curve, it has resolution of 0.001% and accuracy of 0.008%. Though it is difficult to setup, very expensive and most of them are water-non-submersible as such coating is applied to seal it. Illustration of proximity transducer is shown in Fig. 7. Stiffness measurement at small strain using proximity transducer has been demonstrated by Hird and Yung (1989), Yimsiri et al. (2009), and Ratananikom et al. (2013).

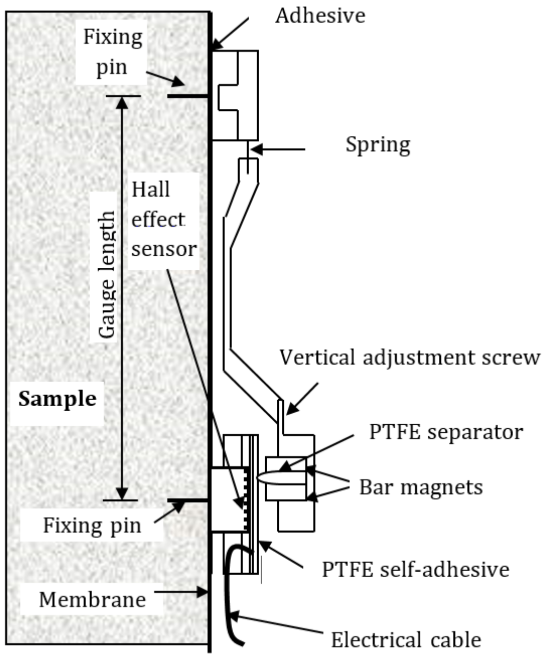


Fig. 6: Diagram of hall effect transducers on a triaxial specimen (Clayton and Khatrush, 1987)

4.5. Linear deformation transducer (LDT)

LDT is a system consisting four strain gauges, two thin flexible strip of phosphor bronze and four pseudo-hinged fabricated to form local deformation transducers (LDTs).

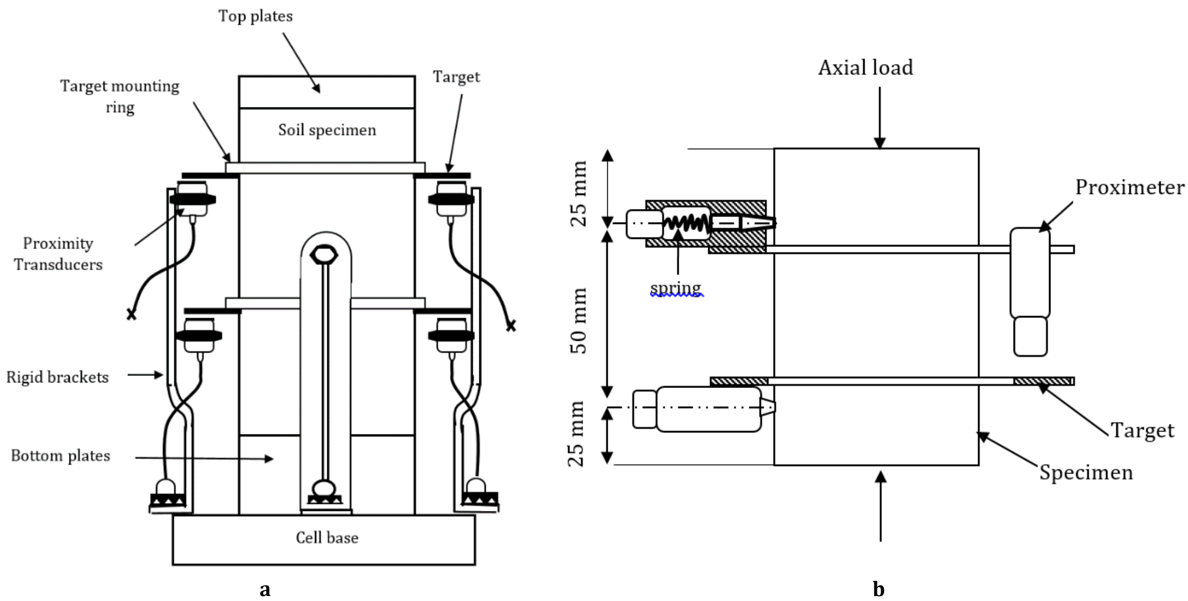


Fig. 7: Schematic view of proximity transducers; (a) Fixed-arrangement (Hird and Yung, 1989); (b) Floating-arrangement (Shibuya et al., 1994)

