Overview about rock mechanical lab testing – part III: sensors

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1 Introduction

Basic quantities, which have to be determined during rockmechanical lab testing are:

- Forces (stresses)
- Displacements (strains)

Besides that for specific tests additional parameters have to be determined like:

- Temperature
- Fluid pressure
- Fluid flow velocity
- Vibration velocity or acceleration

Sensors incl. connected data processing/storage units have different size, accuracy and sampling rate. They can deliver integral or local values of the tested samples. Therefore, they can be digitized and automated or work simply via manual reading.

Please note: this e-book considers only popular force (stress) and displacement (strain) sensors used for rockmechanical lab testing.

2 Load cells

Load cells measure the applied force. On can distinguish between different types:

- Strain gauge load cells
- Hydraulic load cells
- Pneumatic load cells
- Capacitive load cells
- Piezoelectric transducer based load cells

Note, that forces or pressure cannot be measured directly. Strain (displacement) or electric (voltage) is measured and transformed into mechanical stress (force) values based on a calibrated scale.

In rock mechanics with relatively high forces and high precision demand, load cells are typically based on strain gauges and the use of a Wheatstone bridge (see also chapter 5).

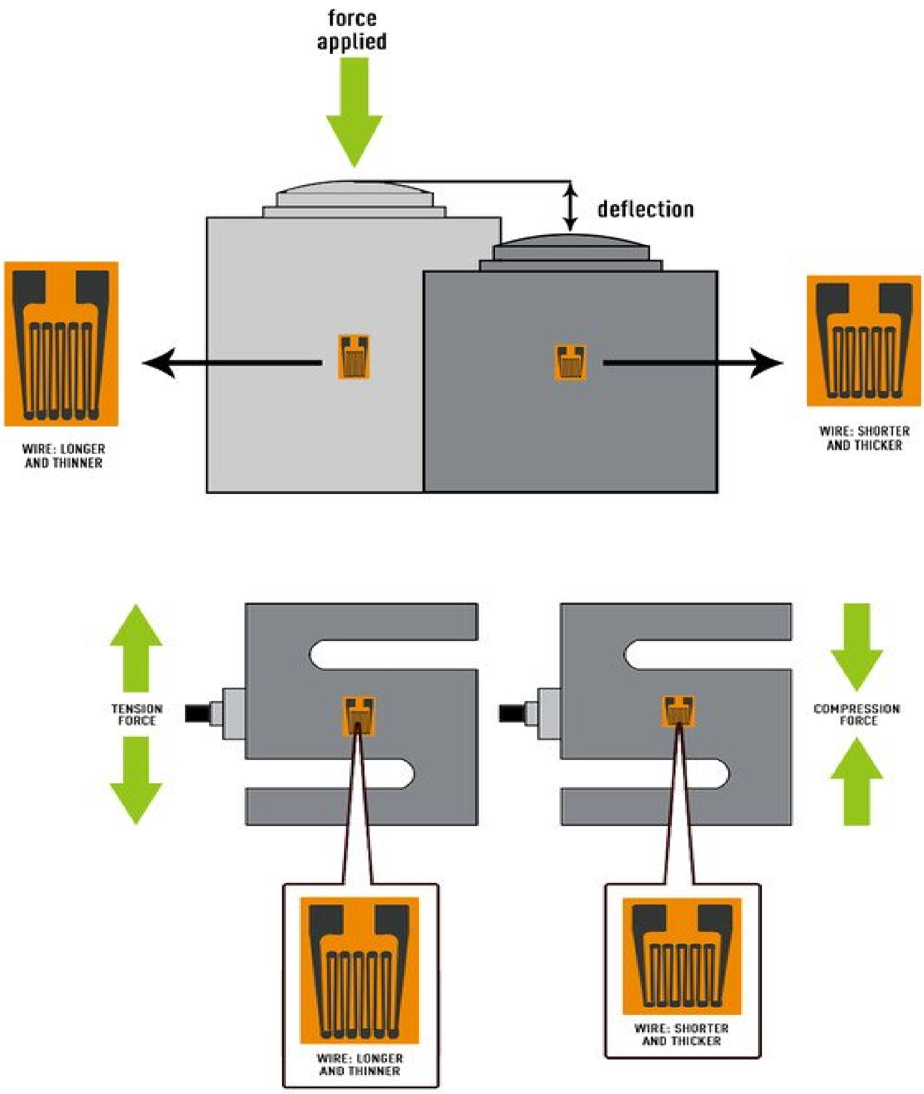

Fig. 2.1: Working principle of strain gauge based load cells (company material)

Fig. 2.2: Exemplary: different load cells (company material)

Because a lot of rockmechanical test machines use a hydraulic pressurization system, it is also possible to measure the hydraulic pressure via hydraulic pressure sensors. This is typical done inside the machine to controle the pressure regime (stress path) and to deliver machine data for later evalution. Another typical application is the circumferential hydraulic pressure control for classical triaxial testing (Karman chamber).

Fig. 2.3 illustrates typical hydraulic measuring principles.

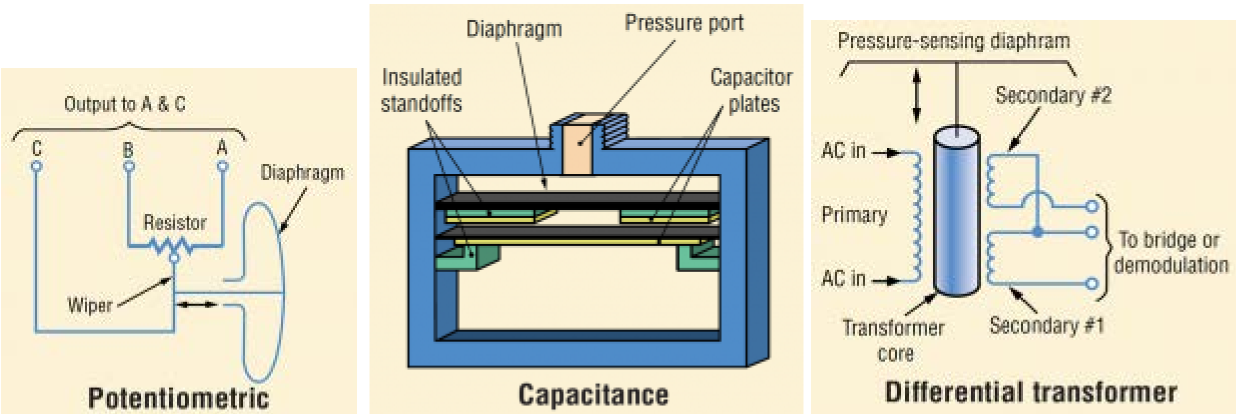

Fig. 2.3: Typical measuring principles for measuring hydraulic pressures (company material)

The accuracy of measurements (see also our e-book “Overview about field measurements in rockmass”) is basically determined by intrinsic technical components and the environmental conditions (e.g. temperature).

