FINITE ELEMENT ANALYSIS OF A TI6AL4V (ELI) MEDICAL IMPLANT PRODUCED THROUGH ADDITIVE MANUFACTURING

LEHLOHONOLO FRANCIS MONAHENG

Dissertation submitted in partial fulfilment of the requirements for the degree
Master of Engineering in Mechanical Engineering

in the

Department of Mechanical and Mechatronics Engineering
Faculty of Engineering and Information Technology
Central University of Technology, Free State

Supervisor: Prof WB du Preez
Co-supervisor: Mrs A Olwagen

December 2017

Declaration

I, Lehlohonolo Francis Monaheng, hereby declare that the study submitted for the Master of Engineering in Mechanical Engineering in the Department of Mechanical and Mechatronics Engineering, Central University of Technology, Free State, is my own original work and that I have not previously submitted this work, either as a whole or in part, for a qualification at another university or at another faculty at this university.

I also hereby cede copyright of this work to the Central University of Technology, Free State.

Signature of student Date

....

Acknowledgements

First of all, I give all the praise and glory to Almighty God for enabling me to complete this study.

I wish to express my sincere thanks to my supervisor, Prof WB du Preez. He has set aside plenty of time to provide me with all the support, sincere and valuable guidance and often much needed encouragement.

I place on record my sincere gratitude to my co-supervisor, Mrs A Olwagen, and my technical advisor, Mr P Haupt, for the continuous writing and mechanical engineering technical support.

I also thank Mr JA Bothma my former supervisor in this study for introducing me to the research field and providing me with the very first guidance in the field of research. I also thank my former co-supervisor Mr M Potgieter for the mechanical and technical support.

I take this opportunity to express my sincere gratitude to the following departments for their financial support: Department of Higher Education and Training, Department of Science and Technology under the South African Research Chairs Initiative and the Collaborative Program in Additive Manufacturing and the Department of Mechanical and Mechatronics Engineering at the Central University of Technology. I am extremely gratefully for the valuable support extended to me by these departments.

Furthermore, I also take the opportunity to thank Mr C Visser and Mr P Naudé from ESTEQ Engineering for the assistance with regard to the strain gauges' installation and finite element analysis support, respectively.

To my family, friends and colleagues thank you very much for helping me to manage the work load and not letting me give up.

Abstract

Medical implants created by Ti6Al4V (ELI) through Additive Manufacturing (AM) processes have a very positive impact on the quality of life of patients who have undergone skeletal reconstructive surgery. The effectiveness of medical implant design for AM processes would be significantly improved if finite element analysis (FEA) could be established as an accepted design tool. This study is aimed at validating FEA as a tool for predicting the strain distribution in a Ti6Al4V (ELI) medical implant produced through a selective laser melting (SLM) process by comparing the FEA results with strain gauge measurements.

The approach followed was to demonstrate the correlation between an FEA model and strain gauge measurements performed on a human mandibular implant. For the design of the mandibular implant the geometrical data of an adult human mandible obtained from a computer tomography (CT) scan was transferred to a computer-aided design (CAD) software package. A CAD model based on this data, which was suitable for experimental validation, was used for FEA when subjected to typical static mastication load condition. Through this FEA simulation the distribution of strain in the implant under basic functional condition was determined. Using the same CAD model, an implant was manufactured through SLM and strain gauges were mounted on the implant at locations corresponding to the areas of significant strain as determined on the FEA model.

The results obtained from both FEA and strain gauge measurements were compared and a correlation within a deviation of less than 10% for most of the measurements was obtained. Requirements for achieving this level of correlation were determined. It was concluded that FEA is indeed a powerful tool for improving the effectiveness of design for AM of medical implants.

Keywords: Finite element analysis, Strain gauge measurements, Additive manufacturing, Medical implants, Ti6Al4V (ELI) material.

Publications Resulting from this Research

a) L.F. Monaheng, W.B. Du Preez, A. Olwagen and P. Haupt, "Strain gauge validation of finite element analysis of a Ti6Al4V (ELI) mandibular implant produced through additive manufacturing", Proceedings of the 17th Annual International Conference of the Rapid Product Development Association of South Africa, 2016. ISBN 978-0-620-72061-8

b) T.C. Dzogbewu, L.F. Monaheng, J. Els, I. van Zyl, W.B. Du Preez, I. Yadroitsava, and I. Yadroitsev, "Evaluation of the compressive mechanical properties of cellular DMLS", Proceedings of the 17th Annual International Conference of the Rapid Product Development Association of South Africa, 2016. ISBN 978-0-620-72061-8