Two strain gauges are attached to the centre of each strip which is mounted in between a couple of pseudo-hinged adhered to the triaxial membrane using powerful glue and the whole setup aligned vertically. During the test, the deformation of the specimen causes the distance between the two attachments to change. The changes are then detected by the strain gauges and recorded as an axial strain. The average of readings obtained from the strain gauges is taken as an axial strain. The instrument can measure strain as low as 0.001%. Nonlinear calibration, errors due to noise from the amplifier, hysteresis of LDTs, mechanical imperfections and variation of voltage inputs couple with shallow working range have crippled the performance of this transducer. In addition, the contact force between the membrane and the hinges tend to increase with increase in deformation which leads to error. The setup of LDTs on the triaxial specimen is shown in Fig. 8. This device has been utilized by Goto et al. (1991) and Tatsuoka (1992).

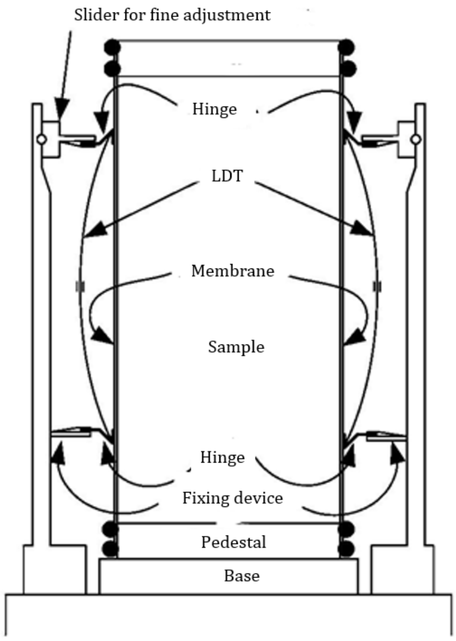


Fig. 8: Schematic view of LDTs on triaxial sample (Goto et al., 1991)

4.6. Cantilever linear deformation transducer (Cantilever-LDT)

This is a modification of LDT in the form of cantilever local deformation transducer (Cantilever-LDT), composed of two cantilevers positioned at two different levels on the same vertical alignment to measure the vertical movement between two points on the specimen. The cantilever is made up of heat-treated phosphor-bronze strip. The design principle is the same as the original LDT only that it operates in a cantilever style. When the L-hinge pinned on the sample moves, the cantilever will deflect, and the movement will be sense by the gauges. The transducer has resolution of approximately 0.0012%, accuracy of 0.003% and the range of 6%. One of the advantages of cantilever-LDT over LDT is the ability of cantilever-LDT to release itself at large strain which allows the specimen to be taken to failure, unlike the original LDT which must be removed before the specimen is subjected to large strain. It also has linear calibration curve compared to original LDT which is nonlinear. The major critic in this method is that the cantilever most be pre-bended below the hinge prior to the test which induces stress to the soil around the L-hinge. This may lead to failure prior to the test. The setup of cantilever-LVDs is illustrated in Fig. 9a. This transducer was employed by Yimsiri et al. (2005), Yimsiri and Soga (2011), Enomoto (2016), and Enomoto et al. (2016).

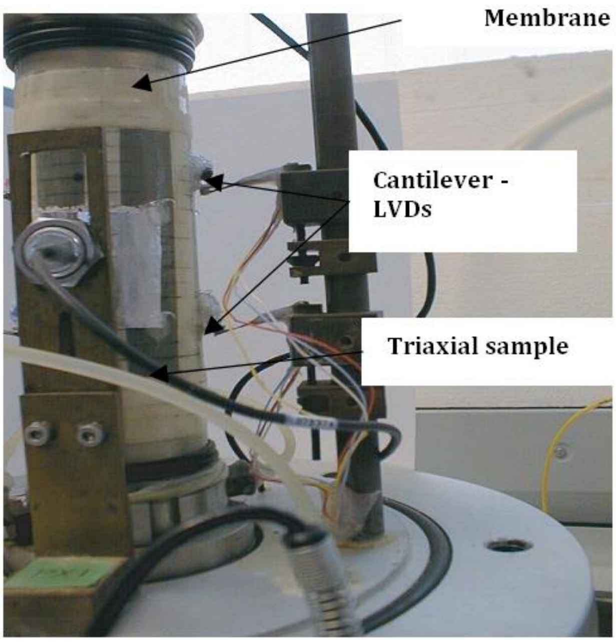
4.7. Fibre Bragg grating linear deformation transducer (FBG-LDT)