FSO (full-scale output) refers to the variation in the output signal the transducer performs over its calibrated range from minimum to maximum pressure at a specified temperature. Tolerance and temperature are generally given. Output, with maximum pressure applied and rated excitation, is FSO. Accuracy is typically given as plus or minus a percentage of

FSO, including the mathematically combined effects of linearity, hysteresis, and repeatability errors. Resolution refers to the smallest change in pressure that can be detected in the transducer's output. It is usually expressed as a percentage of FSO.

The accuracy of load cells is given in percent full scale output (FSO), also called rated output (RO). High precision load cells can reach an accuracy of about 0.01%.

Fig. 2.4 illustrates the different parameters related to the accuracy of the measurements, valid for both, stress (force) and strain (displacement) measurements.

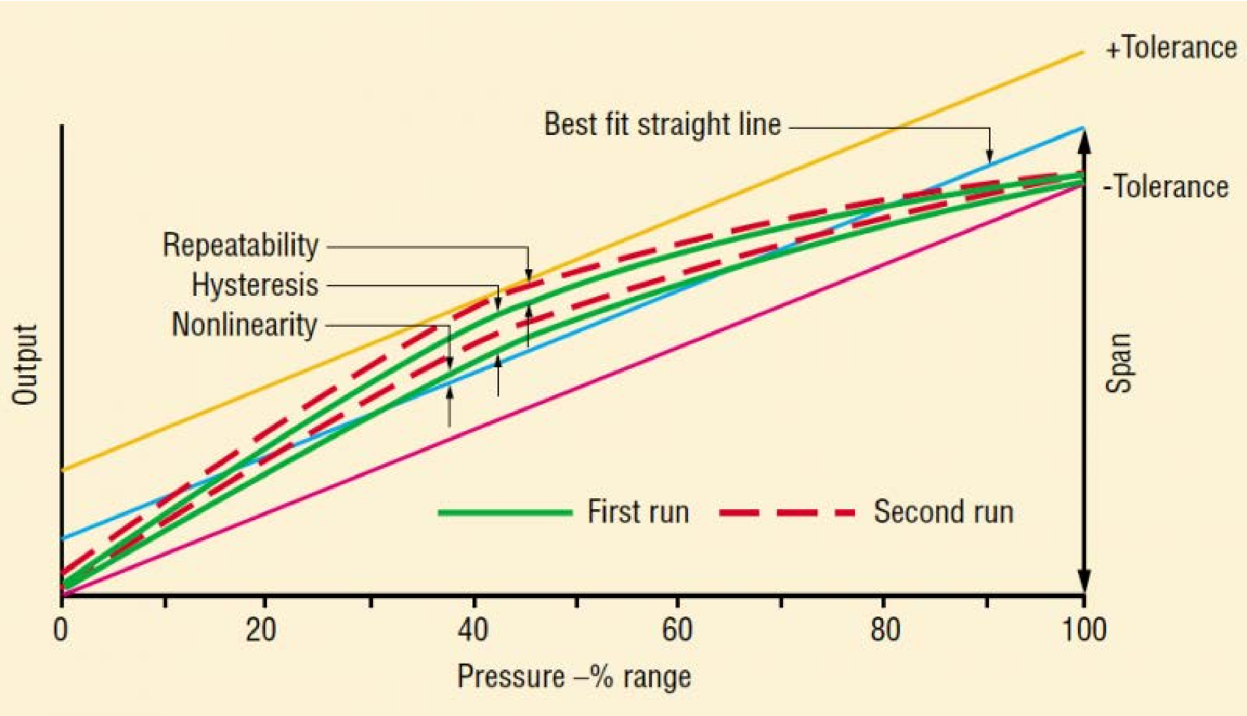

Fig. 2.4: Illustration of basic parameters determining the accuracy of measurements (company material)

3 Dial gauges

Dial gauges can be obtained in two different versions as:

- digital dial gauges
- analog dial gauges

The application range varies typically between 1 and 100 mm and the graduation varies between 0.01 and 0.001 mm. Instrumental error of such devices is in the order of ± 1µm.

The working principle (see Fig. 3.1) is as follows (mech4study, 2021):
"The prior component of the dial indicator, plunger carry a rack in its back and slides over the bearing to create the contact between rack and pinion. The plunger is attached within the dial indicator in such a way so that it can rotate to its axis. Therefore, for securing the precision level of the measurement, a pin can be used by operators to restrict the same. The pin is mounted by operators for guidance. Apart from that, the plunger remains at its position with the help of coil spring. Pinion at the rack made the connection between them and the gear rotates which is mounted on the same spindle. Hence, the gear and pinion are meshed with each other to magnify the measurement. After that, the second gear has meshed with the second pinion and those have meshed with the third pinion. Therefore, the process ends here and the magnification can be recorded by the operator."