Table of Contents

List of Figures

List of Tables

Abbreviations

AM	Additive Manufacturing
ASTM	American Standard Testing Method
CAD	Computer Aided Design
CRPM	Centre for Rapid Prototyping and Manufacturing
CSIR	Council for Scientific and Industrial Research
CT	Computer Topography
CUT	Central University of Technology
CNC	Computer Numerical Control
DAQ	Data Acquisition
DED	Directed Energy Deposition
DMLS	Direct Metal Laser Sintering
DSPI	Digital Speckle Pattern Interferometry
ELI	Extra-Low Interstitial
FEA	Finite Element Analysis
FEM	Finite Element Method
FDM	Fused Deposition Modelling
GF	Gauge Factor
HBM	Hottinger Baldwin Messtechnik
NLC	National Laser Centre
PC	Personal Computer
RMS	Reinigungsmittel Spray
SG	Strain Gauge
RP	Rapid Prototyping
SLS	Selective Laser Sintering
.stl	Standard Triangulated Language
SLA	Stereolithography
SU	Stellenbosch University
3D	Three Dimensional
TiCoC	Titanium Centre of Competence

TMJ	Temporomandibular Joints
VUT	Vaal University of Technology
UTS	Ultimate Tensile Stress
YS	Yield Strength

Chapter 1: Introduction

1.1. Background

The manufacturing of complex and customer-specific medical implants is made possible through additive manufacturing (AM) processes and the benefits that patients can enjoy are often much better than with the conventional standard implants. However, it has been reported that these AM manufactured implants often fail due to several factors, such as poor design, manufacturing malpractices, installation procedures and aggressive operational conditions [1]. In order to obtain a medical implant of high quality, the design should be optimized. Finite Element Analysis (FEA) could be used as a powerful tool to achieve optimal medical implant designs with regard to strength and durability. FEA makes it possible for designers to identify potential implant weaknesses before manufacturing commences and allows them to modify the initial design in order to achieve improved mechanical properties of implants. However, it is imperative for FEA models to be validated through appropriate experimental measurements, before these can be generally applied and relied on.

Two recognised techniques that are used to validate FEA are strain gauge measurements and optical sensoring [2]. Strain gauges can be used for accurate validation of FEA, provided that the preferred positions of the gauges on the surface of the FEA model correspond accurately with those on the experimental model [3]. With such compliance, the magnitude of the principal strain can be compared between an FEA model and experimental results obtained with strain gauges, as the strain gauges can be installed in the direction of the strain as determined from the FEA model.

1.2. Problem statement

The effectiveness of the process of designing a medical implant for production by AM can still be improved, because poorly designed AM implants, as well as implant failures, still occur. An implant designed without due consideration of mechanical properties needed for typical operational conditions results in unexpected failure. Furthermore, designing an implant without utilising FEA could lead to over design or under design. Such designs could be an implant which is unnecessarily bulky or an implant which is too thin to the extent that it is structurally weak. This could be significantly improved if the stress and strain distribution that an implant experiences during operational conditions could be predicted during the design phase before proceeding to the AM process. FEA offers the ability to calculate such stress and strain distributions and allows consideration of these in the design process. However, to establish confidence in the FEA modelling approach as design tool for AM components, FEA models of typical medical implants must be validated through experimental verification.

1.3. Aim of the study

The aim of this study is to establish confidence in FEA as a powerful design tool during design for AM by validating an FEA model of a mandibular implant produced by AM in Ti6Al4V (ELI) through experimental strain gauge measurements.

1.4. Objectives

a) To design a mandibular implant that would allow the strain distribution under typical operational load conditions to be determined through FEA and strain gauge measurements to be performed.
b) To predict through FEA the strain distribution in the mandibular implant under selected static load conditions obtained from typical mastication conditions.
c) To determine the strain distribution in a mandibular implant produced by AM from the CAD model of the implant through strain gauge measurements.
d) To compare the FEA and strain gauge results to validate the FEA model.

1.5. Layout of the dissertation

The layout of the dissertation is shown in Figure 1.1. Chapter 1 provides the background to the study, the problem statement and the aim and objectives of the study. In Chapter 2 the literature study that was conducted to determine the boundary conditions applicable to the mandibular implant and to investigate what has been done in this field, is presented. Thereafter, in Chapter 3 the research methodology followed for the FEA modelling and the experimental testing is explained. In Chapter 4 the FEA and experimental results are presented and discussed. Assessments of the correlation between these two types of results are made. Finally, Chapter 5 presents the conclusions drawn from the study.

