
Alvaro Jesús Castro Caicedo

Universidad Politécnica de Madrid.
Escuela Técnica Superior de Ingenieros de Minas y Energía.
Madrid, España.
Diciembre de 2015.

Alvaro Jesús Castro Caicedo

Director:
Ph.D., Ricardo Laín Huerta.
Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros de Minas y Energía.

Codirector:
Ph.D. Pedro Torres Trujillo.
Facultad de Ciencias
Universidad Nacional de Colombia, Sede Medellín.

Universidad Politécnica de Madrid
Escuela Técnica Superior de Ingenieros de Minas y Energía.
Madrid, diciembre de 2015.
Acknowledgements

The author wishes to gratefully acknowledge the following people who have contributed to this work: Prof. Pedro Torres Trujillo; Prof. Ricardo Laín Huerta; Ing. German Castro Caicedo, Prof. Juan Felipe Santa, Ing. Jaime Castro Caicedo, Prof. Iván Sarmiento Ordosgoitia, Prof. Ángela B. Mejía, Prof. Jorge Iván Gómez, Prof. Juan F. Ramirez, Prof. Manuel Villarraga, Ing. Maria Julia Nieto, Ing. John Betancur Maya, Prof. Astrid Blandón, Ing. Eder Emery, Sr. Duvian Diaz, Sr. Jorge A. Osorio, Prof. Orlando Giraldo.

The author acknowledges to COLCIENCIAS and Universidad Nacional de Colombia Sede Medellín for the financial support, and the next laboratories of the this University: Laboratorio de Geotecnia, Laboratorio de Óptica, Laboratorio de Estructuras and Laboratorio de Carbones.
Dedicatoria

La alegría y la tristeza caminaron de la mano durante la elaboración de esta Tesis, no solo por las dificultades ya esperadas, sino también por la propia vida que sigue su camino de la mano del Creador.

Al Señor de la vida gracias por haberme dado la oportunidad de peregrinar en este camino, gracias por tener ahora en Su compañía a quienes partieron durante esta travesía, mi papi Claudio y mi hermano Jairo, partidas que agregaron a estas letras enseñanzas no menos valiosas.

Al Señor del amor, que con la llegada de Aurora nos devolvió la felicidad. Gracias a Él por la compañía de Yohana y Santiago, por mi mamy Marta, por mis hermanos y sobrinos, todos fuerza y vida.

A los maestros Jesus y Paramahansa Yogananda, guías de nuestro caminar, Jai Guru.
Abstract

Optical fiber sensors are a technology that has matured in recent years, however, further development for rock applications is needed. Rocks contain mineral particles and features larger than electrical strain gauges traditionally used in laboratory tests, causing the results to be unrepresentative.

In this work were designed, manufactured, and tested large area and curved shape strain gages, using fiber Bragg gratings in optical fiber (FBG) in order to obtain representative measurement on surface rocks samples containing minerals and structures of different compositions, sizes and directions. This reports presents the processes of manufacturing, mechanical characterization, calibration and evaluation under uniaxial compression tests on rock samples.

To verify the efficiency of rock deformation transmitted to attached sensor, it was also performed the analysis of the strain transfer including the effects of the bonding, the sample and the transducer.

The experimental results indicate that the developed sensor enables reliable measurements of the strain and its transmission from rock to sensor, appropriate for use in heterogeneous materials, pointing an interesting perspective for applications on irregular surfaces, allowing increasing at will the size and shape of the measurement area.

This research suggests suitability of the optical strain gauge for real scale, where traditional electrical systems have demonstrated some limitations.

Keywords: Strain. Rock. Uniaxial compression test. FBG. Fiber Bragg grating. Optical fibre sensors.
**Resumen**

Los sensores de fibra óptica son una tecnología que ha madurado en los últimos años, sin embargo, se requiere un mayor desarrollo de aplicaciones para materiales naturales como las rocas, que por ser agregados complejos pueden contener partículas minerales y fracturas de tamaño mucho mayor que las galgas eléctricas usadas tradicionalmente para medir deformaciones en las pruebas de laboratorio, ocasionando que los resultados obtenidos puedan ser no representativos.

En este trabajo fueron diseñados, fabricados y probados sensores de deformación de gran área y forma curvada, usando redes de Bragg en fibra óptica (FBG) con el objetivo de obtener registros representativos en rocas que contienen minerales y estructuras de diversas composiciones, tamaños y direcciones. Se presenta el proceso de elaboración del transductor, su caracterización mecánica, su calibración y su evaluación en pruebas de compresión uniaxial en muestras de roca. Para verificar la eficiencia en la transmisión de la deformación de la roca al sensor una vez pegado, también fue realizado el análisis de la transferencia incluyendo los efectos del adhesivo, de la muestra y del transductor.

Los resultados experimentales indican que el sensor desarrollado permite registro y transferencia de la deformación fiables, avance necesario para uso en rocas y otros materiales heterogéneos, señalando una interesante perspectiva para aplicaciones sobre superficies irregulares, pues permite aumentar a voluntad el tamaño y forma del área de registro, posibilita también obtener mayor fiabilidad de resultados en muestras de pequeño tamaño y sugiere su conveniencia en obras, en las cuales los sistemas eléctricos tradicionales tienen limitaciones.

**Palabras clave:** Deformación. Roca. Compresión uniaxial. FBG. Sensores de fibra óptica. Reads de Bragg.
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.1</td>
<td>Scheme of a device for measuring longitudinal and transversal strain on an rock test.</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Idealized deformation and stress states in rock specimen under uniaxial compression.</td>
<td>13</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Expected deformation and non-uniform deformation</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Displacement vector</td>
<td>15</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Scheme of a fiber optic cable.</td>
<td>16</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Outline of the different types of sensors</td>
<td>17</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Classification of FBG sensor types</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Principle of a Fiber Bragg grating operation</td>
<td>20</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>Schematic representation of an optical fiber sensor</td>
<td>22</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Schematic representation of the proposed FBG strain sensor</td>
<td>23</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Manufacturing of planar sensor packaging probes.</td>
<td>25</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Planar FBG sensor packaging</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>Curved longitudinal FBG strain sensor packaging</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>Curved transversal FBG strain sensor packaging</td>
<td>27</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>GRP sensor packaging specimen at testing machine</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Stress-strain curves for the FBG sensor packaging specimens</td>
<td>30</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Failure modes of some sensor packaging specimens</td>
<td>31</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>Uniaxial stress-strain curves for six rock types and mean stiffness of the manufactured strain sensor</td>
<td>31</td>
</tr>
<tr>
<td>Figure 4.11</td>
<td>Finite element model of the longitudinal strain in the FBG sensor packaging</td>
<td>33</td>
</tr>
<tr>
<td>Figure 4.12</td>
<td>Finite element model of the longitudinal strain in the FBG sensor packaging</td>
<td>33</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Static calibration device</td>
<td>35</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Static calibration of the #1 FBG packaging</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Static calibration of the #1 FBG packaging</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Static calibration of the #1 FBG packaging, relationship between strain measured by ESG and Bragg wavelength shift</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Static calibration of the #2 FBG packaging. Relationship between loading and strain measured by ESG</td>
<td>38</td>
</tr>
<tr>
<td>Figure 5.6</td>
<td>Static calibration of the #2 FBG packaging. Relationship between Bragg wavelength and strain measured by ESG</td>
<td>38</td>
</tr>
<tr>
<td>Figure 5.7</td>
<td>Static calibration of the #2 FBG packaging. Relationship between strain measured by ESG and Bragg wavelength shift</td>
<td>39</td>
</tr>
<tr>
<td>Figure 5.8</td>
<td>Quasi-static tensile test of the FBG sensor packaging</td>
<td>40</td>
</tr>
<tr>
<td>Figure 5.9</td>
<td>Quasi-static calibration of the FBG #1 specimen. Relationship between strain and loading</td>
<td>42</td>
</tr>
<tr>
<td>Figure 5.10</td>
<td>Quasi-static calibration of the FBG #1 specimen. Relationship between loading and Bragg wavelength</td>
<td>42</td>
</tr>
<tr>
<td>Figure 5.11</td>
<td>Quasi-static calibration of the FBG packaging. Relationship between Bragg wavelength shift and tensile strain measured by ESG</td>
<td>43</td>
</tr>
<tr>
<td>Figure 5.12</td>
<td>Quasi-static calibration of the FBG packaging. Relationship between loading and tensile strain measured by ESG</td>
<td>44</td>
</tr>
<tr>
<td>Figure 5.13</td>
<td>Quasi-static calibration of the FBG packaging. Relationship between loading and Bragg wavelength shift</td>
<td>44</td>
</tr>
<tr>
<td>Figure 5.14</td>
<td>Quasi-static calibration of the FBG packaging. Relationship between Bragg wavelength shift and tensile strain measured by ESG</td>
<td>45</td>
</tr>
<tr>
<td>Figure 6.1</td>
<td>Amphibolite rock sample with bonded FBG and ESG sensors</td>
<td>49</td>
</tr>
</tbody>
</table>
Figure 6.2. Thin section of the amphibolite rock sample. ................................................................. 49
Figure 6.3. Thin section of the amphibolite with epidote and titanite. .......................................... 50
Figure 6.4. Location of FBG and ESG strain sensors bonded to amphibolite sample. ...................... 51
Figure 6.5. Schematic of the experimental setup for rock uniaxial compression test with FBG and ESG
sensors.............................................................................................................................................. 52
Figure 6.6. Experimental set-up showing rock sample in the compression loading device. ............. 52
Figure 6.7. Graphical relationship obtained between loading and strain measured by ESG in the uniaxial
compression test.. .......................................................................................................................... 55
Figure 6.8. Relationship between axial strain and Bragg wavelength.............................................. 55
Figure 6.9. Relation between strain and Bragg wavelength shift obtained from FBG sensor.............. 56
Figure 6.10. Stress–strain curve obtained from ESG and FBG measurements.................................. 57
Figure 6.11. FBG surface bonded on a rock substrate ...................................................................... 58
Figure 6.12. Cross-sectional view and dimensions of the bonding layer and the optical fiber ....... 59
Figure 6.13. Relationship between bonding layer thickness and strain transmission rate ................60
Figure 6.14. Strain transmission rate for rock specimens. ............................................................... 60
Figure 6.15. FBG spectra by regular and irregular bonding layer thickness. .....................................61
Figure 7.1. The size effect in the uniaxial stress-strain curve..............................................................65
List of Tables

Table 2.1. Standard procedures related to compression tests of rock specimens........................................9
Table 4.1. Some features of FBG strain sensor packagings used for rock and concrete.................................24
Table 4.2. Mechanical properties of the GRP planar specimens under tensile tests. ......................................29
Table 4.3. Strain numerical results for central zone of the the glass fiber packaging specimens. .........................32
Table 5.1. #1 FBG specimen, static calibration measurements..................................................................................35
Table 5.2. #2 FBG specimen, static calibration measurements..................................................................................37
Table 5.3. #1 FBG specimen, quasi-static calibration measurements in tensile test. ...........................................41
Table 5.4. #2 FBG specimen, quasi-static calibration measurements in tensile test. ...........................................43
Table 5.5. Summary of the static and quasi-static calibration of the FBG sensors. ..............................................46
Table 5.6. Output strain ranges of the commercial Geokon FP 4000 FBG planar sensor. ....................................47
Table 6.1. Dimensions and material parameters for uniaxial compression test on rock sample.......................51
Table 6.2. Properties of the used electrical strain gauges. .....................................................................................52
Table 6.3. Uniaxial compression testing measurements on the rock sample......................................................53
1. Introduction

1.1 Motivation

The design and construction of rock structures by mining engineering, geotechnical engineering, and civil engineering, among others, requires the knowledge of mechanical properties of rock material, since they are important factors governing the behavior of structures in response to an applied load. Therefore, obtaining these parameters is of fundamental importance, and this can be done by means of laboratory or in situ tests.