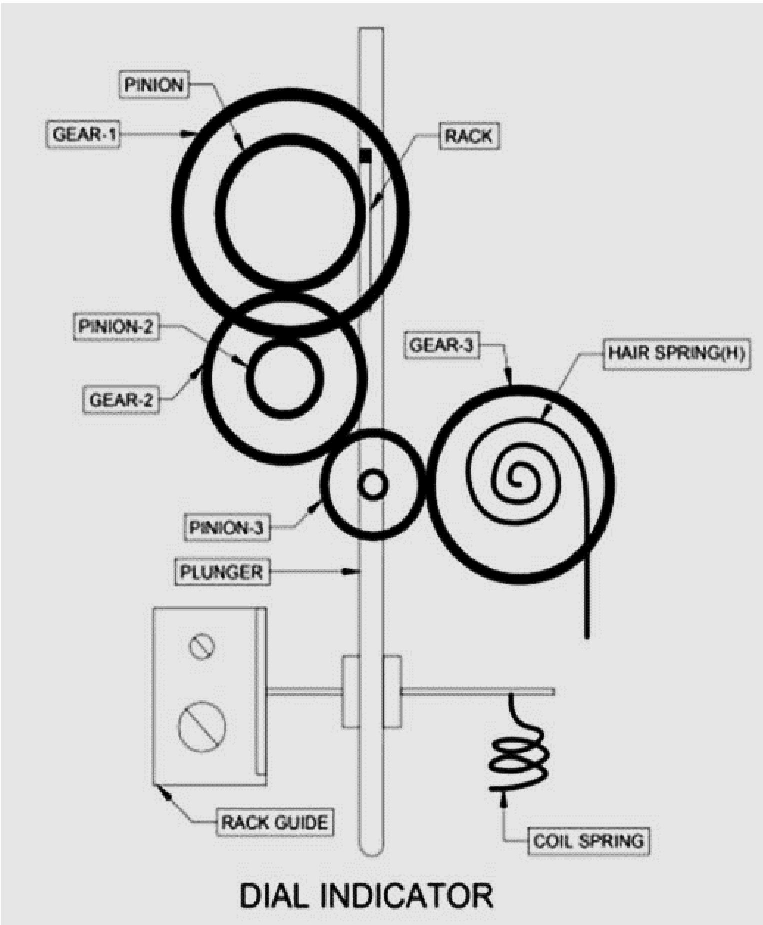

Fig. 3.1: Working principle of a dial gauge (mech4study, 2021)

Exemplary, Fig. 3.2 shows a digital and an analoge device and Fig. 3.3 illustrates the main components.

Fig. 3.2: Digital (left) and analog (right) dial gauges (company material)

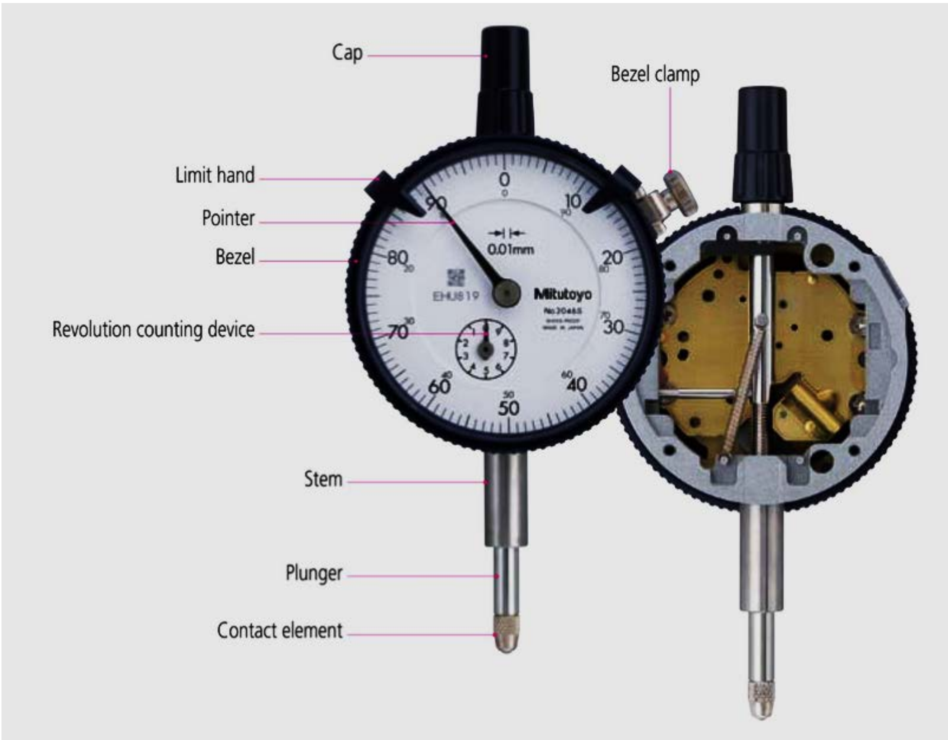

Fig. 3.3: Components of an analog dial gauge (company material)

4 LVDT's

LVDT's are used to measure displacements. Common LVDT (Linear Variable Differential Transformer) sensors used for rockmechanical tests have measuring ranges from about 1 mm up to about ± 25 mm. Resolution is in the order of 0.01%. Assembly and working principle are illustrated by Fig. 4.1 and 4.2. A LVDT is an electromechanical transducer. According to the position of the core - which is connected mechanically to the object under consideration – a differential voltage is induced between the two secondary windings (S1 and S2 in Fig. 4.2), which is correlated to the displacement of the core inside the bore.