In order to overcome shortcomings such as the effect of electrical noise associated with original and cantilever LDT, the technology of the original LDT was advanced to fibre optic technology from electrical such that the strain gauges of the original LDT are replaced with FBG sensors. The working principle is the same as that of the original LDT only that the sensor is FBG instead of strain gauges (Fig. 9b). The approach is less expensive, more accurate and reliable. However, there is still an error due to mechanical noise as the force at the point of contact between the membrane and the hinges tend to get mobilized at certain displacement. The transducer has been deployed by Xu et al. (2014) and Xu (2017). The accuracy of the device is subject to the resolution of the FBG sensor interrogator, the calibration coefficient, the type of adhesive used, the hinges and the creep errors which may be introduced between the specimen and the membrane.

FBG sensors are sophisticated bread of intrinsic sensors with are inscribed along the length of an optical fibre. They are formed by engraving an unseen permanent periodic refractive index changes in fibre core. When a broad spectrum of incident light is propagated through the gratings, all the light will get transmitted except for the Bragg wavelength which will get reflected back. Like many other strain gauges; FBG have being used to build transducers for measuring many different physical quantities in a triaxial testing apparatus (Lee et al., 2010). Even though the setup is too cumbersome, as the design of some of the transducers (notably axial displacement FBG base transducer) is bulky. The loss of energy due to system compliance affects the performance of the setup. However, data obtained using the setup has shown agreement compared to the existing instruments.

4.8. Distributed fibre optic strain sensor (Conjuncture helical configuration)

Recently, fibre optics sensing technique have shown prospect for use in laboratory experimentations. A novel alternative approach for on-specimen strain measurement using high spatial fibre optics distributed sensing technology on a uniaxial testing machine in the laboratory was illustrated by Uchida et al. (2015). Conjuncture helical envelope configuration CHC (Fig. 10) developed (to ensure full-field deformation monitoring) was fully glued on acrylic glass specimen (cylindrical in shape) as it ensured joint-movement of the fibre and the specimen. Deformation data is acquired at every increment from local LVDTs and the fibre optic sensor. The results showed strong similarities between the Young's modulus measured from both instruments. Measurement of both circumferential and axial strains was obtained from the fibre sensing technique while LVDT gave only the partial view of the deformation.



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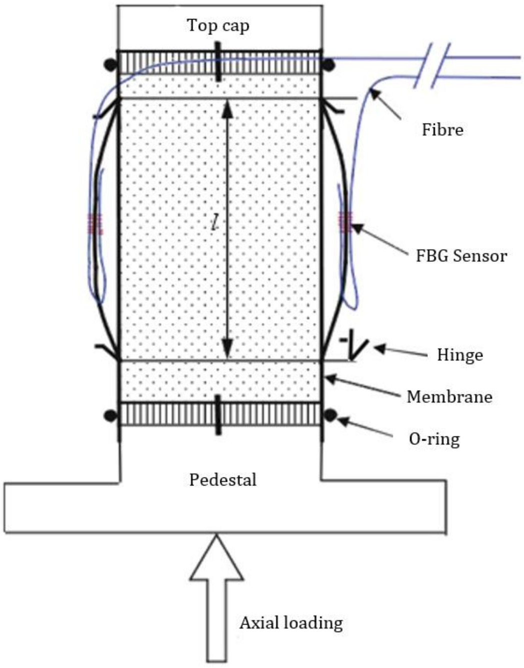

b

Fig. 9: (a) Cantilever- LDTs setup (Yimsiri et al., 2005); (b) Diagram of FBG-LDTs setup on the specimen (Xu et al., 2014)

Uchida et al. (2015) suggested the application of fibre distributed sensing technology for on-specimen strain measurement in a triaxial testing apparatus. However, to date, the technique of fully glued fibre on soil specimens have yet to be implemented.

Fig. 10: Distributed fibre optics conjuncture helical configuration (Uchida et al., 2015)

5. Measurement of both local axial and radial strain using the same transducer

The importance of local radial strain measurements will never be overemphasized. In order obtain bulk modulus and poison's ratio, it is necessary to determine radial strain. Many of the existing local axial transducers can be configured to measure local radial strain. Therefore, it is possible to measure both axial and radial strain from the same type of device. Several types of local radial strain transducers exist and most of them have no reported studies regarding their accuracy (Yimsiri and Soga, 2002). The classification of the transducers based on their ability to measure radial and axial strain was given in Fig. 11. Local radial LVDTs that uses mercury indicator column with resolution of 0.025% was invented by Bishop and Henkel (1957). Floating-type lateral strain LVDT suitable for use in air and transformer oil was discussed by Yuen et al. (1978).