Strain is a very important parameter to be measured in rock structures such as tunnels, slopes, foundations, dams, mining, and some others structures that require Structural Health Monitoring (SHM) in order to improve their design, construction and operation.

The uniaxial compression test of rock is probably the most widely performed test. It is used to determine the elastic properties and the strength of rocks. In the simplest version of this test, a cylindrical rock core is compressed between two parallel metal plates. The objective of this test is to induce a state of uniaxial stress in the specimen which produces deformation.

The use of fiber optic sensors (FOSs) has represented a major opportunity for SHM. Through modification of the fiber, the light traveling through the fiber can be made sensitive to the external environment. FOSs offer advantages over traditional sensing systems such as longer lifetime, immunity to electromagnetic interference, high sensitivity, multiplexing capability and remote sensing. Engineers and scientist can now perform measurements that were previously impractical or, in some cases, impossible with conventional sensors (Naseer Sabri, et al 2015).

Fiber Bragg grating (FBG) sensors have attracted a considerable amount of interest for use in optical-fiber sensing applications, such as quasidistributed measurements of strain, temperature, pressure, acceleration, etc. (Cusano et al 2011). In recent years there have been a number of research initiatives towards the development and deployment of FBG sensors for sensing applications in geotechnical engineering.

1.2 Objectives

The main objective of this work is to investigate the application of a strain sensor based on FBG suitable for rock specimens under uniaxial compression tests on laboratory. The possibility of application of this sensor to be attached on the surface of the rocks is evaluated through the following partial objectives:
• Define the characteristics of a strain sensor in order to overcome the difficulties inherent to inhomogeneity and anisotropy of rocks.
• Select the appropriate materials and manufacture the transducers under limited technological resources.
• To obtain experimental evidence in order to demonstrate application of the FBG sensor for hard rocks.

In recent years there have been a number of research initiatives towards the development and deployment of FBG sensors for sensing applications in geotechnical engineering. Schmidt-Hattenberger (2003) used surface-mounted FBG sensors in compression test of granite rock. A comparison of the strain results is given for mechanical extensometers based on cross-flexure strain gages and a noncontacting laser extensometer measuring system for benchmarking the FBG strain sensors. Bhalla et al. (2005) reviewed various available sensor technologies for rocks and underground facilities. The critical nature of the underground structures as well as their complex interactions and influences on the nearby ground structures make a strong case for pursuing active research and development in the area of SHM. Yang et al. (2007) compared FBG strain sensors against electrical strain gages (ESG) in compression tests of granite rock, but they did not consider the strain transfer between the rock, the bonding layer and the sensor packaging. Yang examined the feasibility of employing FBG and piezoelectric sensors for comprehensive monitoring of rocks. Multiplexed FBG sensors, surface bonded on the rock specimens, were used as strain and temperature sensors. Their performance was compared with conventional ESGs. Moore et al. (2010) used FBGs to monitor the long term relative displacement of fractures at the Randa rockslide site in southern Switzerland; sensors were grouted to boreholes that extended to fractures that had been previously been mapped and were prone to movement. Recently, Chai et al. (2011) reported a sensing network of 18 FBG incorporated into GFRP for monitoring the settlement of uncompacted strata. It is the first time that a FBG sensor is embedded into a 180-m deep stratum. In another study Gage et al. (2013) presented a new technique for monitoring in situ strains and temperatures in rock masses. Their design consists of pretensioned steel segments instrumented with FBG embedded into a grout. The grout is then embedded into a rock mass for long term deformation monitoring, similar to a traditional extensometer. Initial laboratory validation of their design proved to successfully measure strains in a quantitative sense. However, they note the importance of properly coupling the FBG strain sensor to the host rock material in order to obtain an accurate measure of strain.

Most of these studies focus on sensing and multiplexing capabilities of FBG sensors. Little attention has been paid to the packaging and bonding condition of these sensors for rocks. At this point it is
important to say that conventional FBG sensors are manufactured in planar configuration, which is not appropriate for the irregular surface of the rocks since an unacceptable bonding layer fails to transfer enough strain from the substrate to the FBG. Yung (2005) concluded that the thickness and Young’s modulus of the glue have little influence on the strain transmission when the thickness of the glue is less than the diameter of an optical fiber. On the other hand, Chih (2005) and Li (2009) developed an analytical model of bonding layer for a fiber bonded on a substrate. They found that the effectiveness of the strain transfer depends on the shear lag parameters, the shear modulus of the glue, the thickness of the bonding layer, and the bonding length. Recently, Torres (2011) presented a planar FBG sensor for SHM. Their study includes an analysis of the influence of the thickness and mechanical properties of the adhesive and configuration of the packaging on the accuracy of the sensor. They measured the reading errors and concluded that adhesive thickness values of 400 μm lead to error below 2.5%, and thickness around 1000 μm yield a reading error below 6%. More recently, Zhang (2014) demonstrated that the bonding layer is a direct factor in producing stress birefringence within FBGs and concluded that the bonding layer is the major limiting factor for the application of surface-bonded FBG sensors in large strain measurements—until 3000 με; therefore bonding materials and bonding processes deserve serious consideration.

The application of a sensor as here developed, with high curved area and high sensitivity, can be adapted to the irregularities of the rocks and offers an attractive alternative as sensor method for complex structures in rock engineering.
2. Literature review: Uniaxial Testing of Rock Samples in Elastic Compression

2.1 Introduction

Compression is an important load process in some of the main structures in rock materials; mining pillars, tunnel abutments, slopes, and others structures which require study of this process in order to improve their design, construction and operation. The compression process produces stresses and strain in the rocks, these important mechanical effects could be studied in situ or in laboratory tests.

In laboratory, the uniaxial compression of cylindrical specimens prepared from a drill core is probably the most widely performed test on rock. It is used to determine the uniaxial or unconfined compressive strength and the elastic constants: Young’s modulus E, and Poisson's ratio of the rock material. The uniaxial compressive strength of the intact rock is used in rock mass classification schemes and as a basic parameter in the rock mass strength criterion.

Despite its apparent simplicity, great care must be taken in interpreting the results obtained in the test (Brady & Brown, 1985); the observed response will depend on the nature and composition of the rock and on the condition of the test specimens. Consequently, the mechanical properties of rock vary not only among different rock types but also between different specimens of the nominally same rock. Hence, unlike engineering materials such as steel, for which property values can be measured and listed on standard specimens, only very rough approximate values of the mechanical properties of a given rock can be estimated from tabulated handbook data (Jaeger, et al 2007). For this reason, laboratory testing necessarily plays a major role in rock mechanics.

In the simplest version of this test, a cylindrical rock core is compressed between two parallel metal platens (Fig. 2.1). Hydraulic fluid pressure is typically used to apply the load. The objective of this test is to induce a state of uniaxial stress in the specimen which produces deformation, i.e. the axial stress is the controlled independent variable and the axial strain is the dependent variable.
Figure 2.1. Scheme of a device for measuring longitudinal and transversal strain on a rock test cylinder, A: Load cell, B: Steel spacer, C: Rock sample, D: Spherical seat, E: Displacement transducer. (Adapted from Pariseau, 2007).

Longitudinal strain can be measured by a strain gage glued to the lateral surface of the rock. Alternatively, the total shortening of the core in the direction of loading can be measured by an extensometer that monitors the change in the vertical distance between the platens. In this case, the longitudinal strain is calculated from the relative shortening of the core, that is \( \varepsilon = \frac{d_l}{l} \). Because the stress level is measured, then the Young’s modulus of the rock could be estimated from \( E = \frac{\sigma}{\varepsilon} \). The stress can be increased until failure occurs; the stress at which the rock fails is known as the Uniaxial Compressive Strength of the rock, UCS.

### 2.2 Laboratory Standard Test and Procedure

The most widely used standard techniques for determining the Uniaxial Compressive Strength and deformability of rock material are given by the International Association for Rock Mechanics (ISRM 1979) and by the ASTM International, formerly known as the American Society for Testing and Materials.

Preparation and verifying of the rock specimen is needed before the compression test; similarly, relating standard terminology relating must be applied; a compilation of the standards techniques to be used in this work are listed in the Table 2.1.
Table 2.1. Standard procedures related to compression tests of rock specimens.

<table>
<thead>
<tr>
<th>Standard Name</th>
<th>Standard Code</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vocabulario de términos básicos y generales en metrología.</td>
<td>NTC 2194</td>
<td>Spanish terminology relating to metrology.</td>
</tr>
<tr>
<td>Standard terminology relating to soil, rock, and contained fluids.</td>
<td>ASTM D653</td>
<td>Terminology relating to rock.</td>
</tr>
<tr>
<td>Preparing rock core as cylindrical test specimens and verifying conformance to dimensional and shape tolerances.</td>
<td>ASTM D4543</td>
<td>Preparing rock specimens.</td>
</tr>
<tr>
<td>Compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures.</td>
<td>ASTM D7012-10</td>
<td>Compressive strength and elastic modulus of rock.</td>
</tr>
<tr>
<td>Ensayos para la determinación de la resistencia. Parte 3: Determinación del módulo de elasticidad (Young) y del coeficiente de Poisson.</td>
<td>Norma española UNE 22-950-90</td>
<td></td>
</tr>
</tbody>
</table>

The essential features of the recommended procedure are:

a. Test specimens should be right circular cylinders having a height to diameter radius from 2 to 2.5 under ASTM standards and from 2.5 to 3 under ISRM standards, and a preferred diameter not under 50 mm. The specimen diameter should be at least 10 times the size of the largest grain in the rock.

b. The ends of the specimens should be flat to within 0.02 mm and should not depart from perpendicularity to the specimen axis by more than 0.001 radian or 0.05 mm within 50 mm.

c. The sides of the specimen shall be smooth and free of abrupt irregularities and straight to within 0.3 mm over the full length of the specimen.

d. The use of capping materials or end surface treatments other than machining is not permitted.
e. Specimens should be stored for not longer than 30 days, in such a way as to preserve the natural water content, and tested in those conditions.

f. Load should be applied to the specimen at a constant stress rate of 0.5 to 1 MPa/s.

g. Axial load and axial and radial or circumferential strains or deformations should be recorded throughout each test.

h. The number of specimens tested should be determined from practical considerations but at least five are preferred.

i. The specimen should not contain geological discontinuities.

### 2.3 Suggested Standards for Measurement of Strain and Deformation

ASTM Standards suggests that deformations or strains may be determined "from data obtained by electrical resistance strain gages, compressometers, linear variable differential transformers (LVDTs), or other suitable means" (ASTM D7012-10). The same Standard says: "The strain/deformation measuring system shall measure the strain with a resolution of at least 25×10⁻⁶ strain and accuracy within 2% of the values of readings above 250×10⁻⁶ strain and accuracy and resolution within 5×10⁻⁶ for readings lower than 250×10⁻⁶ strain, including errors introduced by excitation and readout equipment. The system shall be free from non-characterized long term instability (drift) that results in an apparent strain of 10⁻⁸/s or greater."

The design of the measuring device shall be such that the average of at least two axial strain measurements can be determined. Measuring positions shall be equally spaced around the circumference of the specimen, close to midheight. The gauge length over which the axial strains are determined shall be at least ten grain diameters in magnitude.

The lateral deformations or strains may be measured by any of the methods mentioned above. At least two diametric deformation sensors shall be equally spaced around the circumference of the specimen close to midheight. The average deformation (or strain) from the diametric sensors shall be recorded.