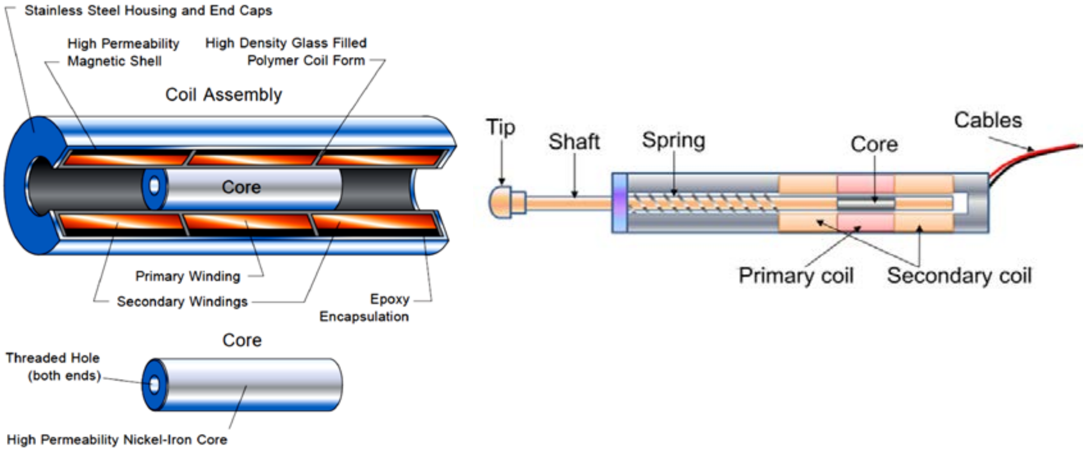

Fig. 4.1: Components of a LVDT device (company material)

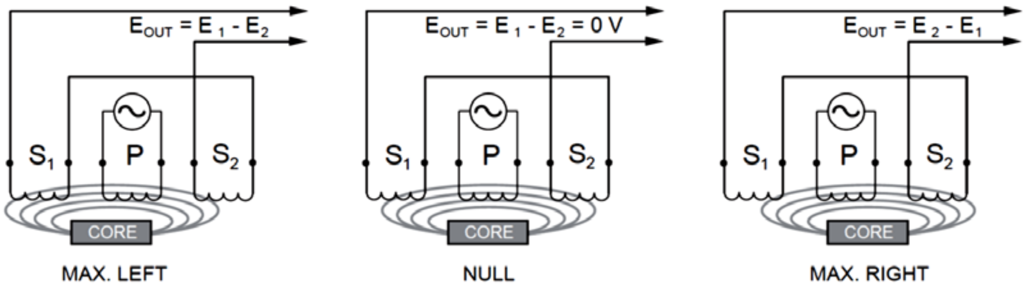

Fig. 4.2: Working principle of a LVDT device (company material)

Fig. 4.3: Examples of LVDT devices (company material)

5 Strain gauges

Strain gauges can be used to measure compressive or tensile strain.

Strain gauges are produced as either foil gauge or wire gauge. Foil gauges consist of a metallic alloy film laminated onto an insulating carrier. Wire gauges consist of a grid of fine wire sandwiched between very thin insulating membranes. This carrier serves as a support and protection for the grid and also as an electrical insulator between wire and test surface.

The basic construction of a gauge has an insulating flexible backing to support a metallic foil structure. This metallic coil is glued to a thin backing called a carrier. The entire setup is fixed to an object using a suitable adhesive. As the object is deformed under tension, compression or bending the electrical resistance of foil changes. A Wheatstone bridge measures the change in resistivity, which is related to strain through a quantity known as gauge factor (see Fig. 5.1).

The measuring is based on electrical resistivity change caused by deformations. However, also temperature changes can change the electrical resistivity. Therefore, temperature compensation should be performed. On the other side, strain gauges can also be used directly as temperature sensor.

Strain gauges are delivered in quite different size and design. Strain gauges with only one grid can measure deformation only in one direction. If more grids are applied, the complete 2-dimensional deformation field can be detected (see Fig. 5.2). Typical grid sizes vary between about 1 to 20 mm.

In most cases strain gauges are fixed to samples tested by a special glue. In this case the strain gauge is lost after finishing the experiment. However, they can also be installed in a permanent manner and act as force, torque or temperature measuring device like illustrated in Fig. 5.3.

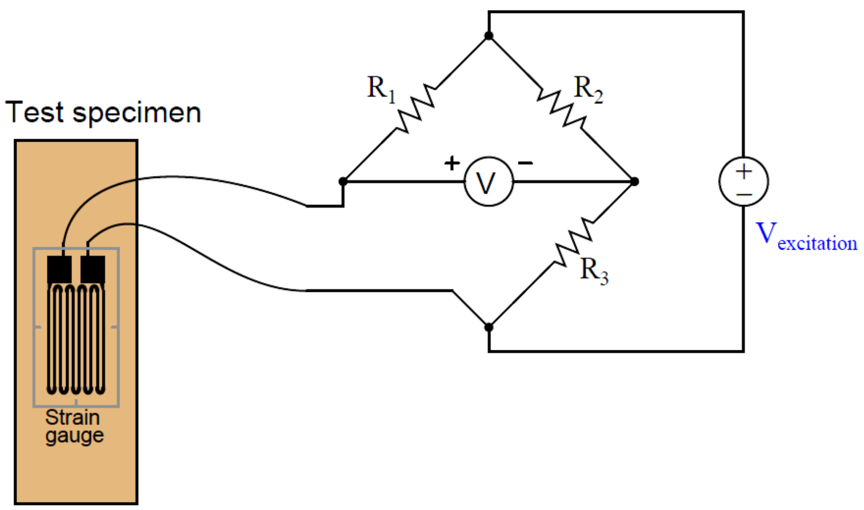

Fig. 5.1: Examples of LVDT devices (company material)