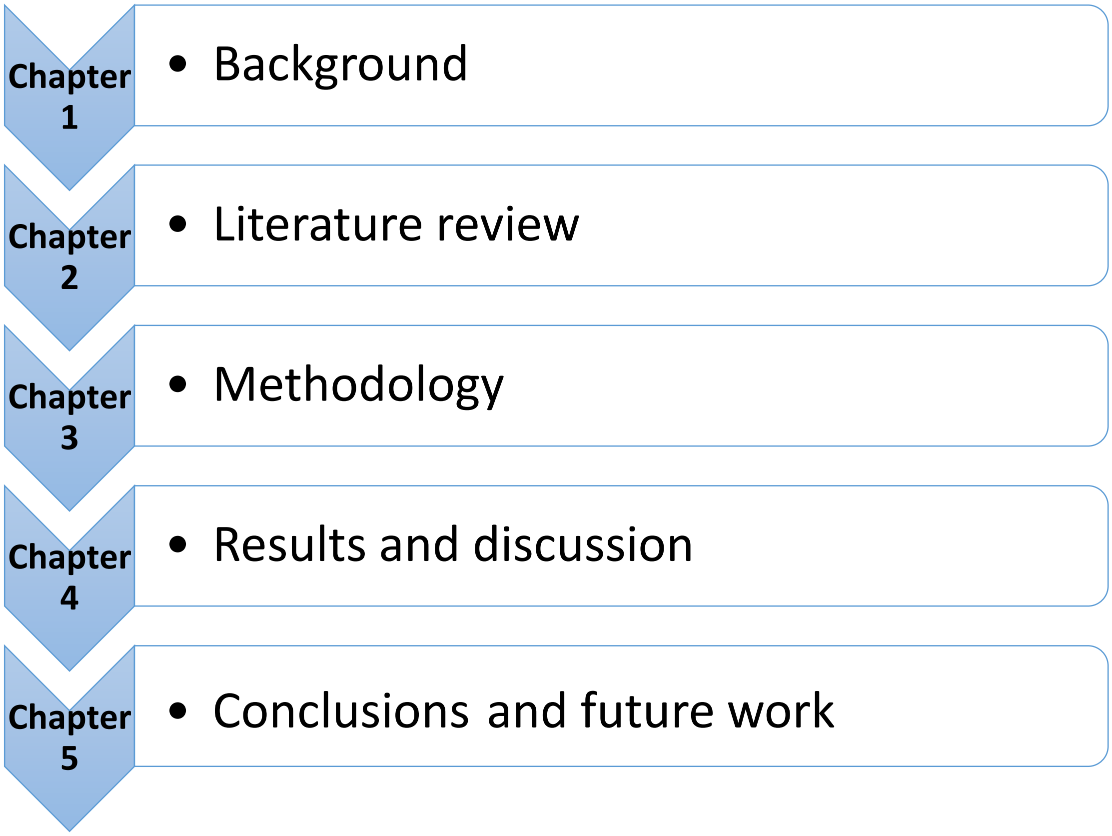


Figure 1.1: Dissertation layout.

Chapter 2: Literature Review

2.1. Introduction

A human mandible is the lower jawbone that is used for chewing, speaking and protecting the contents of the oral cavity. It performs its function through the help of jaw muscles which control its movement and regulates the forces acting on the teeth for biting and chewing food [4]. Unfortunately, cancer, trauma, other pathologies and congenital defects can result in the degradation of the mandible and may lead to its malfunction [5].

The replacement of degraded parts of the human skeleton with additively manufactured metal implants is a potential solution [6] to such patients' discomfort. To date, AM has been extensively applied for the fabrication of customized medical implants directly from a geometric model generated through a three dimensional CAD system (e.g. SolidWorks®, Pro/Engineer, CATIA) without the need for tooling processes [7]. However, various factors such as the material used for manufacturing an implant, implant loading conditions and the method used for fixation of the implant, could all lead to an implant failure [8][9]. This can result in significant disabilities, deformation of the facial geometry and dysfunction of the implanted components. Furthermore, it would also impose a financial burden and increased workload on the healthcare system worldwide [10].

FEA has been extensively applied to evaluate the stress distribution of conventionally manufactured implant designs [11]. However, there is a need for widespread use of FEA as a design tool for predicting the stress and strain distribution in Ti6Al4V (ELI) medical implants produced through AM. In this chapter the process of medical implant designs for AM and validation of FEA are reviewed.

2.2. Additive manufacturing applied to medical implants

2.2.1. Background on additive manufacturing

According to the ASTM standard F2792-10, AM is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technology" [12]. AM technology is applied through various processes, such as Stereolithography (SLA), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS) and Three-dimensional (3D) Printing [13]. Currently, AM processes are divided into seven categories, namely Vat Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Sheet Laminating, Direct Energy Deposition and Powder Bed Fusion [14].

AM is seen by many as the next chapter in the industrial revolution, especially when it is applied to metal products. AM processes have specific advantages over conventional ways of manufacturing, such as injection moulding, computer numeric controlled (CNC) machining and milling. These advantages are, among others, minimum material wastage, the ability to create complex detail and the elimination of intermediate processing steps used in traditional manufacturing methods [15]. In CNC machining as an example, the intermediate processing steps such as solid material clamping, tool setup and machine programming are eliminated if AM is used. The AM process chain passes directly from a 3D CAD model to production of an end product [15].

In Europe AM was recognized as a key emerging technology to produce more innovative, customized and sustainable products, while utilising low volumes of material [6]. In addition, Europe's AM Platform identified two distinct markets in which AM has flourished. These are the production market (for example medical implant-, dental implant-, aerospace-, automotive production and power generation) and the consumer market, such as home accessories, fashion and entertainment [6].

In South Africa the Department of Science and Technology, through the Collaborative Program in Additive Manufacturing, has shown a keen interest in qualification of AM of Ti6Al4V for medical implants and aerospace components [16]. Through this program various research projects were stimulated and the current study was funded. The study contributes to the qualification of AM of Ti6Al4V medical implants through establishing computational modelling as an important tool for design for AM.