The use of strain gages adhesives requiring cure temperatures above 65°C is not allowed unless it is known that microfractures do not develop and mineralogical changes do not occur at the cure temperature.

Axial strain and lateral strain shall be obtained directly from strain-indicating equipment or shall be calculated from deformation readings, depending on the type of device employed. Strain readings shall be recorded to six decimal places.
Axial strain shall be calculated as follows:

$$\epsilon_a = \frac{\Delta L}{L}$$ \hspace{1cm} (1)

Where:

L = original undeformed axial gage length, and

\(\Delta L\) = change in measured axial gage length.

Lateral strain shall be calculated as follows:

$$\epsilon_l = \frac{\Delta D}{D}$$ \hspace{1cm} (2)

Where:

D = Original undeformed diameter.

\(\Delta D\) = change in diameter, with positive sign for increase in diameter.

The stress versus strain curves shall be plotted for the axial and lateral direction. The complete curve gives the best description of the deformation behavior of rocks having nonlinear stress-strain relationship at low and high stress levels.

The value of Young’s modulus E shall be calculated using any of several methods employed in engineering practice. The most common methods are as follows:

Tangent modulus at a stress level represented by some fixed percentage (usually 50%) of the maximum strength.

Average slope of the nearly straight-line portion in the stress-strain curve. The average slope shall be calculated either by dividing the change in stress by the change in strain or by making a linear least square fit to the stress-strain data in the straight-line portion of the curve.

Secant modulus, usually from zero stress to some fixed percentage of maximum strength.

The value of Poisson’s ratio \(\nu\) is greatly affected by nonlinearities at low-stress levels in the axial and lateral stress-strain curves. It is desirable that Poisson’s ratio be calculated from the following equation:

$$\nu = \frac{\text{slope of axial curve}}{\text{slope of lateral curve}}$$

or

$$\nu = \frac{E}{\text{slope of lateral curve}}$$
Where the slope of lateral curve is determined in the same manner as it was done for Young’s modulus.

2.4 Factors Affecting Rock Strain Under Compressive Loads.

The deformation of the rock specimen under compressive loads is influenced by the conditions of the rock and by the test conditions. These factors can be classified as the properties of the rock sample (rock conditions) and the geometrical factors that are reflected on stress distribution on the specimens. Factors on which the uniaxial strain depends are as follows:

- Length of the specimen on stress distribution.
- Effect of friction between platens and specimen end surfaces.
- Effect of specimen geometry: shape, size and height/diameter ratio (H/D).
- Rate of loading on the specimen.
- Rate of strain.
- Effect of intrinsic rock properties: moisture content, mineralogy, porosity, weathering, microfissuring and density of the rock.

2.5 Rock Conditions

a. Moisture: The ASTM D 653 defines moisture contents the percentage by weight of water contained in the pore space of a rock with respect to the weight of the solid material. The ASTM and ISRM standards suggest testing rock at natural moisture conditions; therefore it is necessary to perform the tests as quickly as possible after sample collection, especially for rocks like mudstone, claystone and other argillaceous rocks due to disintegration originated by desiccation.

b. Mineralogy: According to Singh and Ghose (2006) the rocks containing quartz as a binding material are the strongest, followed by those with calcite and ferrous minerals, and rock grains bound by clay as binding material are the weakest. The higher the quartz content in the rock the greater its strength.

c. Grain size: Brace (in Singh and Ghose, 2006) reported that the strength of rock is greater from the finer to the medium size grain in comparison to the coarse grained rock.

d. Density: It has been observed that the denser the rock, the higher is its compressive strength.

e. Porosity: weathering, microfissuring: In general, compressive deformability decreases with the increasing in rock porosity (Brady & Brown, 2005), increasing in degree of weathering an increasing in degree of microfissuring.
2.6 Stress Distribution on Cylindrical Specimens

Tang and Hudson (2010) showed than one of the most important effects in the stress distribution is the specimen Height/Diameter ratio or slenderness. Both the loading plates and the specimens will deform when compressive stress is applied. This loading condition causes a multi-axial stress state near the contact zone between the specimen and the loading platen, which can affect the overall specimen behavior. The stress states in the specimens and the failure modes are shown in an idealized form on Figure 2.2. Due to this elastic mismatch between the platen and the specimen, the lateral deformations in the platen and specimen, are different. As a result, some friction between the platens and specimen ends will occur. This friction may cause either a lateral confining compressive stress at the specimen ends if $Ep/Es > 1$ (a stiffer constrain) or a lateral tensile stress at the specimen end if $Ep/Es < 1$ (a softer constrain) where $Ep/Es$ is a Young Modulus platen/Young Modulus specimen ratio.

These effects reach their maximum at the ends of the specimen and decrease from the ends toward the specimen center. So, two cones of compression develop in the specimen when stiffer constraint occurs and, consequently, fewer fractures are expected to appear in these cone-shaped zones. On the other hand, two cones of tension will develop when softer constraint is applied and more fractures are expected, resulting in a splitting failure mode in the specimen. Since the axial stress field in the specimen is thus not uniformly distributed, radial tension develops specially in the outer perimeter closer to the middle part of the specimen for stiffer constraint, and a layer in this area may buckle outward resulting in lateral tensile failure. The appearance of a thicker layer in the middle that
becomes thinner at the ends, reflecting the geometry of the two compression cones at the ends, can be predicted. For softer constrains the situation is completely different. Although the ideal compression test searches a uniform deformation and, as said before, the real compression test induces a non-uniform deformation on the rock specimen; Figure 2.3 shows the initial and the resulting final deformation produced by the compression load.

![Figure 2.3. Expected deformation and non-uniform deformation obtained by restraints influences on stresses and displacements induced in a uniaxial compression test. a) Initial situation. b) Deformation with complete radial restraint at the specimen-platen contact.](image)

2.7 Displacement and Strain

The fundamental kinematic variable in mechanics of rigid bodies is the displacement which is the vector quantifying the change in the position of a given particle of rock. If the position related to some coordinate system is taken as the rock "initial" state, this position can be denoted by \(X=(x,y,z)\). If loads are then applied to the rock, causing the rock particle, initially located at point \(X\), to be displaced to a new position \(X^*=(x^*, y^*, z^*)\). The vector that connects the original and the final position is known as the "displacement at \(X\". This vector is denoted by \(u\), and its components are \((u, v, w)\). The displacement vector must be defined by:

\[X^*=X-U,\text{ that is, } x^*=x-u,\ y^*=y-v,\ z^*=z-w.\]
To solve rock mechanics problems such as mine closure, surface subsidence above mines or tunnel convergence, it is necessary to study the displacements based on knowledge of applied surface tractions and body forces, and the boundary conditions. To do this, it is necessary to introduce a quantity known as strain. The reason is that the stresses are directly related to the strains than to the displacements themselves.

Strain is a measure of the relative displacement of nearby particles, rather than a measure of their absolute displacement. The concept behind strain can be introduced in a one-dimensional context (Figure 2.4). Consider a short bar, with an initial length \( L \), which left edge is initially located at point \( x \), and which right edge is located at point \( x + \Delta x \). This bar initial length is given by \( L = \Delta x \). This bar is now deformed, such that its left edge moves to the position \( x - u(x) \) and its right edge moves to the position \( [x + \Delta x] - u(x + \Delta x) \). The new length of the bar is equal to \( L^* = [x + \Delta x] - u(x + \Delta x) - [x - u(x)] \). We now define the mean strain for this bar as the fractional decrease in the length of the bar, that is,

\[
\varepsilon = \frac{L - L^*}{L} = \frac{\Delta x - [x + \Delta x] - u(x + \Delta x) - [x - u(x)]}{\Delta x} = \frac{u(x + \Delta x) - u(x)}{\Delta x}
\]

According to this definition, the strain will be a positive number if the bar becomes shorter.

The strain at the point \( x \) can be found by taking the limit of an infinitesimally short bar, which is mathematically equivalent to letting the initial length of the bar reaching zero:

\[
\varepsilon(x) = \lim_{\Delta x \to 0} \frac{L - L^*}{L} = \lim_{\Delta x \to 0} \frac{u(x + \Delta x) - u(x)}{\Delta x} = \frac{du}{dx}
\]

The strain is seen to be related to the spatial derivative of the displacement. The strain discussed above is called normal strain, and can be generalized to two or three dimensions; however in higher dimensions other types of strains occurs, those are called shear strains, which measure angular distortion, rather than stretching.

3.1 Introduction

Optical fibers have thicknesses ranging from microns to thousands of microns in diameter and use their optoelectronic properties to generate signals indicative of external physical parameters to be measured.

The first photosensitive fiber effect was observed in silicon dioxide (SiO$_2$) doped with germanium, in works conducted by Hill in the Communication Research Center in Canada in 1978, using as light source an argon laser. The physical process consists basically of the incident light in fiber being partly reflected and partly refracted; the variation in the refractive index is then measured and provides the possibility of being established as a standard for many types of physical changes.

At the beginning, optical fiber applications focused on telecommunications. Later, their potential both as intrinsic sensors, -in which the fiber behaves as a sensor itself- and as extrinsic sensors, in which the fiber transmits light from the measured parameter and detection system or in which the sensor is deposited on the fiber-was found.

![Figure 3.1. Scheme of a fiber optic cable.](image)

The Fiber Optics Strain Sensor -FOSS- are highly suitable for monitoring the status of civil structures- on the Structural Health Monitoring, SHM- and geological structures, due to their accuracy which is very convenient in the long term. There is a wide range of applications and technologies FOSS, being an attractive option in cases where it offers superior performance when compared with conventional sensors. According to Geotechnical Instrumentation News (2007) (http://www.bitech.ca/instrumentation_news.php) an additional value for this type of sensors is their better quality and reliability of the measurements, the possibility of replacing manual readings with automated measurements, easy installation and maintenance.
Nowadays four FOSS technologies are considered to have reached a high level of maturity due to their applications in structural and geotechnical monitoring, these technologies are outlined in Figure 3.2.

a. Point sensors Fabry-Perot type, which offers a single measure at the end of the cable. Figure a.
b. Multiplexed sensors, which allow multiple measurements along the line of fiber Bragg grating FBG case. Figure b.
c. Long-base sensors, measured on the length, they are also called long-gauge sensors, such SOFO. Figure c.
d. Distributed sensors, adapted for measurements at several points along a single strand of fiber, can reach several meters long, possibly miles, Brillouin and Raman type. Figure d.

![Figure 3.2. Outline of the different types of sensors. a. Fabry-Perot sensors. b. Fiber Bragg Grating sensors. c. SOFO sensors. d. Brillouin & Raman sensors.](image)

The classification of fiber optic sensors can be made according to several criteria, as shown in Figure 3.3:

a) According to the function performed by the optical fiber:

Extrinsic fiber optic sensors: optical fiber is used only for transportation of light that is modulated in an external element under the action of the measured variable.

Intrinsic fiber optic sensors: the measurand affects the optical characteristics of the fiber. The changes can be induced in the light intensity, phase, or polarization.
One can also distinguish transmission sensors (top row) and reflection sensors (bottom row). The former are simpler in structure because no couplers are required to separate forward and backward traveling light. The latter are more convenient to use, because only one end of the fiber needs to be accessible.

b) According to the optical modulation type used:

Fiber-optic sensors based on amplitude or intensity modulation. The amount of light detected is a function of external disturbances, they use optical and simple circuits, they can also use an incoherent light source such as an LED or an incandescent light source with a cheaper high-intensity multimode fiber. They are the most widespread commercial sensors.