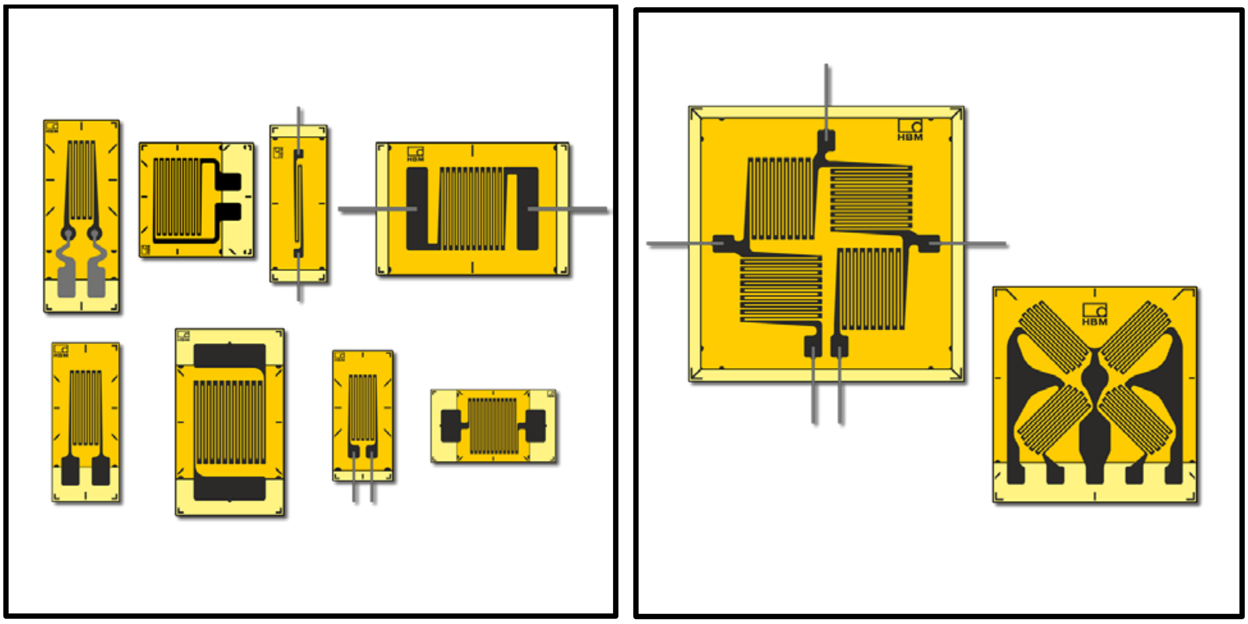

Fig. 5.2: Examples of strain gauges, left: one grid sensors, right: four grid sensors (company material)

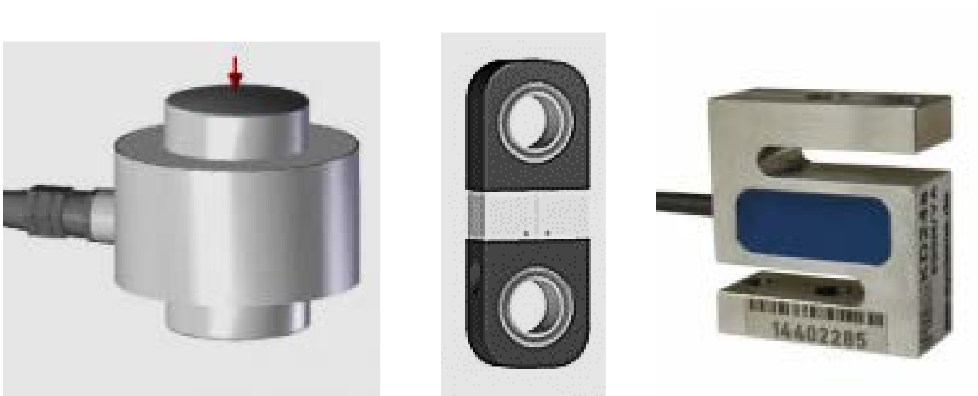

Fig. 5.3: Examples of strain gauges, left: one grid sensors, right: four grid sensors (company material)

6 Fiber optics

Fibre optical methods are becoming popular in several fields. Fenta et al. (2021) give an overview in respect to the use in geophysics. The optical fiber is an inhomogeneous medium. Scattering arises from microscopic or macroscopic variations in density, composition or structure of a material through which light is passing. The random ordering of the molecules and the presence of dopants cause localized variations in density (and therefore refractive index). These give rise to Rayleigh scattering which causes attenuation of the forward-propagating signal and creation of a backward-propagating wave. Fig. 6.1 shows the assembly of an optical fiber, which consists typically of 4 parts:

- Core
- Cladding
- Inner coating
- Outer couting

The spectrum of the scattered light (see Fig. 6.2) allows to define certain peaks, which are used as basic measuring value.

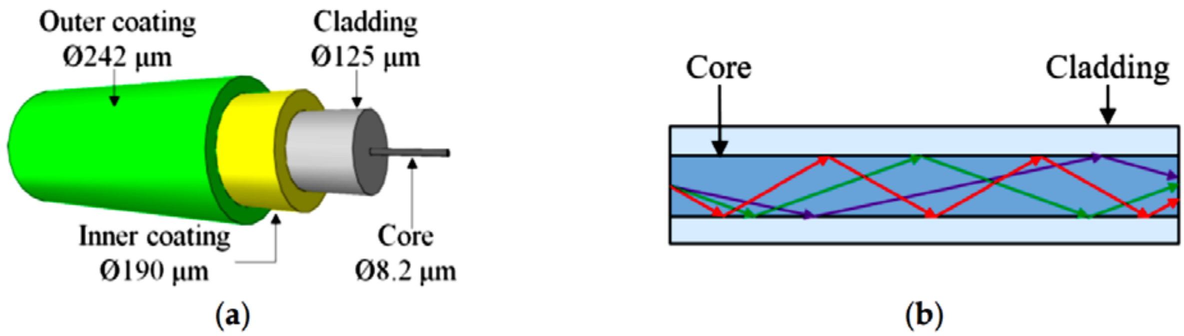

Fig. 6.1: Typical optical fiber assembly (a) and wave guide principle (b) (Bao et al., 2019)