2.2.2. Additive manufacturing at CUT

In 1997, the Central University of Technology (CUT) (at the time known as the Technikon Free State) was the first university in SA to establish a Rapid Prototyping (RP) centre, known as the Centre for Rapid Prototyping and Manufacturing (CRPM). About eleven years later the CRPM was recognized as the national centre of excellence for utilising titanium alloy powder in the field of AM (RP had evolved into AM). Today it is recognised as the leading centre for metal AM in South Africa. CUT also collaborated with the National Laser Centre (NLC) at the CSIR and Stellenbosch University (SU) to apply their AM machines for successfully building qualified customized medical implants from titanium (Ti6Al4V) powder. Apart from this, CUT has been collaborating successfully with orthopaedic and maxillo-facial surgeons locally and internationally in manufacturing medical implants. As a result of the rising interest in AM, the Titanium Centre of Competence (TiCoC) included a focus area on producing customized titanium parts through AM processes in its portfolio [6]. The TiCoC program has shown that there is a need for research that will provide insight into locally available metal AM technologies and their ability to deliver components that consistently comply with the required physical and mechanical properties of industrial applications such as medical implants [16].

2.2.3. Direct metal laser sintering (DMLS)

Starting in 1994 DMLS was developed as the first commercial AM method to produce metal parts [17]. DMLS is a powder bed fusion technology, in which a layer of metal powder particles, such as Ti6Al4V, is fused with a laser beam. The laser beam is controlled directly from 3D CAD visualization data (.stl file) to follow the contours of the particular layer and eventually, layer upon layer, build a component, such as a medical implant.

In the powder bed method as illustrated in Figure 2.1, the layer of powder is evenly distributed onto the powder bed by a roller or wiper blade which sweeps an even layer of powder from a powder dispenser platform over a building platform. Thereafter, the laser beam which passes through lenses and is directed by a scanning mirror onto the powder bed, fuses the powder particles into a solid layer before further layers of powder are distributed onto the building platform and fused onto the existing layer to manufacture a three dimensional part.

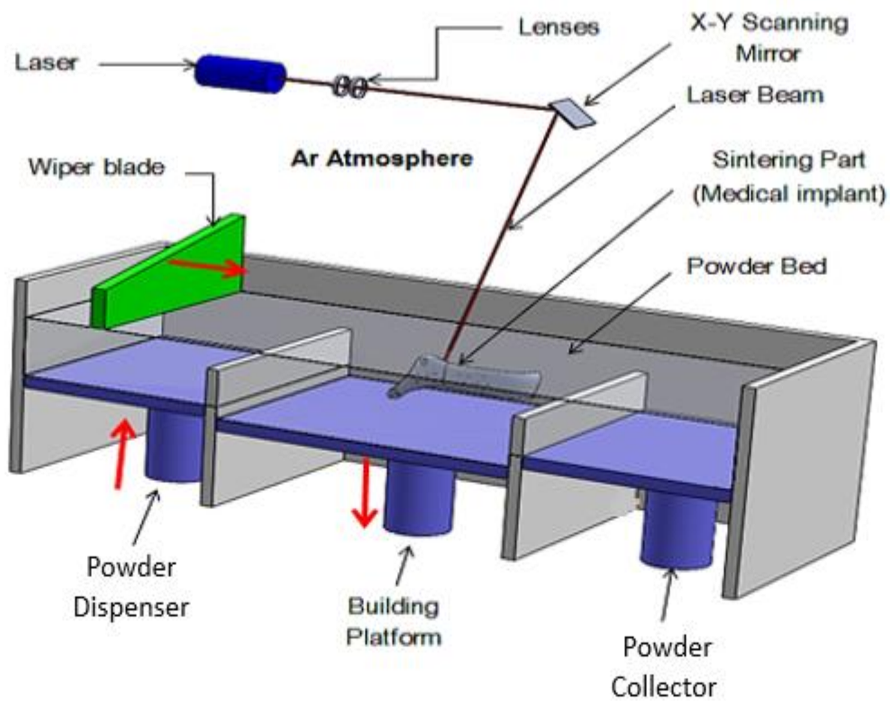


Figure 2.1: Direct Metal Laser Sintering Process.

2.2.4. Residual stress in AM components

Residual stresses are defined as the stresses induced by manufacturing processes and that remain in a component that is not subjected to any external load. These stresses have a negative influence on the reliability and mechanical properties of components, such as fatigue life, fracture toughness and corrosion or wear resistance [18][19]. Therefore, residual stresses should be relieved and, where possible, also measured. However, measuring residual stress in both magnitude and direction is complicated. Nevertheless, various residual stress measurement techniques have been developed, such as X-ray and neutron diffraction, ultrasonic velocity, hole drilling, layer removal techniques and the stress relaxation method [20].

During DMLS the layers undergo repeated heating, melting, solidification and cooling cycles as more layers are added [21]. Consequently, residual stress is generated in the manufactured component due to the thermal gradient induced through this process. To release the residual stresses in a component such as a medical implant produced through DMLS, a stress relieving heat treatment is performed. Through further controlled heat treatment, the following can be obtained: the most acceptable combination of ductility, machinability, dimensional accuracy, structural stability and, most importantly, the optimization of fatigue properties and strength [22].