Fiber-optic sensors based on phase modulation. Interferometric techniques are used to detect the measured variable. They have several advantages, such as: geometric flexibility, immunity to electromagnetic interference, large bandwidth and high resolution (e.g. a displacement sensor based on amplitude modulation can have a resolution of $10^{-10}$ and $10^{-7}$ m resolution, while sensor based on interferometric techniques can have a resolution of $10^{-14}$m.)

c) According to their application:

-Physical fiber optic sensors: temperature measurement, pressure, displacement, flow, rotation, etc.
-Chemical fiber optic sensors: measurement of pH, gas analysis, spectroscopy, etc.
-Biomedical fiber optic sensors: measurement of glucose, blood tests, etc.
A fiber optic sensor system generally have a light source, a fiber optic interface, a modulator that alters the light in proportion to the disturbance (physical quantity to measure) and an optical detector that detects and measures changes in the light of fiber, displaying an electrical signal at its output, which is processed electronically.

The physical quantity to be measured alters the optical fiber parameters: refractive index, light absorption coefficient, linear dimensions. This alteration is due to physical phenomena from different nature: electro-optic, magneto-optical, piezo-electric, acoustic-optic, piezo-optical, etc. The modulator converts the change in the fiber optical parameter into a change in the parameter of the optical signal transmitted by the fiber. There may be a shift in amplitude, phase, rotation of the polarization plane, or wavelength of the optical signal.

### 3.2 Principle of Optical Fiber Bragg Gratings as Strain Sensors

FBG are fabricated by inscribing periodic or quasi-periodic variations of the refractive index in the silica (SiO₂) fiber core, usually based on simple exposure to spatially modulated ultraviolet radiation along a piece of fiber.

In a single mode optical fiber, light travels in the fundamental mode along the fiber axis. The main characteristic of the FBG is the selective reflection of a very narrow band of wavelengths as shown in Fig. 3.4. The light that meets the Bragg’s condition is reflected significantly, while the other spectral components are transmitted through the FBG structure without suffering appreciable attenuation levels.

The wavelength that satisfies the condition of maximum reflection, called the Bragg wavelength, \( \lambda_B \), is given by the expression

\[
\lambda_B = 2n_{eff} \Lambda
\]

(1)

where \( \lambda_B \) is the Bragg wavelength, \( n \) is the effective refractive index of FBG fundamental mode and \( \Lambda \) is the grating period.

When the Bragg condition is satisfied, reflections from each successive period will be in the phase. Light that does not satisfy the Bragg condition passes through the FBG as if it belonged to the uniform refractive index \( n \). All these situations are represented in the Figure 3.4.
Maul & Kipp (2007) declare fiber Bragg Gratings are appropriate for sensing strain because the grating period \( \Lambda \) itself serves as flexible length scale. Any elongation or compression of the Bragg grating translates directly into the strain signal \( \epsilon \) when the measured Bragg wavelength shift \( \Delta \lambda_B \) is related to the reference Bragg wavelength \( \lambda_B^0 \):
\[
\frac{\Delta \lambda_B}{\lambda_B^0} = k \epsilon
\]

(2)

The strain \( \epsilon = \frac{\Delta L}{L} \) is thereby given by the relative change in the grating length. Here, the reference Bragg wavelength \( \lambda_B^0 \) is referred to the initial measurement situation, i.e. with typically zero strain and an initial temperature \( T^0 \) which remains constant during the strain measurements. The strain sensitivity \( k \) translates the relative wavelength shift into strain.

In general, both the refractive index \( n_{\text{eff}} \) and the grating period \( \Lambda \), and hence also the Bragg wavelength \( \lambda_B \) are however affected by strain and temperature.

The absolute Bragg wavelength shift upon thermal and mechanical excitations reads:
\[
\Delta \lambda_B = 2n_{\text{eff}}\Lambda \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \epsilon} \right) \Delta \epsilon + 2n_{\text{eff}}\Lambda \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \epsilon} \right) \Delta \epsilon + 2n_{\text{eff}}\Lambda \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right) \Delta T + 2n_{\text{eff}}\Lambda \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \right) \Delta T
\]

(3)

Here \( \Delta \epsilon \) compares initial and final strain. Correspondingly, the relative Bragg wavelength shift yields:
\[
\frac{\Delta \lambda_B}{\lambda_B} = \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \epsilon} \right) \Delta \epsilon + \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \epsilon} \right) \Delta \epsilon + \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right) \Delta T + \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \right) \Delta T
\]

(4)

This is the complete expression for first-order strain and temperature influences on the relative Bragg wavelength shift. It comprises a set of four optical coefficients:
\[
\alpha_{ne} = \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \epsilon} \right) \quad (5)
\]
\[
\alpha_{\Lambda\epsilon} = \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \epsilon} \right) \quad (6)
\]
\[
\alpha_{nT} = \left( \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} \right) \quad (7)
\]
\[
\alpha_{\Lambda T} = \left( \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \right) \quad (8)
\]
The photo elastic coefficient $\alpha_{n_e}$ expresses the change of the refractive index upon strain, the coefficient $\alpha_{Ae}$ describe the relative change of the Bragg grating length with elastic strain, the thermo-optical coefficient $\alpha_{nT}$ expresses the thermal change of the refractive index of the germanium-doped silica fiber core and the longitudinal thermal expansion coefficient $\alpha_{AT}$ gives the reversible change in length of the silica fiber when exposed to a change in temperature.

Using experimental data available in the bibliography for the coefficients (Maul J., & Kipp T. 2007) yields:

$$k = \alpha_{Me} + \alpha_{n_e} = 1 - 0.21 = 0.79$$
$$\alpha_T = \alpha_{AT} + \alpha_{nT} \approx 6.4 \times 10^{-6} / K$$

It is interesting to notice that the main thermal influence for the wavelength shift is originated from the refractive index in a 14/1 ratio approximately, and not from the thermal fiber expansion.

In total, the temperature-dependent strain signal of the Bragg grating is finally given by:

$$\frac{\Delta \lambda_B(\epsilon, T)}{\lambda_B} = k \Delta \epsilon + \alpha_T \Delta T \quad (9)$$

$k$ and $\alpha_T$ are obtained experimentally, $k$ being dependent on the material of the host structure.

It is important to emphasize that the sketched case only to the bare uncoated silica fiber which is neither bonded to a surface nor embedded in a sensor.

If $\Delta T = 0$, $\frac{\Delta \lambda_B(\epsilon, T)}{\lambda_B} = k \Delta \epsilon \quad (9)$

Otherwise, $k$ can be described as strain gage factor, GF or the calibration coefficient of strain:

$$\frac{\Delta \lambda_B}{\lambda_B} = GF \Delta \epsilon$$

For FBG sensor made from germanium-doped silica fiber, the typical value of GF is $0.78 \times 10^{-6} \ \mu e^{-1}$.

For an FBG of 1550 nm central wavelength, the typical strain sensitivity is $\frac{\Delta \lambda_B}{\Delta \epsilon} = 1.2 \ \text{pm/\mu e}$ and typical temperatures sensitivity $\frac{\Delta \lambda_B}{\Delta T} = 13 \ \text{pm/^\circ C}$. However, the strain and temperature sensitivities of FBG sensor depend on the type of fibers as well (Gangopadhyay et al. 2009).

### 3.3 Temperature Compensation

As noted above, a FBG sensor is sensitive to temperature and strain. An ideal sensor should be sensitive to only one parameter and be immune to others. A simpler way to correct a strain measurement for the effect of temperature is using physically separated sensors, where the one for temperature compensation is isolated from the strain field. It is clear that working under controlled laboratory conditions, the temperature remains constant and the photoelastic effect is not induced during strain measurements, then equation (4) reduces to equation (2).
4. Manufacturing of the FBG Strain Sensor Packaging

4.1 Introduction

Under the action of loads, rock structures such as tunnels and dams undergo displacements and deformations. The main purpose of any structure is to support the loads coming on it by properly transferring them to the foundation. Hence, it is necessary to measure this distortion as a source of reliable information about structural health monitoring (SHM). A method for measuring the structural behavior under loads is to weld or attach with adhesives foil strain gages on the surface of the structure.

Strain gages can be mechanical, electrical, optical, or a combination of these techniques. They all have in common that need to be physically packaged to prevent damage and have good strain transmission efficiency. This packaging has the following main purposes:

i) To facilitate and improve the adhesion between optical sensor and host material.

ii) To increase the contact area between optical sensor and host material.

iii) To provide optimum strain transfer between host specimen and sensor.

iv) To protect the optical sensor against shocks, moisture ingress or harsh environments.

FBG sensor packaging consists of materials that encapsulate the optical fiber sensor and facilitate the bonding to host material. Figure 4.1 shows the representation of the host material, adhesive, and FBG packaging it as provided in this work.

Figure 4.1. Schematic representation of an optical fiber sensor attached to the host material under stress.

The commercial surface mountable FBG strain sensors are packaged in planar configuration, which is not appropriate for the cylindrical rock cores in uniaxial compression test. Therefore, in order to use the FBG technology for measuring strain in rock specimens under compression, FBG sensors
packaging were designed and manufactured fitting the cylindrical shape of the rock samples. The proposed design is shown in Figure 4.2.

![Sensor packaging diagram](image-url)

Figure 4.2. Schematic representation of the proposed FBG strain sensor directly bonded to the curved surface of a cylindrical specimen.

The sensor packaging was designed to be adaptable to the curved surface of cylindrical rock cores in order to obtain an optimal surface covering and consequently, reliability strain records. The use of the appropriate sensor packaging allows to cover area bigger than ESG, and so overcome the difficulties inherent to inhomogeneity and anisotropy of rocks.

### 4.2 Manufacturing process of the FBG strain sensor packaging

According to Decusatis (2008), there are some requirements for optoelectronic packaging, primarily concerning with optical performance, thermal performance, reliability, cost, manufacturability, testability, device protection, size, weight and mechanical integrity.

According to some researchers (Horoschenkoff, et al, 2006), the materials have been used for manufacturing FBG strain sensor packaging for concrete and rocks materials are glass fiber reinforced polymer (GRP), carbon fiber reinforced polymer (CFRP), epoxy resin, and synthetic fibers (SFRP). Table 4.1 shows a compilation of the main features of some sensors packaging used for rock and concrete.
Table 4.1. Some features of FBG strain sensor packagings used for rock and concrete.

<table>
<thead>
<tr>
<th>Name/Reference</th>
<th>Long mm</th>
<th>Wide mm</th>
<th>Thickness mm</th>
<th>Adhesive</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPV. Torres et al (2011)</td>
<td>100-200</td>
<td>10-20</td>
<td>0.6</td>
<td>-</td>
<td>Glass fiber and polyester resin.</td>
</tr>
<tr>
<td>P. Biswas (2010)</td>
<td>70</td>
<td>12</td>
<td>5</td>
<td>Epoxy</td>
<td>Stainless steel (embedded in concrete)</td>
</tr>
<tr>
<td>Gangopadhyay et al (2009)</td>
<td>50</td>
<td>15</td>
<td>3</td>
<td>NA</td>
<td>Epoxy resin (Araldite *) Fiber reinforced plastic FRP</td>
</tr>
<tr>
<td>Vieira et al (2009)</td>
<td>50</td>
<td>15</td>
<td>1</td>
<td>Epoxy</td>
<td>Carbon</td>
</tr>
<tr>
<td>Singapur NanyangTU. Yang et al (2007)</td>
<td>50</td>
<td>NA</td>
<td>0.5</td>
<td>Epoxy</td>
<td>Carbon layers</td>
</tr>
<tr>
<td>Gebremichael et al (2005)</td>
<td>10</td>
<td>NA</td>
<td>1.8</td>
<td>Epoxy</td>
<td>Glass fiber and polymer resin</td>
</tr>
<tr>
<td>Kister (2007)</td>
<td>1 m</td>
<td>NA</td>
<td>1.8</td>
<td>Epoxy</td>
<td>Epoxy and cyanoacrilate</td>
</tr>
<tr>
<td>Moyo (2005)</td>
<td>50</td>
<td>NA</td>
<td>0.5</td>
<td>NA</td>
<td>Carbon</td>
</tr>
<tr>
<td>This research.</td>
<td>150</td>
<td>25</td>
<td>0.5 approx.</td>
<td>Elstomeric modified methacrylate</td>
<td>Glass fiber and polyester resin</td>
</tr>
</tbody>
</table>

Two main reasons guided this research about the sensor packaging. Firstly, cost is a prime driver in the industry, so glass fiber and polyester resin may be selected because they have low cost and easy acquisition. Secondly, and very important, an acceptable reliability level about mechanical behavior is needed.