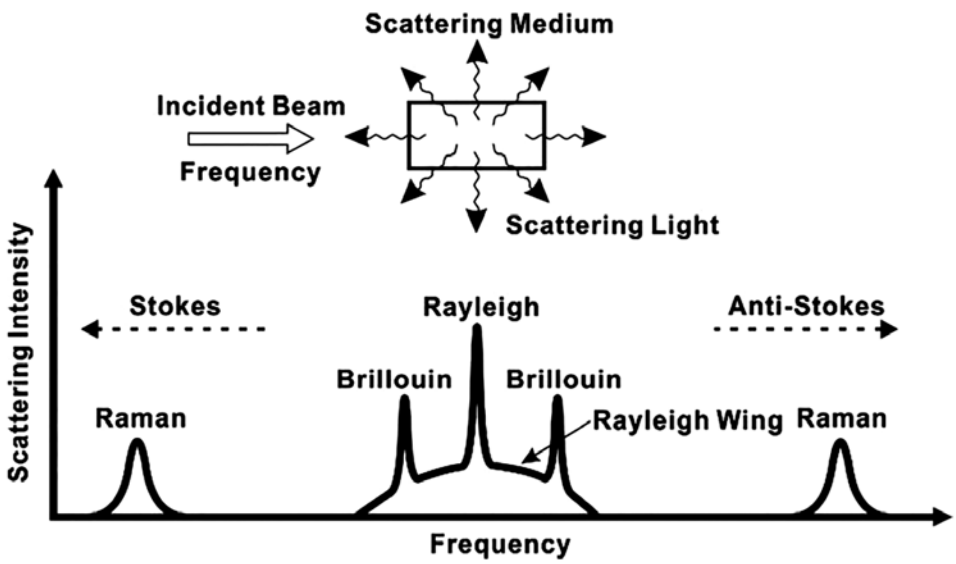

Fig. 6.2: Typical spontaneous light scatter spectrum (Lu et al., 2019)

Fig. 6.3 provides a general overview about all commom fiber optical sensors.

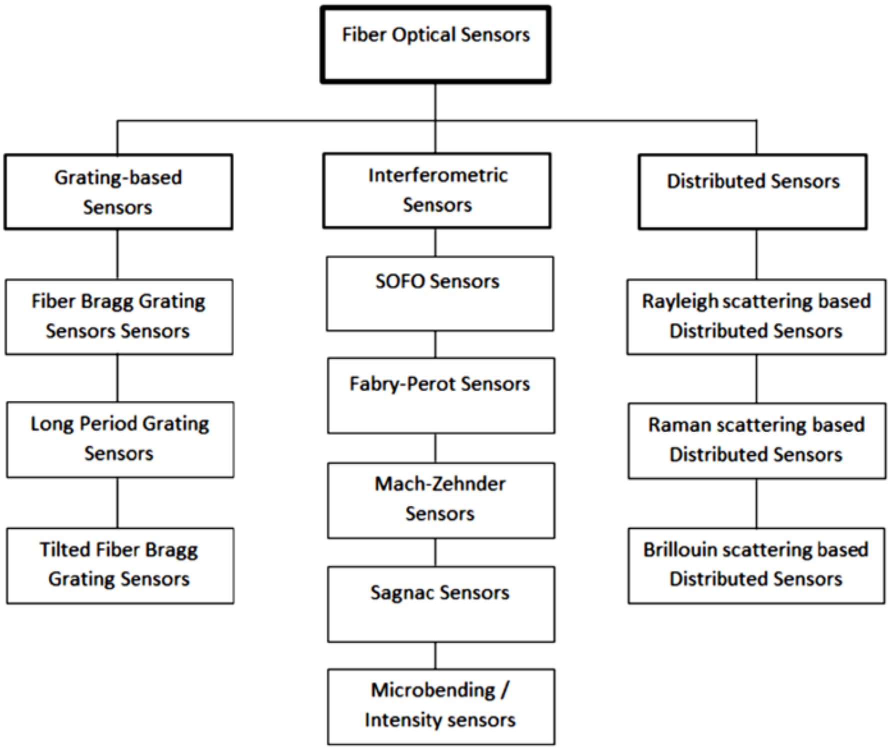

Fig. 6.3: Classification of fiber optic sensors (Guo et al., 2011)

According to Fig. 6.2 distributed sensor measurement techniques can be subdivided into:

- Rayleigh reflectometry (OTDR) based on Rayleigh scattering
- Raman reflectometry (ROTDR) based on Raman scattering
- Brillouin reflectometry (BOTDR) based on Brillouin scattering

Extremely important for correct measurements is the interaction of the different layers of the optical fiber and the connection of the fiber with the sample, especially in respect to the shear deformation at the interfaces like illustrated in Fig. 6.4

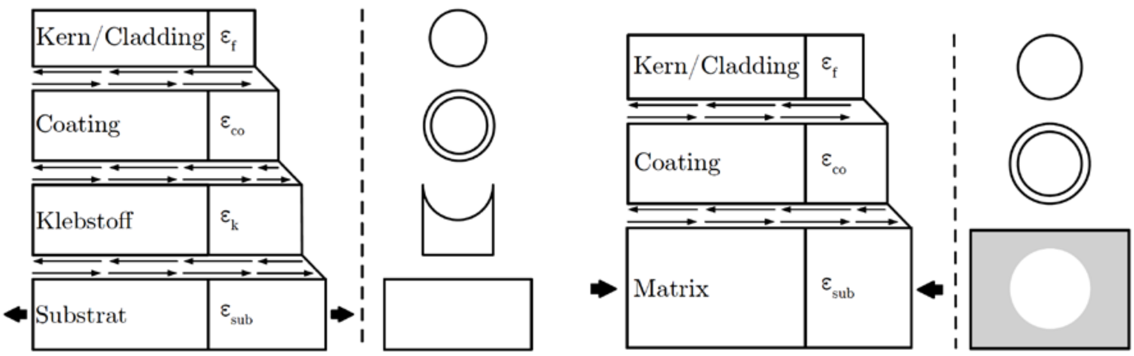

Fig. 6.4: Interface structure of optical fiber and sample (Weisbrich, 2020)

Two types of optical sensors are of special interest for rockmechanical lab tests:

- FBG (Fiber Bragg grating) as a distributed Bragg reflector constructed in a short segment of the optical fiber (see Fig. 6.5)
- Distributed optical fibers (e.g. Zhang et al. 2020; Xu et al. 2020), using the optical backscattering reflectometry (OBR) which allows a continuous measuring along the complete optical fiber (see Fig. 6.6 and 6.2)