2.3. Mandible anatomy

2.3.1. Mandible characteristics

The word mandible was derived from Latin, in which "mandere" means "to chew". The mandible carries the lower teeth opposite to those on the upper jaw and provides attachment to the muscles of mastication [23] (see Figure 2.3). Furthermore, the mandible is the largest and strongest bone of the face and it has a horizontally convex-forward curved body. Its ramus ascends posteriorly to support the coronoid and condylar process [24]. The various facets of a mandible are illustrated in Figure 2.2.

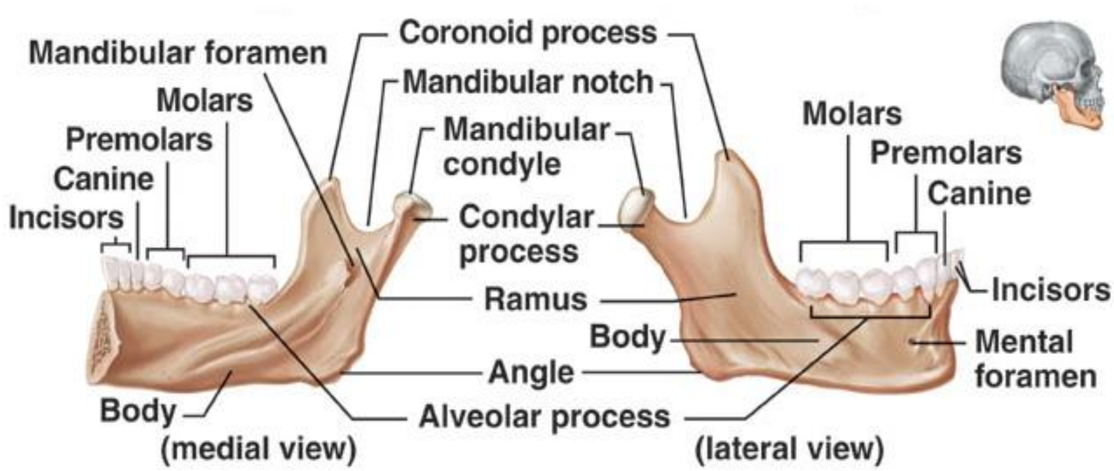


Figure 2.2: Medial and lateral view of the human mandible.

The design and selection of a material to reconstruct part of a mandible should resemble the original bone mandible as closely as possible. In addition, the understanding of the mechanics of a human mandible is vital for the design of an effective mandible implant.

2.3.2. Mandible mechanics

The mandible is the only bone in the skull that is capable of individual movements. It moves with respect to the skull and is guided by two mutually linked temporomandibular joints (TMJ) through the contraction of the mastication muscles. At the TMJs the condyles of the mandible articulate incongruently (meaning, different in nature as to be incapable of coexisting) with the articular surface of the temporal bone (see the TMJ in Figure 2.3). As a result of this articulation, the joint is allowed to move in six degrees of freedom (namely translation in x, y and z and rotation about x, y and z axes as shown in Figure 2.4(b)) [25].