For this research, the material selected was glass fiber reinforced polymer (GRP). GRP is a well know material, nevertheless, an experimental stress-strain study of the packaging was conducted.

GRP can be described as multi-constituent materials that consist of reinforcing fibers embedded in a rigid polymer matrix. The fibers used in GRP materials can be in the form of small particles, whiskers or continuous woven tapes or fabrics. The polymer is usually an epoxy, vinylester or polyester thermosetting plastic.

Glass fiber is a lightweight, strong, and robust material. Although strength properties are somewhat lower than carbon fiber, and it is less stiff, the material that is typically far less brittle, and the raw materials are much less expensive. Its bulk strength and weight properties are also very favorable when compared to metals, and it can be easily formed using molding processes.
For this research, the materials selected were the glass fiber woven tape because of its maneuverability. The size projected is 25 mm in width, 150 mm in length, and 0.5 mm in thick, a polyester resin and a catalyst type methyl ethyl ketone (MEKP) peroxide, all readily available. The two-dimensional arrangement of fibres provides less stiffness and strength in the through-thickness direction because these properties are determined by the low mechanical properties of the resin and fiber-to-resin interface.

Figure 4.3 shows the manufacturing process of the packaging. Final packaging are shown in the Figures 4.4 to 4.6.

Figure 4.3. Manufacturing of planar sensor packaging probes. 1. Glass fiber woven tape used for sensor packaging. 2. Spreading the polymeric resin by brush on glass fiber tape. 3. Using roller to remove air bubbles. 4. Waiting a drying time. 5. Shape of the probes. 6. Adjusting size.
Figure 4.4. Planar FBG sensor packaging. The approximate dimensions are: thickness of the glass fiber laminate is 0.5 mm, the optical fiber diameter is 0.125 mm.

Figure 4.5. Curved longitudinal FBG strain sensor packaging.
4.3 Stress-strain characterization of the FBG sensor packaging

The mechanical performance of the sensor packaging must be similar when manufacturing multiple sensor units, especially when considering the repeatability of the hand-made process. This characterization is intended to measure the influence of the manufacturing process on the dispersion of mechanical properties of the packaging. To do this, the mechanical characterization under tensile load was performed on four GRP specimens of 25 mm wide and 150 mm long manufactured as previously explained.

It is important to note that a subsequent step to the manufacturing of the FBG strain sensors is the calibration process; this procedure will be presented in the Five Chapter.

For mechanical evaluation process, quasi-static tensile tests were conducted on an Instron 3366 electro-mechanical universal test machine for rate of grip separation of 2 mm/min. This velocity corresponds approximately to strain rate of 0.0019 s-1, nominal strain rate based on the gage length in this research. The actual strains and strain rates were measured by Micro-Measurements strain gage type EA-250BG-120 with a maximum strain capability of 5%. These electrical strain gages were directly bonded on the central zone of specimens. Longitudinal and transversally strain gages were attached, the adhesive used was the cyanoacrylate Loctite 495.

Table 4.2 summarizes the results of the mechanical characterization for the four samples. Figure 4.8 shows the respective stress-strain curves.
Figure 4.7. GRP sensor packaging specimen at testing machine; longitudinal and transversal electrical strain gages and material failure after test are visible.
Table 4.2. Mechanical properties of the GRP planar specimens under tensile tests. The four probes were all manufactured as explained in the 4.2 Section.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>Specimen</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PS1</td>
<td>PS2</td>
<td>PS3</td>
</tr>
<tr>
<td>Thickness</td>
<td>mm</td>
<td>0.478</td>
<td>0.558</td>
<td>0.452</td>
</tr>
<tr>
<td>Transversal area</td>
<td>Square mm</td>
<td>11.95</td>
<td>13.95</td>
<td>11.30</td>
</tr>
<tr>
<td>Maximum stress (*)</td>
<td>MPa</td>
<td>82.425</td>
<td>49.171</td>
<td>62.280</td>
</tr>
<tr>
<td>Maximum longitudinal strain (*)</td>
<td>Microstrain</td>
<td>2992.048</td>
<td>2725.216</td>
<td>2905.898</td>
</tr>
<tr>
<td>Maximum elongation length (*)</td>
<td>mm</td>
<td>4.109</td>
<td>4.539</td>
<td>4.510</td>
</tr>
<tr>
<td>Tensile strength at break</td>
<td>MPa</td>
<td>199.177</td>
<td>186.317</td>
<td>227.280</td>
</tr>
<tr>
<td>Tensile strength load at break</td>
<td>kN</td>
<td>2.38</td>
<td>2.59</td>
<td>2.56</td>
</tr>
<tr>
<td>Poisson's Ratio (*)</td>
<td></td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
</tbody>
</table>

(*) Measured until failure of the electrical strain gages.
Figure 4.8. Stress-strain curves for the FBG sensor packaging specimens measured until failure of the electrical strain gage. Analytical results were obtained using linear elastic model for the mean values reported in Table 2.

In Figure 4.8, the analytical results were obtained with the linear elastic relation \( \sigma_y = E_m \varepsilon_y \) where \( \sigma_y \) is the tensile stress, \( E_m \) is the mean Tensile Modulus (12.785 MPa) and \( \varepsilon_y \) is the tensile strain, all of them in the longitudinal direction. From the results reported in Table 2 and graphically presented in Figure 4.8 and, it is possible verify an acceptable dispersion of experimental results on the elastic model, and the packaging process is considered as acceptable, but it can be improved in order to be compared to commercial optical gages. The data obtained in the tests are similar to those obtained in Torres et al (2011).

Figure 4.9 shows some failed sensors packaging specimens under tensile testing. Diagonal failure is visible mainly in the intersection between longitudinal and transversal pieces.
The obtained tensile strength, elastic modulus and Poisson's ratio of the FBG packaging specimens are all compatible with the requirements to properly measure small deformations in rock materials considering its usual stiffness and strength. In the Figure 4.10 the stiffness of some intact rocks and the manufactured FBG packaging are graphically compared. The sensor stiffness must be lower than measured material for not artificially increase hardening of the rock.

![Figure 4.9. Failure modes of some sensor packaging specimens are marked with blue lines, failure of the electrical strain gages are visible too.](image)

![Figure 4.10. Uniaxial stress-strain curves for six rock types and mean stiffness of the manufactured strain sensor. The sensor stiffness must be lower than rock stiffness. Modified from Brady & Brown (2005).](image)
4.4 Numerical simulation of the FBG sensor packaging

In order to evaluate the accuracy obtained in measuring the strain on the FBG sensor packaging samples, and to estimate the quality of the hand-made manufacturing process, it was conducted a numerical simulation using the finite element method through the commercial software Ansys.

Intending to quantify the difference between the values of the numerical model and the elastic analytical model, the error NE is calculated by:

\[ NE = \frac{\text{Numerical results} - \text{Analytical results}}{\text{Numerical results}} \times 100 \]

In Table 4.3 there are some values of NE under tensile stress values.

Table 4.3. Strain numerical results for central zone of the the glass fiber packaging specimens. Tensile loads from 5 to 50 MPa were modeled. Analytical results were obtained from mean values reported in Table 2.

<table>
<thead>
<tr>
<th>Tensile Stress (MPa)</th>
<th>Strain (με)</th>
<th>Numerical error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Elastic Numerical strain</td>
<td>Elastic Analytical strain</td>
</tr>
<tr>
<td>5</td>
<td>391</td>
<td>391.08</td>
</tr>
<tr>
<td>10</td>
<td>782</td>
<td>782.16</td>
</tr>
<tr>
<td>15</td>
<td>1173</td>
<td>1173.24</td>
</tr>
<tr>
<td>20</td>
<td>1564</td>
<td>1564.33</td>
</tr>
<tr>
<td>25</td>
<td>1955</td>
<td>1955.41</td>
</tr>
<tr>
<td>30</td>
<td>2346</td>
<td>2346.49</td>
</tr>
<tr>
<td>35</td>
<td>2737</td>
<td>2737.58</td>
</tr>
<tr>
<td>40</td>
<td>3129</td>
<td>3128.66</td>
</tr>
<tr>
<td>45</td>
<td>3520</td>
<td>3519.74</td>
</tr>
<tr>
<td>50</td>
<td>3911</td>
<td>3910.83</td>
</tr>
</tbody>
</table>

Figure 4.11 shows an example of the obtained results for elastic longitudinal strain in the planar GRP packaging samples using the finite element method.
Figure 4.11. Finite element model of the longitudinal strain in the FBG sensor packaging under 20 MPa tensile stress.

In the Figure 4.11 the arrow indicates the elastic strain in the central zone. The numerical strain results for point where the strain gage was bonded is 1564 microstrain whereas the elastic analytical result obtained from mean values reported in Table 2 is 1564.33 microstrain.

Figure 4.12. Finite element model of the longitudinal strain in the FBG sensor packaging under tensile stress. The label indicates the elastic strain in the central zone.

The strain obtained from the numerical simulation and the analytical results agree very well, this means that elastic modulus obtained from manual manufacturing of the sensor packaging is representative for the linear elastic behavior.
5. Calibration process of the FBG strain sensor

5.1 Introduction

Static and Quasi-static calibrations of the sensor packaging were conducted. High stiffness rocks have low strain values (below 1000 με) under laboratory conditions. In order to obtain a sensitive calibration in this strain range, it was considered to perform a static calibration in which it can be applied very low values of load, since the available universal test machine cannot maintain constant the applied load; thus low strain levels were achieved. The Quasi-static calibration is appropriate in a process like the compression test of rock, which can produces higher levels of strain at higher load levels.

In both calibration process, ESGs were bonded to the FBG sensor packaging using the method suggested for its manufacturers and characterized by tensile testing. The ESG was directly bonded about mid-span, mid-width of the packaging.

The dimensions of the specimens were 250 mm overall length, 25 mm width and 1 mm thickness, as suggested for the ASTM D3039-95 for balanced and symmetric fiber orientation (glass fiber woven tape).

(ASTM D3039 is the standard test method for tensile properties of polymer matrix composite materials).

Load, stress, strain, and Bragg wavelength of the packaged FBG sensor were recorded. A Micron Optics si 425 Sensing Interrogator and a Bay Spec interrogator system was used as readout unit for the FBG strain sensors. The thermal environment was stable, and no additional temperature detection was necessary.

5.2 Static calibration

The packaged FBG sensors were calibrated using mass loading and measuring strain using ESG sensors attached to the packaging surface. In the loading stage were applied successive increments of 20 N up to 200 N, and the respective tensile strain and FBG wavelength were recorded. In the unloading stage, the masses were removed and the contraction strain and FBG wavelength were recorded. Two FBG packaging specimens were used for calibration procedure in order to capture possible differences in manufacturing. Figure 5.1 shows the calibration device. Table 5.1 shows the calibration measurements and Figure 5.2 to 5.4 shows graphically the calibration results.
Figure 5.1. Static calibration device. ESG was bonded to the surface of the FBG packaging for strain measurements.