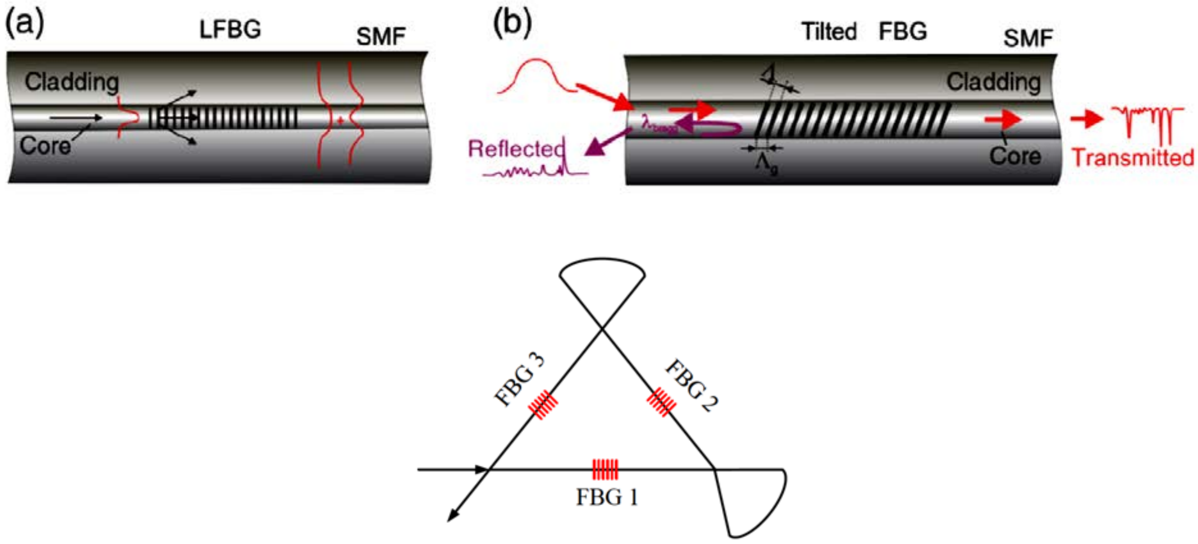

Fig. 6.5: Principle of FBG and application of rosette configuration of FBG sensors (Guo et al., 2011; Pevec & Donlagic, 2019)

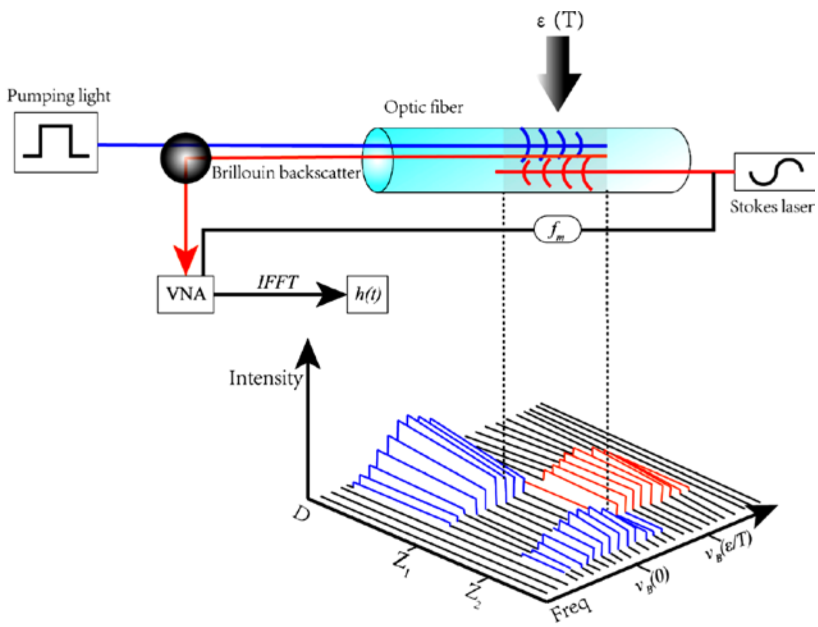

Fig. 6.6: Principle of Brillouin optical time domain reflectometer (BOTDR) (Xu et al., 2020)

Spatial resolution of optical sensors can go down to app. 1 mm. Accuracy in strain measurement can reach 10^{-6}. Sensing length can be several meters (for in-situ applications up to several km). Maximum strain recordable is in the order of 10^{-2}.

Multi-component optical sensors allow to combine strain and temperature measurements. This allows to compensate the influence of temperature on strain.

Exemplary, Fig. 6.7 illustrates the use of an OTDR technique to observe the surface deformation of a sandstone sample during uniaxial compression and Fig. 6.8 shows an FBG application.

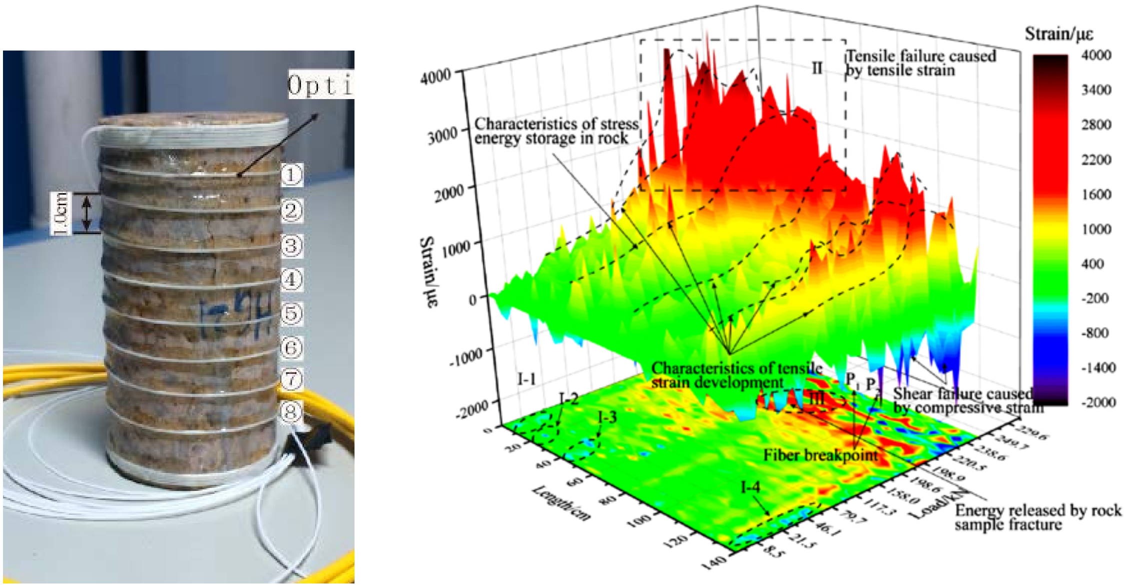

Fig. 6.7: Rock sample with optical fibre (OTDR) to measure surface strain to detect crack initiaition and propagation during uniaxial compression test (Xu et al., 2020)