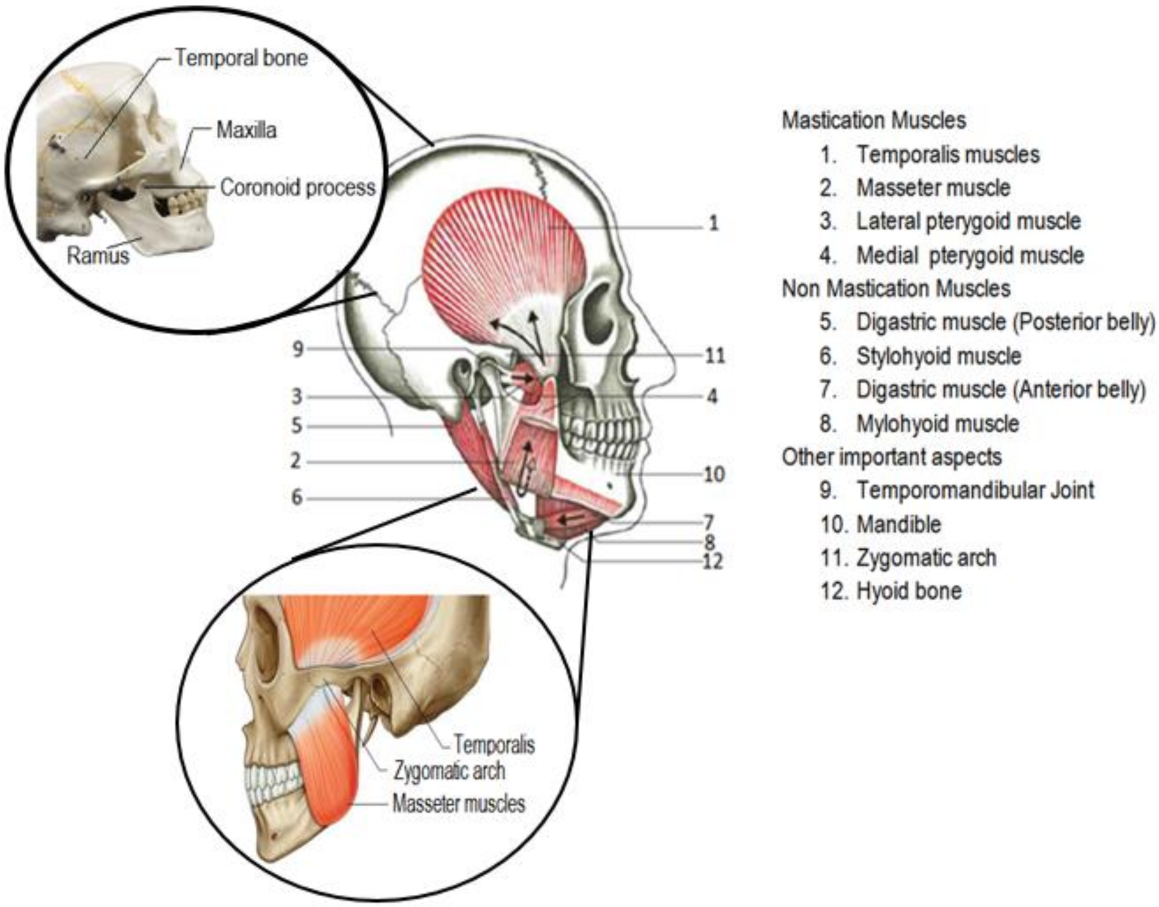
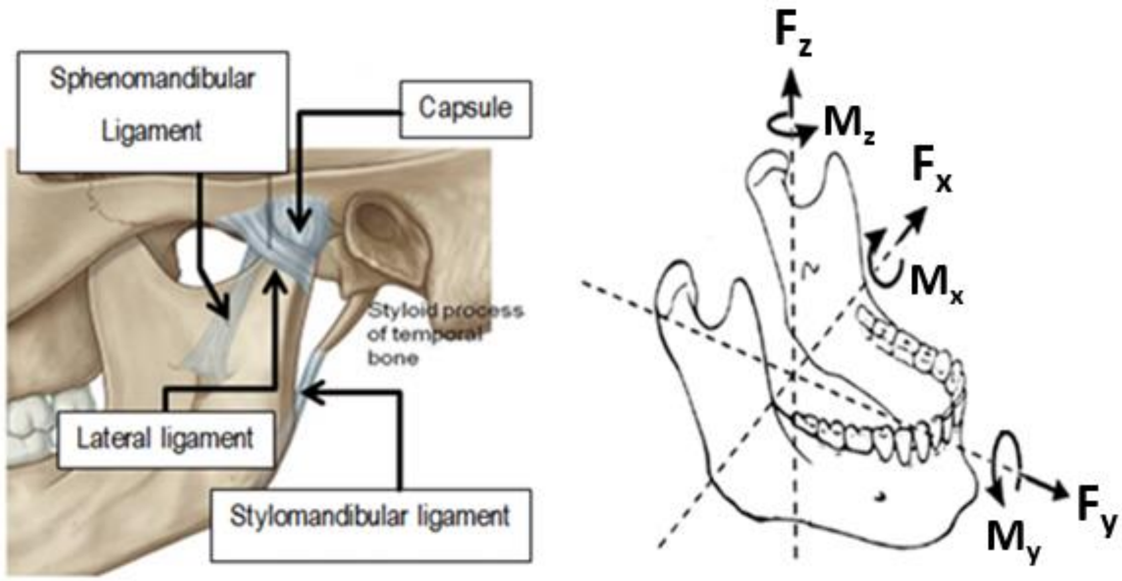


Figure 2.3: Illustration of the muscles and features of the human mastication system [26]***.***

Furthermore, the active mastication muscle forces that cause the lower jaw movement also have six components since a moving body obeys Newton's law of motion [27]. For each movement there is a linear force (F_x, F_y, F_z) that is accompanied by a moment or torque (M_x, M_y, M_z). In addition, these active forces are balanced by the passive (reaction) forces generated by the joint ligament, such as the sphenomandibular, stylomandibular and lateral ligaments, to keep the mandible attached to the skull [28]. In Figure 2.4 (a) and (b) the ligaments that help to restrict excessive movement and the six degrees of freedom of the mandible, respectively, are illustrated. The dashed lines represent the principal axes along and about which movements take place. Furthermore, F_x, F_y, and F_z represent the translating movements allowed along the x, y and z axes, while M_x, M_y and M_z represent the rotation about the x, y and z axes [28].



(a) Mandible's ligaments (b) Mandible motion's degrees of freedom

Figure 2.4: (a) Ligaments related to the mandible and (b) diagram in which the six degrees of freedom in which the mandible is allowed to move are indicated [28].