**Static calibration of the #1 FBG sensor specimen**

Table 5.1. #1 FBG specimen, static calibration measurements under tensile strain in loading and contraction strain in unloading.

<table>
<thead>
<tr>
<th>Interrogator device</th>
<th>Micron Optics</th>
<th>Bayspec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (N)</td>
<td>Strain (µε)</td>
<td>Wavelength (nm)</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0,000</td>
<td>1545,613</td>
</tr>
<tr>
<td>40</td>
<td>192,626</td>
<td>1546,027</td>
</tr>
<tr>
<td>80</td>
<td>437,977</td>
<td>1546,314</td>
</tr>
<tr>
<td>120</td>
<td>672,052</td>
<td>1546,597</td>
</tr>
<tr>
<td>160</td>
<td>925,522</td>
<td>1546,898</td>
</tr>
<tr>
<td>200</td>
<td>1184,928</td>
<td>1547,218</td>
</tr>
<tr>
<td><strong>Unloading</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>977,555</td>
<td>1546,958</td>
</tr>
<tr>
<td>120</td>
<td>704,876</td>
<td>1546,630</td>
</tr>
<tr>
<td>80</td>
<td>468,654</td>
<td>1546,336</td>
</tr>
<tr>
<td>40</td>
<td>241,712</td>
<td>1546,058</td>
</tr>
<tr>
<td>0</td>
<td>45,789</td>
<td>1545,830</td>
</tr>
<tr>
<td><strong>Sensitivity (pm/ms)</strong></td>
<td>1,35</td>
<td>1,12</td>
</tr>
</tbody>
</table>
Figure 5.2. Static calibration of the #1 FBG packaging. Relationship between loading and strain measured by ESG.

Figure 5.3. Static calibration of the #1 FBG packaging. Relationship between Bragg wavelength and strain measured by ESG.
Figure 5.4. Static calibration of the #1 FBG packaging, relationship between strain measured by ESG and Bragg wavelength shift. Linear fitting for loading and unloading process.

**Static calibration of the #2 FBG sensor specimen**

Table 5.2. #2 FBG specimen, static calibration measurements under tensile strain in loading and contraction strain in unloading.

<table>
<thead>
<tr>
<th></th>
<th>Interrogator device</th>
<th>Micron Optics</th>
<th>Bayspec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load (N)</td>
<td>Strain (με)</td>
<td>Wavelength (nm)</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>7,719</td>
<td>1565,669</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>225,459</td>
<td>1565,939</td>
<td>0,27</td>
</tr>
<tr>
<td>80</td>
<td>545,640</td>
<td>1566,184</td>
<td>0,515</td>
</tr>
<tr>
<td>120</td>
<td>771,988</td>
<td>1566,534</td>
<td>0,865</td>
</tr>
<tr>
<td>160</td>
<td>988,131</td>
<td>1566,805</td>
<td>1,136</td>
</tr>
<tr>
<td>200</td>
<td>1377,146</td>
<td>1567,122</td>
<td>1,453</td>
</tr>
<tr>
<td><strong>Unloading</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160</td>
<td>1160,237</td>
<td>1566,864</td>
<td>1,195</td>
</tr>
<tr>
<td>120</td>
<td>919,214</td>
<td>1566,602</td>
<td>0,933</td>
</tr>
<tr>
<td>80</td>
<td>664,727</td>
<td>1566,331</td>
<td>0,662</td>
</tr>
<tr>
<td>40</td>
<td>408,555</td>
<td>1566,077</td>
<td>0,408</td>
</tr>
<tr>
<td>0</td>
<td>128,676</td>
<td>1565,662</td>
<td>-0,007</td>
</tr>
<tr>
<td><strong>Sensitivity (pm/ms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.5. Static calibration of the #2 FBG sensor. Relationship between loading and strain measured by ESG.

Figure 5.6. Static calibration of the #2 FBG sensor. Relationship between Bragg wavelength and strain measured by ESG.
In the loading stage, the calibration equation of #1 and #2 specimens presents a difference around 6 %, and $R^2$ present a difference around 7%.

In the unloading stage, the calibration equation of #1 and #2 specimens presents a difference around 16%, and $R^2$ present a difference around 0.5%.

Otherwise, according of Micron Optics interrogator, specimen #1 offers 24% better sensitivity than #2; there are no differences in the Bay spec sensitivity.

In static calibration the loading range is from 0 to 200 N and the strain range is from 0 to 1400 με.
5.3 Quasi-static calibration

Tensile test of the FBG sensor packagings #1 and #2 was conducted in an Instron 3366 universal test machine as shown in Figure 5.8. The actual strains and strain rates were measured by means of ESG with a maximum strain capability of 5% at room temperature. The ESG was directly bonded about mid-span, mid-width of the packaging. The speed of testing was 2 mm/min as suggested for ASTM D3039.

Figure 5.8. Quasi-static tensile test of the FBG sensor packaging. The actual strain and strain rates were measured by electrical strain gage (ESG).
Quasi-static calibration of the # 1 FBG sensor specimen

Table 5.3. #1 FBG specimen, quasi-static calibration measurements in tensile test.

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Stress (MPa)</th>
<th>Wavelength (nm)</th>
<th>Strain (με)</th>
<th>Wavelength shift (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1545,41</td>
<td>-0,33</td>
<td>0,00</td>
</tr>
<tr>
<td>50</td>
<td>4.16</td>
<td>1545,65</td>
<td>-306</td>
<td>0,24</td>
</tr>
<tr>
<td>100</td>
<td>8.32</td>
<td>1545,98</td>
<td>-579,5</td>
<td>0,57</td>
</tr>
<tr>
<td>150</td>
<td>12.5</td>
<td>1546,29</td>
<td>-865,5</td>
<td>0,88</td>
</tr>
<tr>
<td>200</td>
<td>16.67</td>
<td>1546,63</td>
<td>-1118,5</td>
<td>1,22</td>
</tr>
<tr>
<td>250</td>
<td>20.8</td>
<td>1547,01</td>
<td>-1428,5</td>
<td>1,60</td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>1547,33</td>
<td>-1720,5</td>
<td>1,92</td>
</tr>
<tr>
<td>350</td>
<td>29.16</td>
<td>1547,66</td>
<td>-2042,5</td>
<td>2,25</td>
</tr>
<tr>
<td>400</td>
<td>33.33</td>
<td>1548,13</td>
<td>-2366,5</td>
<td>2,72</td>
</tr>
<tr>
<td>450</td>
<td>37.5</td>
<td>1548,47</td>
<td>-2693,5</td>
<td>3,06</td>
</tr>
<tr>
<td>500</td>
<td>41.66</td>
<td>1548,99</td>
<td>-3014</td>
<td>3,58</td>
</tr>
<tr>
<td>550</td>
<td>45.83</td>
<td>1549,32</td>
<td>-3396,</td>
<td>3,91</td>
</tr>
<tr>
<td>600</td>
<td>50</td>
<td>1549,62</td>
<td>-3676,5</td>
<td>4,21</td>
</tr>
</tbody>
</table>

Strain Sensitivity (pm/με) = 1,14

Calibration relationship: Strain(με) = 874.47*Wavelength shift (nm)

R² = 0,997

Next Figures shows the relationship between loading, Bragg wavelength and tensile strain obtained in the quasi-static calibration process.
Figure 5.9. Quasi-static calibration of the FBG #1 specimen. Relationship between strain and loading.

Figure 5.10. Quasi-static calibration of the FBG #1 specimen. Relationship between loading and Bragg wavelength shift.
Figure 5.11. Quasi-static calibration of the FBG packaging. Relationship between Bragg wavelength shift and tensile strain measured by ESG.

**Quasi-static calibration of the #2 FBG sensor specimen**

Table 5.4. #2 FBG specimen, quasi-static calibration measurements in tensile test.

<table>
<thead>
<tr>
<th>Load (N)</th>
<th>Stress (MPa)</th>
<th>Wavelength (nm)</th>
<th>Strain (με)</th>
<th>Wavelength shift (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1565,153</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>50</td>
<td>4.16</td>
<td>1565,772</td>
<td>-339,63</td>
<td>0,62</td>
</tr>
<tr>
<td>100</td>
<td>8.32</td>
<td>1566,103</td>
<td>-609,50</td>
<td>0,95</td>
</tr>
<tr>
<td>150</td>
<td>12.5</td>
<td>1566,439</td>
<td>-901,00</td>
<td>1,29</td>
</tr>
<tr>
<td>200</td>
<td>16.67</td>
<td>1566,756</td>
<td>-1180,50</td>
<td>1,60</td>
</tr>
<tr>
<td>250</td>
<td>20.8</td>
<td>1567,069</td>
<td>-1498,50</td>
<td>1,92</td>
</tr>
<tr>
<td>300</td>
<td>25</td>
<td>1567,539</td>
<td>-1799,50</td>
<td>2,39</td>
</tr>
<tr>
<td>350</td>
<td>29.16</td>
<td>1567,856</td>
<td>-2152,00</td>
<td>2,70</td>
</tr>
<tr>
<td>400</td>
<td>33.33</td>
<td>1568,330</td>
<td>-2488,50</td>
<td>3,18</td>
</tr>
<tr>
<td>450</td>
<td>37.5</td>
<td>1568,647</td>
<td>-2833,50</td>
<td>3,49</td>
</tr>
<tr>
<td>500</td>
<td>41.66</td>
<td>1569,111</td>
<td>-3165,00</td>
<td>3,96</td>
</tr>
</tbody>
</table>

Strain Sensitivity (pm/με) = 1.25

Linear equation: Strain(με) = 783.98 * Wavelength shift (nm) \( R^2 = 0.993 \)
Next Figures shows the relationship between loading, Bragg wavelength and tensile strain obtained in the quasi-static calibration process.

**Figure 5.12.** Quasi-static calibration of the FBG packaging. Relationship between loading and tensile strain measured by ESG.

**Figure 5.13.** Quasi-static calibration of the FBG packaging. Relationship between loading and Bragg wavelength shift.
Figure 5.14. Quasi-static calibration of the FBG packaging. Relationship between Bragg wavelength shift and tensile strain measured by ESG.

5.4 Summary of the calibration process

In the Quasi-static testing, the calibration equation of #1 and #2 specimens presents results with difference around 10% and $R^2$ presents a difference around 0.5%. Otherwise, according of Bay Spec interrogator, specimen #1 offers 9% better sensitivity than #2. In this case the loading range is from 0 to 600 N and the strain range is from 0 to 3500 με.

One possible explanation of the difference in the calibration results between static and quasi-static methods is that load machines have different gripping jaws and samples can slide. From the calibration results we can say that the developed FBG sensors are sensitive to low and high deformations under static or quasi-static conditions, and the FBG #1 has higher sensitivity under static and quasi-static loading than FBG #2.

All equations obtained before will be used for measuring strains in the rock samples under compression, the results will be compared between specimens #1 equation, #2 equation and ESG. Summary of the calibration results are presented in Table 5.5.
Table 5.5. Summary of the static and quasi-static calibration of the FBG sensors. The calibration strain equations are linear of the type: $y = b * x$, where $y$ is the strain, $x$ is the wavelength shift measured for the interrogator system and $b$ is the experimental coefficient.