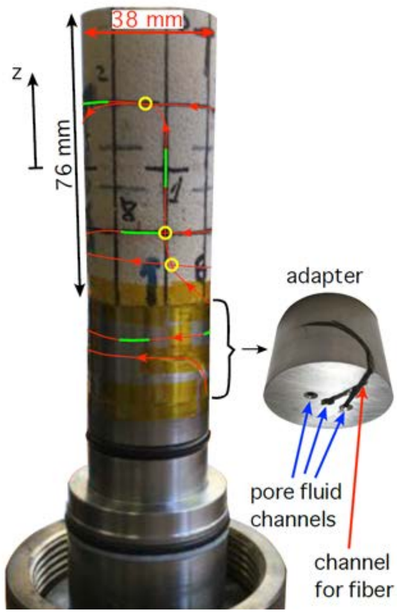

Fig. 6.8: Rock sample prepared with optical fiber (FBG) to conduct 3-axial compression tests, in green: FBG sensors (Kovalyshen et al., 2018)

7 Piezoelectic sensors

In general piezoelectric sensors are used in science and industry to measure:

- Force
- Torque
- Strain
- Pressure
- Acceleration
- Acoustic emission

Most applications of piezoelectric sensors rely on the produced voltage or the use of the spectrum of the signal. Both of them change, when pressure or strain is applied to the sensor. Strain measurements using the piezoelectric effect can be performed by (Sirohi & Chopra (2001)):

- Piezoceramics (PFZ)
- Piezofilms (PVDF)

Piezoelectric sensors show very small deformation when force is applied. They are characterized by very high stiffness. This results in a high resonance frequency, which, in principle, is very favorable in dynamic applications. Main applications are related to low strain levels, high noise level and high forces.

Piezoelectric sensors typically comprise two crystal disks with an electrode foil mounted in between. Applied force results in an electrical charge that can be measured using a charge amplifier. The charge is proportional to the applied force.

Exemplary, Fig. 7.1 illustrates a test where a piezoelectric sensor is used for strain measurement. Fig. 7.2 shows an application for force measurement. Fig. 7.3 shows different piezoelectric sensors used for lab testing.

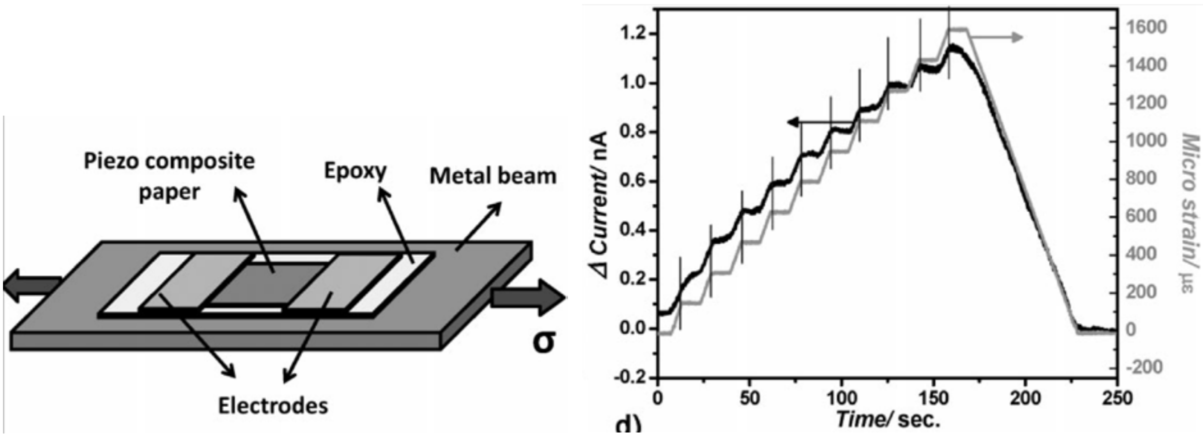

Fig. 7.1: Schematic depicting experimental setup and measured strain under static loading using a piezoelectric sensor (Gullapalli et al., 2010)

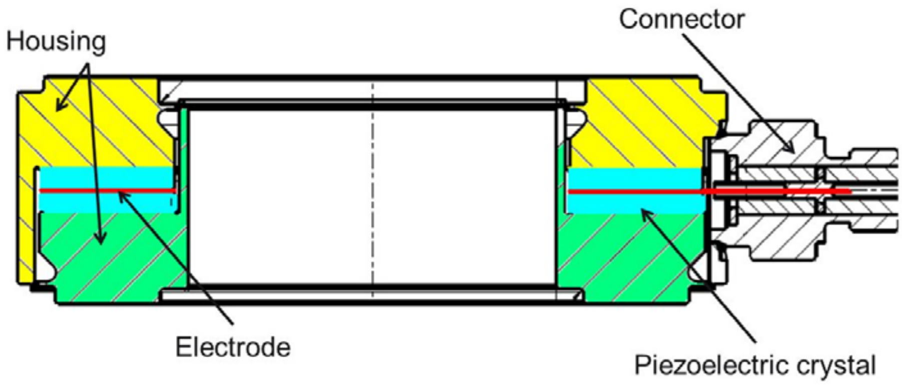

Fig. 7.2: Typical assembly of a piezoelectric force sensor (piezoelectric crystal in green) (Kleckers, 2013)

Fig. 7.2: Examples of piezoelectric sensors (company material, 2021)

8 References

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