There is still need for an LVDT that can work perfectly in water. LVDT that adopts radial belt mechanism which can work in water was successively invented by Kuwano et al. (2000). Recently, a fixed system of measuring radial strain made of three LVDTs which is robust and accurate was elucidated by Ackerley et al. (2016). The resolution of radial LVDT can be measured up to 0.0001%.

Radial proximity transducer was introduced by Hird and Yung (1989) and Shibuya et al. (1994). It was then adopted by Yimsiri and Soga (2011) and

Surarak et al. (2012). The resolution can be measured up to 0.00024%. However, there was no reported data on accuracy of radial proximity transducer.

Linear deformation transducer was also configured to measure radial strain by Hoque et al. (1997). Subsequently, radial LDT with resolution of 0.0007% was initiated by Lo Presti et al. (1995). Horizontal LDT which can be resolve to 0.0002% was developed by Zlatović and Szavits-Nossan (1999), the accuracy of LDT can be up to 0.004%.

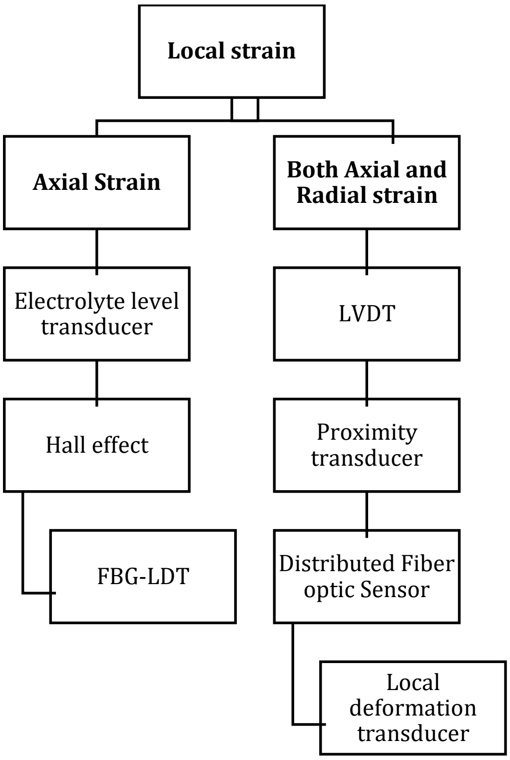

Fig. 11: Systems that can measure both radial and axial strain

5.1. Other local radial strain measuring techniques

Small strain measuring devices have been discussed in the previous sections. However, it is worth to mention other techniques of measuring local radial deformation. Lateral strain device with resolution of 0.04% was illustrated by El-Ruwayih (1976). Boyce and Brown (1976) illuminated that local radial strain can be measured using radial strain ring with resolution of 0.0005%. The use of lateral strain collar with resolution of 0.01% was demonstrated by Kolymbas and Wu (1989). Another technique of using resistance wire transducer was illustrated by Skopek and Cyre (1995). Comparatively, there is no much data regarding the accuracy of these devices in the literature.

6. Conclusion

A state of the art review of local strain instrumentation system in a triaxial testing apparatus for stiffness measurement at small strain is been presented succeeding Scholey et al. (1995) and Yimsiri and Soga (2002). The technology behind the transducers, the principle of operation, advantages and disadvantages of each technique including how they a mounted on the specimen were discussed. Comparatively, LVDT happened to be the most frequently used system among its counterpart. It has been employed severally to calibrated newly invented techniques especially the commercially available floating mini-LVDT as it can be employed to measure both local radial and axial strain.

This paper also discussed the trend of advancement of LDT and the transformation of the technology from electrical to fiber optics. Conjecture helical configuration from distributed fiber optics technology was examined. The selection of these instruments by the user is based on the application, requirements, availability and cost. It can be highlighted that development of local radial strain measuring instrumentation is still limited, which brings the need for more studies in this part.

Many other robust techniques that show potentials for use in measuring stiffness at small strain accurately are yet to be implemented. For instance, FBG sensing technology can be employed directly for determining deformation characteristic of materials in the laboratory. FBGs are used as strain sensors, temperature sensors pressure sensors, and for measuring flow rate because they have high resolution, high accuracy, high precision, multiplexing, multifunctional and are light in weight. They also have good resistance to lightning, electromagnetic interference, and electrical short circuiting.

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