<table>
<thead>
<tr>
<th>Summary of the calibration process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Static calibration</td>
</tr>
<tr>
<td>$R^2$ linear regression</td>
</tr>
<tr>
<td>Sensitivity (pm/ $\mu$e)</td>
</tr>
<tr>
<td>Quasi-static calibration</td>
</tr>
<tr>
<td>$R^2$ linear regression</td>
</tr>
<tr>
<td>Sensitivity (pm/ $\mu$e)</td>
</tr>
<tr>
<td>Input range</td>
</tr>
<tr>
<td>Load input range</td>
</tr>
<tr>
<td>Output range (FOS)</td>
</tr>
<tr>
<td>Maximum elongation length</td>
</tr>
<tr>
<td>FBG Sensor resolution</td>
</tr>
<tr>
<td>Interrogator Resolution</td>
</tr>
</tbody>
</table>
For comparative purposes, the commercial Geokon Fiber Optic FP 4000 has the output strain ranges presented in Table 5.6.

Table 5.6. Output strain ranges of the commercial Geokon FP 4000 FBG planar sensor. (http://www.geokon.com/FP4000 Downloaded in 22-6-2015).

<table>
<thead>
<tr>
<th>Geokon FP 4000</th>
<th>Strain ranges (με)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>-1000 to +1000</td>
</tr>
<tr>
<td>2.5</td>
<td>-2500 to +2500</td>
</tr>
<tr>
<td>5.0</td>
<td>-5000 to +5000</td>
</tr>
</tbody>
</table>

This manufactured gage achieved output strain ranges comparable to offered by the commercial product. Other commercial features are not public available.
6. Strain Measurements on Rock Specimens using FBG Sensor

6.1 Introduction

In order to evaluate the performance of the developed FBG sensors compared to electrical strain gages ESG, uniaxial compression tests on rocks specimen was performed to obtain the stress-strain curve. In this test, the rock specimens were submitted to monotonic compressive load and longitudinal strain were measured using both manufactured FBG sensors and the traditional ESG system.

The main goal of the tests is to evaluate the strain data obtained from the FBG sensors using the calibration equations obtained in the Chapter 5 and compare these values versus measurements obtained by the traditional system using ESG bonded to rock sample.

6.2 The Rock Specimen

The rock sample was a cylindrical rock core 300 mm high, 60 mm diameter, petrographically designated as amphibolite with epidote and titanite, identified as AC3 sample, and it was taken from Medellin region in Colombia. This amphibolite is anisotropic, with initial foliation, defined by the preferential orientation of hornblende crystals, sphen and plagioclase, as revealed on thin sections; Figure 6.1 shows the rock sample.
Figure 6.1. Amphibolite rock sample with bonded FBG and ESG sensors and cables.

The Figures 6.2 and 6.3 shows thin sections of this rock; mainly minerals are identified, such as epidote, chlorite and titanite. The mineralogical composition in thin section analyzed is hornblende 50.6%, plagioclase 37.4%, quartz 5%, and the metamorphic minerals epidote-zoisite 5% and titanite 2%. The original igneous structure is partially observed, hence rock may be classified as meta-diorite with hornblende, and anyway metamorphic condition must be considered for designation.

Figure 6.2. Thin section of the amphibolite with epidote and titanite. Left: non polarized light. Right: polarized light. Note at the center the venilla chlorite, surrounded by epidote and hornblende crystals.
Figure 6.3. Thin section of the amphibolite with epidote and titanite. Left: non polarized light. Right: polarized light. Hornblende, plagioclase and sphene (titanite).

About size of the rock sample, the ASTM D7012-10 standard suggests as “desirable” length to diameter ratio from 2:1 to 2.5:1, otherwise this standard says “laboratory specimen length to diameter ratios must be employed with proper judgement in engineering applications”. In this testing, the length to diameter ratio is 5:1; this size was used for two reasons:

a) To reduce the strain in the sample central zone in order to evaluate the FBG sensor sensitivity for small strains.

b) To facilitate handling of the cables and sensors.

The diameter of the rock core is ten times bigger than the diameter of the largest mineral grain, as presented in Figure 6.4. The rock core was prepared following the ASTM D4543 practice and the moisture of the specimen is considered as zero.

### 6.3 Experimental procedure for rock strain measurements using FBG sensors

One FBG sensor was taken from the batch previously manufactured (as presented in Chapter 4) and calibrated (as presented in Chapter 5), this FBG packaging was optically measured in order to know the initial wavelength before bonding to rock, the Micron Optics si 425 and Bay Spec interrogator were used. Afterwards, the sensor was axially bonded in the mid-height of the rock specimen. Both FBG and ESG were bonded using the Loctite 330 No-Mix Adhesive acrylic type (Urethane methacrylate ester and heptane/isopropanol activator). The figure 6.4 shows the FBG and ESG sensors bonded to rock surface.
The dimensions and material parameters for uniaxial compression test on rock sample are presented in Table 6.1.

Table 6.1. Dimensions and material parameters for uniaxial compression test on rock sample.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s Modulus (GPa)</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphibolite rock core</td>
<td>165 (in the loading range)</td>
<td>Height: 300 Diameter: 60</td>
</tr>
<tr>
<td>FBG packaging</td>
<td>13.6</td>
<td>100 x 25 x 0.48</td>
</tr>
<tr>
<td>Bonding layer</td>
<td>3 to 4 (Krishnan &amp; Xu, 2011)</td>
<td>100 x 25 x 0.03</td>
</tr>
<tr>
<td>ESG</td>
<td>34.5x8.4 (area 290 mm²)</td>
<td>34.5x8.4 (area 290 mm²)</td>
</tr>
<tr>
<td>FBG</td>
<td>70 GPa</td>
<td>100 x 0.125</td>
</tr>
</tbody>
</table>

Figure 6.5 shows a schematic of the experimental setup.
Figure 6.5. Schematic of the experimental setup for uniaxial compression test of the rock sample with FBG and ESG sensors.

![Figure 6.5. Schematic of the experimental setup for uniaxial compression test of the rock sample with FBG and ESG sensors.]

Figure 6.6. Experimental set-up showing rock sample in the compression loading device, Micron-Optics interrogator, Bay Spec interrogator, SLED source, and strain gage data acquisition system.

The loading device system was hydraulic Controls Digimax with a capacity up to 200 t. The load rate was of 0.01 MPa/s. The longitudinal strain of rock specimens was measured using a Geodatalog series 6000 and Wheatstone bridge from Controls Ltd, the electrical strain gages (ESG) are from Vishay-Micromeasurements.

Table 6.2. Properties of the used electrical strain gauges.

| Vishay-Micromeasurements resistance strain gauges |
A tunable Fabry–Perot filter system from Micron Optics Inc. has been used as readout unit for the FBG strain sensors (see Figure 6.6). This interrogation technique allows the simultaneous detection of several sensors in series; their total number depends on the expected quasi-static range of strain. The system has a temperature-stabilized fixed Fabry–Perot multiwavelength reference to achieve stability and accuracy of 5 pm at one measurement per second.

### 6.4 Results

Results were obtained for loading (force) stress, axial strain measured by ESG system, wavelength, and wavelength shift. Table 6.3 presented data results.

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Stress (MPa)</th>
<th>Axial strain from ESG (με)</th>
<th>Wavelength (nm)</th>
<th>Wave length shift Δλθ (nm)</th>
<th>Strain from static calibration equation (10) (με)</th>
<th>Strain from quasi-static calibration equation (11) (με)</th>
<th>Strain relative error FBG Quasi-static/ESG (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,0</td>
<td>0,00</td>
<td>0,000</td>
<td>1525,024</td>
<td>0,000</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>5,0</td>
<td>1,77</td>
<td>3,884</td>
<td>1525,016</td>
<td>0,008</td>
<td>7,12</td>
<td>6,99</td>
<td>80</td>
</tr>
<tr>
<td>10,1</td>
<td>3,57</td>
<td>9,012</td>
<td>1525,003</td>
<td>0,021</td>
<td>18,70</td>
<td>18,35</td>
<td>103</td>
</tr>
<tr>
<td>15,1</td>
<td>5,34</td>
<td>13,722</td>
<td>1524,989</td>
<td>0,035</td>
<td>31,16</td>
<td>30,59</td>
<td>122</td>
</tr>
<tr>
<td>20,1</td>
<td>7,11</td>
<td>21,869</td>
<td>1524,974</td>
<td>0,050</td>
<td>44,52</td>
<td>43,70</td>
<td>99</td>
</tr>
<tr>
<td>25,0</td>
<td>8,84</td>
<td>31,225</td>
<td>1524,963</td>
<td>0,061</td>
<td>54,31</td>
<td>53,31</td>
<td>70</td>
</tr>
<tr>
<td>30,0</td>
<td>10,61</td>
<td>42,379</td>
<td>1524,955</td>
<td>0,069</td>
<td>61,44</td>
<td>60,31</td>
<td>42</td>
</tr>
<tr>
<td>35,1</td>
<td>12,41</td>
<td>54,813</td>
<td>1524,936</td>
<td>0,088</td>
<td>78,35</td>
<td>76,91</td>
<td>40</td>
</tr>
<tr>
<td>40,3</td>
<td>14,25</td>
<td>63,065</td>
<td>1524,936</td>
<td>0,088</td>
<td>78,35</td>
<td>76,91</td>
<td>21</td>
</tr>
<tr>
<td>45,0</td>
<td>15,92</td>
<td>73,976</td>
<td>1524,918</td>
<td>0,106</td>
<td>94,38</td>
<td>92,64</td>
<td>25</td>
</tr>
<tr>
<td>50,1</td>
<td>17,72</td>
<td>81,769</td>
<td>1524,918</td>
<td>0,106</td>
<td>94,38</td>
<td>92,64</td>
<td>13</td>
</tr>
<tr>
<td>55,1</td>
<td>19,49</td>
<td>94,238</td>
<td>1524,904</td>
<td>0,120</td>
<td>106,85</td>
<td>104,88</td>
<td>11</td>
</tr>
<tr>
<td>60,1</td>
<td>21,26</td>
<td>105,685</td>
<td>1524,901</td>
<td>0,123</td>
<td>109,52</td>
<td>107,50</td>
<td>1</td>
</tr>
<tr>
<td>65,3</td>
<td>23,10</td>
<td>117,531</td>
<td>1524,882</td>
<td>0,142</td>
<td>126,43</td>
<td>124,11</td>
<td>5</td>
</tr>
<tr>
<td>70,1</td>
<td>24,79</td>
<td>121,118</td>
<td>1524,890</td>
<td>0,134</td>
<td>119,31</td>
<td>117,12</td>
<td>-4</td>
</tr>
<tr>
<td>75,2</td>
<td>26,60</td>
<td>139,187</td>
<td>1524,840</td>
<td>0,184</td>
<td>163,83</td>
<td>160,82</td>
<td>15</td>
</tr>
</tbody>
</table>

FBG sensor sensitivity= 1.32 pm/με
The FBG sensor sensitivity is the ratio of axial strain to Bragg wavelength shift, as measured by FBG sensor using static calibration equation the FBG sensor has 1.32 pm/με (1 pm =10⁻⁹ m). As previously stated in 3.3 section, according to Gangopadhyay et al. (2009) the typical FBG strain sensitivity is 1.2 pm/με.

It is visible that wavelength shifts are suitable for sensing small strain changes. The data presented in the Table 6.3 shows than values under 20 με (0.002%) are possible to be measured for FBG sensor because its sensitivity , around 1.32 pm/ε.

Strain shows maximum relative error of 122 % between FBG and ESG sensors; the difference may be due to the different contact area between the FBG sensor (2500 mm²) and the ESG (290 mm²); small sensors reflects specific deformations that can be caused by mineral grains with a different rigidity of the mineral matrix.