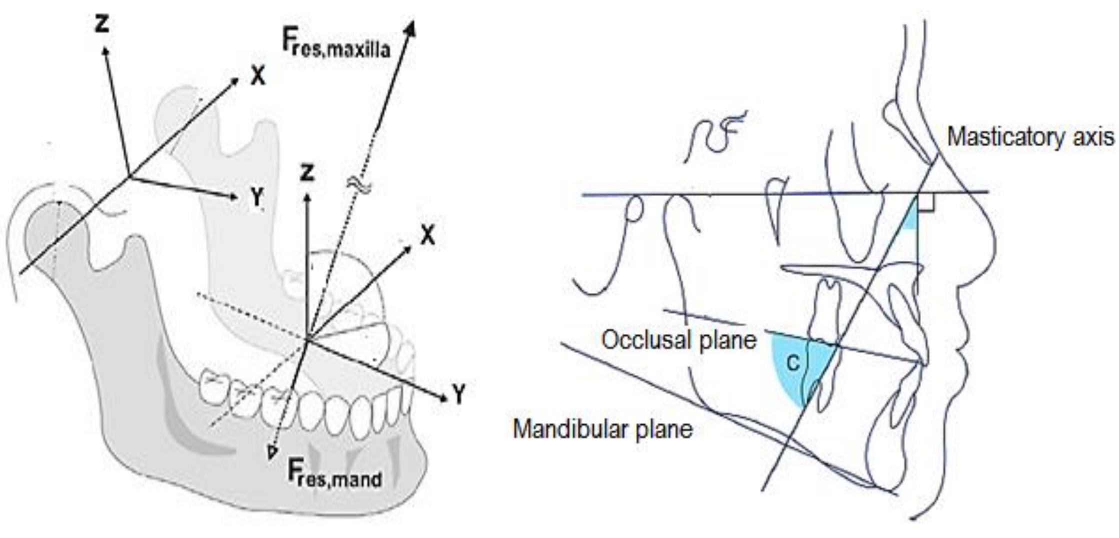
In order to understand the science of the motion and forces acting on the lower jaw, it is important to recognize the load- and boundary conditions of the mandible, allowing analysis and modelling of this using computational software. It is also important to take these load and boundary conditions into consideration when designing a mandible implant.

The muscles involved in the mastication process must be able to exert enough pressure to bite through and chew food before it is swallowed [29]. It was recorded that the magnitude of the resultant static biting force ranges from 246,9 N to 2091,9 N [30][31]. The masseter muscle contributes more load than other muscles of mastication to retract and elevate the mandible [32]. This muscle originates from the zygomatic arch and is attached to the ramus of the mandible to gain a large amount of leverage needed for biting and chewing. It is assisted by the temporal muscle to open and close the mouth, which originates from the temporal bone and is attached to the coronoid of the mandible. Moreover, the medial and lateral pterygoid muscles provide assistance in chewing and moving food within the mouth.

The Medial pterygoid originates from the sphenoid and maxilla, and the lateral pterygoid from the pterygoid process of the sphenoid bone [29].

The lines of action of the mastication muscles' forces act in different directions since they do not originate from the same area on the skull and attach to the same area on the mandible. However, their resultant vectors (magnitude and direction) can be estimated by electromyography (electrical activity muscle tissue recorder) [33]. In Figure 2.5 (a) the resultant force acting on the maxilla ($F_{res,maxilla}$) and the resultant force acting on the mandible ($F_{res,mand}$) during static biting/mastication, is represented. These resultant mastication forces are significantly influenced by the direction of the lines of action [33].

The cephalogram, which is defined as the analysis of the dental and skeleton relationship, done by Sato et al., states that the typical angle between the masticatory axis and the occlusal plane is approximately 69^0 [34]. They also indicated that the angle between the occlusal plane and the anterior border of the masseter muscle remains approximately 69^0, which suggests that the resultant force acts in the direction of the masticatory axis. In Figure 2.5 (b) the occlusal plane and masticatory axis are illustrated, where C represents the angle between them (69°).



(a) Line of action of the resultant force (b) Masticatory axis

***Figure 2.5: Schematic view of mandible showing the mandibular reference plane and the masticatory axis* [33].**

Other very important data to be considered when designing a mandible implant is the reconstruction of the TMJ. It has been accepted that a ball-and-socket design could be a good replacement of the TMJ.

This replacement reduces the degrees of freedom of the articulation bone. Thus, all of its translational degrees of freedom are restrained and only three degrees of freedom are allowed i.e. rotation about x, y and z. [28]. These load and boundary conditions are very important for the CAD design, FEA and experimental analysis of the mandible implant.

2.4. Medical implant design

2.4.1. Computer aided design

The appropriate design of a mandibular implant is imperative for its successful application in maxillofacial reconstruction surgery. The conventional reconstruction methods of a mandible, such as bone grafting, are difficult to adjust according to the anatomical form of an individual's mandible [35] because the plates used are usually manually bent by a surgeon during the surgery. As a result, the restoration of the facial geometry, jaw relationship and the condylar position is difficult to attain. Furthermore, it has been proven that an inappropriate design can lead to a mismatch between an implant and the remaining bone and that it can be painful and may cause implant failure [36].