In Yang Y. W. et al (2007) good correlation between FBG strains and ESG strains was noted for deformations over 1200 με in cycles of compressive load on granite, while in our case is noted for deformations over 100 με (see Figure 6.9), this may indicate the suitability and sensitivity of the sensor developed.

According to Figliola (2006) resolution it is quantified by the smallest scale increment or least count (least significant digit) of the output readout indicator. In the calibration equations two significant digits were obtained, hence the resolution is 0.01 με.

Figures 6.7 to 6.9 shows graphically the relationship between measurements.
Figure 6.7. Graphical relationship obtained between loading and strain measured by ESG in the uniaxial compression test. The length reduction is considered as positive.

Figure 6.8. Relationship between axial strain and Bragg wavelength.
Figure 6.9. Relation between strain and Bragg wavelength shift obtained from FBG sensor for uniaxial compression test on amphibolite rock specimen.

Figure 6.10 shows the stress-strain curves of the rock sample both ESG and FBG, using quasi-static and static calibration equations obtained before, and presented in Table 5.5.
Figure 6.10. Stress–strain curve obtained from ESG and FBG measurements under compression test of the amphibolite AC3 sample. Compression is considered as positive strain. There is little difference using static or quasi-static (Quasi-static) strain calibration. The analysis of the FBG sensor will be presented in Section 7.

6.5 Analysis of the bond condition and strain transmission between rock and sensor

The bonding layer between rock sample and FBG sensor packaging deserves attention due to two main aspects:

(a) The strain transmission quality from rock to sensor, and
(b) Nonuniform thickness causes distorted FBG spectral responses.

The effectiveness of the strain transfer strongly depends on the shear modulus of the adhesive, the thickness of the bonding layer and the bonding length. An unacceptable bonding layer fails to transfer enough strain from the substrate to the FBG.

The adherence quality under different bond conditions of the FBG strain sensor and the host material has been studied by several researchers like as Chih-Chun Cheng et al (2005), W.Y. Li et al (2009),
Torres B. et al (2011), and Zhang et al (2011). Li et al (2009) have concluded that the strain transmission loss becomes large when the substrate is thin and/or made by a low modulus material. The FBG and the bonding layer affect the original strain distribution on the thin and low-modulus substrate; as a result, the substrate strain sensed by the FBG is underestimated and thus required to be corrected.

The proposed model by Li et al. (2009) consider an FBG of diameter $t_F$ and Young’s modulus $E_F$ bonded onto the surface of a substrate of thickness $t_S$ and Young’s Modulus $E_S$ as shown in Figure 6.11. Assume that the cross-sectional area of the FBG is much smaller than that of the substrate. When the substrate is subjected to an external force $F$, the bonded FBG senses the strain of the substrate transferred through the bonding layer of thickness $t_B$.

![Figure 6.11. FBG surface bonded on a rock substrate (a) one-dimensional free-body diagram and (b) cross-sectional view, modified from Li et al (2009).](image)

The strain transferred from the substrate through the bonding layer to the FBG is quantified by the strain transmission rate defined as

$$k = \frac{\epsilon_F}{\epsilon_T}$$

[3]

where $\epsilon_F$ is the strain measured by FBG sensor and $\epsilon_T$ is the true strain of the substrate. For a perfect bonding, the strain sensed by the FBG is the same as that of the rock substrate, and $k = 1$.

Thus, the strain transmission rate can be expressed as:

$$k = \left(1 - \frac{1}{\cosh S}\right) \left(\frac{E_S t_S}{E_S t_S + E_F t_F}\right) \left(\frac{E_S t_S}{E_S t_S + E_F t_F + E_B t_B}\right)$$

[4]

where

$$S^2 = \frac{G L^2}{E_f t_f t_B} \left(1 + \frac{1}{\varphi}\right), \quad \varphi = \frac{t_S E_S}{t_F E_F}$$
and \( L \) is the length of the bonding layer and \( G \) is the shear modulus of the adhesive. In order to determine the thickness of the bonding layer, a microscope photograph of the cross section of the bonding layer and the fiber attached to the rock sample is performed (see figure 6.12).

![Figure 6.12. Cross-sectional view and dimensions of the bonding layer and the optical fiber attached to the rock sample.](image)

Figure 6.13 shows the relationship between bonding thickness and strain transmission rate for the amphibolite with titanite rock tested by using equation [4] and the data presented in Table 1 with \( k = 0.998 \). The strain transmission rate is higher than 95% when the rock Young’s modulus is above 5 GPa. A range of values between 1 and 120 GPa are usual for much kind of intact rock materials.

Figure 6.14 shows the strain transmission rate for rock specimens considering the thickness layer and different rock Young’s modulus. These results are in agreement with the Yung’s analysis (Yung Bin Lin, 2005) in which the thickness and Young’s modulus of the glue have little influence on the strain transmission when the thickness of the glue is less than diameter of an optical fiber. Otherwise, an unacceptable bonding layer fails to transfer enough strain from the substrate to the FBG, then FBG sensors may have distorted spectra as evidenced in Figure 6.15.
Figure 6.13. Relationship between bonding layer thickness and strain transmission rate using equation [4] for rock specimens with 60 mm diameter and different Young’s modulus.

Figure 6.14. Strain transmission rate using equation [4] for rock specimens with Young’s modulus ranging from 0 to 80 GPa and 32 μm thickness bonding layer.
Figure 6.15. (a) FBG spectra by a bonding layer of regular thickness, where it is clear that the Bragg wavelength shift can be established. (b) Distorted FBG spectra by a bonding layer of irregular thickness, where it is not appropriate to analyze the Bragg wavelength. To obtain this spectra, irregular thickness bonding layer was applied on FBG surface attached to rock sample.
7. Conclusions

The next outstanding conclusions were obtained:

- The FBG sensor obtained in this thesis is similar to recently developed commercial products, but, beyond the performance comparison, the aim of this work is to demonstrate than this type of sensors may be completely manufactured exploring uses for rocks and complex natural materials, and its measurements should be acceptable and reliable, even if the sensor is manufactured by manual production.

- Beneath this concept, it was presented a new FBG sensor adapted to the curved surface of cylindrical rock samples appropriate for unconfined compression test. The manufacturing process of the sensor packaging was completely hand-made using economical glass fiber reinforced polymer -GRP- and it has a single layer, so that the optic fiber is in direct contact with the adhesive used to attach the sensor to the rock surface, improving the sensor performance.

- The methodological stages followed to obtain the sensor were: a) to select adequate materials, b) to develop a carefully manufacturing packaging method, c) to obtain mechanical characterization of the sensor, d) to perform adequate calibration procedure, e) test the sensor compared to traditional methods.

- It was demonstrated that GRP material may be used under certain conditions, but the mechanical characterization of the sensor packaging is always required in order to guaranteed that stiffness and strength are suitable for measuring strain in the host material; furthermore, because the hand-made product must be acceptable, it is necessary to demonstrate low scattering of the mechanical parameters, mainly strength and Young's modulus.

- It was shown that the tensile stress on no-bonded FBG sensor manufactured were up to 227 MPa, indicating that GRP sensor are able to withstand high stresses.

- The quasi-static FBG calibration indicates that developed sensor is suitable for operation with high sensitivity and output range similar to commercial products.

- In comparison with traditional foil strain gages (constantan and polyamide), used in the rock test, the glass fiber FBG strain sensor has equally or higher sensitivity but evaluation about accuracy is not conclusive. Considering the ESG as reference, maximum relative strain error was 122 % and the lower was 1%; it was visible than accuracy increases for higher strain. These differences may be due to the different measurement area between the FBG sensor...
(2500 mm²) and the ESG (290 mm²), strain measured by FBG sensor includes more structural features and anisotropic behavior of the minerals and pores, hence is not correctly to affirm that FBG is low accurate in this test because strain sensors must have an appropriate area according to several materials and features of the rock. Anyway, FBG accuracy is an important parameter to be studied with more advanced methods.

- As previously pointed in Section 2.6, the ideal compression test searches a uniform deformation on the rock sample and the real compression test induces a non-uniform deformation on the specimen; this mismatch can be reduced if the sensor covers a proportional bigger area of the sample. The FBG sensors may be produce to embrace larger area with the appropriate curved shape, increasing coverage and including large mineral grains (phenocrysts, porphyroblasts), structures such as pores, foliation, cleavage, lineation, veins, relict features or microcracks and fractures that exist in the rocks, making it possible to obtain representative measurements.

- FBG has advantages over ESG, becoming an attractive sensing method for inhomogeneous rocks in many fields of applications.

- FBG packaging materials such as carbon fiber, Teflon, Kevlar, metal alloys, etc., can offers higher strength and stiffness than glass fiber, these materials may be used under some conditions for rock testing but the sensor manufacturing is similar to developed here.

- The bonding process deserves attention because strain transfer from host rock to sensor depends of the bonding properties. We demonstrated that nonuniform thickness of bonding layer cause distorted FBG spectra and the physical principle of the fiber Bragg sensor cannot be applied.
8. Perspectives

Sensor systems based on fiber optics are increasing applications around the world and strain is a very important parameter to be measured in tunnels, slopes, foundations, dams, mining, and some others structures in order to improve their design, construction and operation.

This FBG strain gage is qualified for use in harsh environments and delivers the many advantages inherent to all optical fiber-based sensors; it is possible to measuring and then record, display and transmit data for large network of sensors using multiplexing possibilities with many sensors, few cables and long range.

The developed sensor can be used alone or in series as a part of an FBG sensor array. Installation and cabling for such arrays is much less expensive and cumbersome than comparable electrical gage networks. If necessary armored cable may be used.

After verifying the practicability of manufacturing the FBG sensor according to the structural characteristics, sample size and shape of the rock host, other uses can be projected founded on the same principle, such as:

- Developing multiple sensing networks for some of the main rock mechanics test, such as: uniaxial tension, indirect tension, uniaxial compression, triaxle compression, direct shear or beam bending, for example. An interesting possibility is to use strain FBG sensor for creep and relaxation testing of rocks; using stress or strain control, the rock can be fatigued with any frequency and stress or strain amplitude. In any of this tests, the thin optical fiber maybe use in order to obtain the stress distribution throughout the specimen.

- In rock mechanics is well-known the size effect, in which the dimensions of the rock sample influences the mechanical behavior studied, the Figure 7.1 shows the complete stress-strain curve for a rock sample under uniaxial compression test, it is visible that if size increase the strength decreases. The use of sensors of larger area may decrease the influence of the sample size on the rock mechanical properties. Samples of small size maybe better studied increasing the size of the sensors or using FBG fitted to rock size, thus “mean” mechanical parameters should be obtained and scattering due to size effect will be reduced.
Figure 8.1. The size effect in the uniaxial stress-strain curve. This dependence is generally attributed to the presence of fractures and cracks in larger specimens than in smaller specimens. From Hudson J., Harrison J., (2007).

- Developing woven fabric deformation sensor or pressure sensor for rocks under loading tests.
- Developing localized or areal FBG sensors, in order to measuring variables such as pressure, humidity, temperature, displacement, and acceleration on rocks, both in the laboratory and in the field. For some of these applications, other packaging materials may be required to obtain higher strength or stiffness; according to the mechanical performance of the GRP sensor, may be used materials such as carbon fiber, metal foils and another.
- Monitoring irregular structures of rocks in works subjected to deformation processes.
- Some applications of FBG sensor in Structural Health Monitoring requires applications for concrete structures, therefore can be developed specific sensors for concrete specimens in shapes and sizes as needed, following the bases explained in this thesis. This is because the concrete is heterogeneous and anisotropic, having fractures and various components, similarly to the rocks.
- It is suggested to develop appropriate FBG sensor packaging for rocks and building materials such as wood, concrete, masonry, bricks, etc.
References