Today, CAD is extensively used to design medical implants. An example of such a medical implant is a mandible implant for the reconstruction of a lower jaw [36][37]. The CAD systems available today offer solutions for the planning of the maxillofacial reconstruction surgery in relation to the aesthetic outcomes and final prosthetic and functional rehabilitation [38]. An accurate CAD design model is based on high-resolution computer tomography (CT) scan data of a maxillofacial skeleton. This data is used to design the lower jaw implant. In Figure 2.6 the CT scan data obtained from a patient with a defect in the right hand side of the lower jaw is shown. A CT scan is done on a patient to achieve 3D visualization of his/her skull. Thereafter, the affected area is removed and replaced by a mirrored unaffected part. Finally, the implant CAD model is generated prior to commencement of the FEA and manufacturing processes.

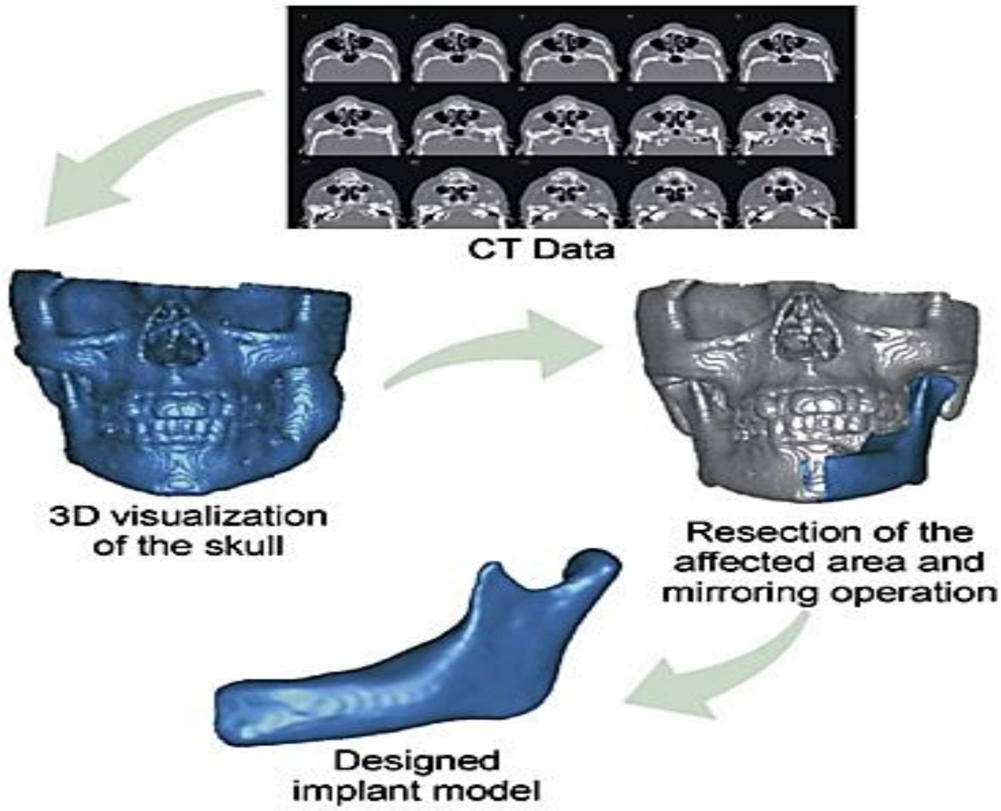


Figure 2.6: Illustration of how CAD data is commonly derived from CT scan data [39]**.**

Another important stage in the design is to select and assign an appropriate material from which the implant could be manufactured. Material properties to consider can include chemical composition, physical- and mechanical properties as well as bio-compatibility. The material selected in this study is titanium Ti6Al4V (ELI) for a number of reasons which will be discussed in the following paragraph.

2.4.2. Titanium alloys for medical implants

Over the past decades metals have been successfully used as biomaterial in the medical field [9]. The materials commonly used in the human body are stainless steel, cobalt-chromium alloys and titanium and its alloys [39]. Titanium, unlike other metals, shows little or no reaction with the tissues surrounding an implant. Furthermore, it is corrosion resistant due to the stable oxide layer on its surface. In addition, this layer can reconstruct itself at body temperature when it is damaged [39]. The most commonly used titanium alloy in the biomedical industry and in reconstructive surgery is Ti6Al4V with extra low interstitial (ELI) content, because of its beneficial properties. For example, Ti6Al4V (ELI) offers superior properties when it is used in an implant with structural loading, because of its high yield- and ultimate tensile strengths, as well as good ductility as compared to other bio-compatible titanium alloys. Its annealed mechanical properties reported for medical application are shown in Table 2.1.

Table 2.1: Typical Ti6Al4V (ELI) tensile properties.

Elastic/Young's modulus (GPa)	Ultimate Tensile Stress (MPa)	0.2% Yield Strength (MPa)	Elongation (%)	Reference
110	965	875	10-15	[40]
114	860	795	10 or more	[41]
101	922	870	-	[42]

Furthermore, to ensure high quality in Ti6Al4V parts, repeatability and consistency during the AM building and machining processes and adherence to the latest international standards (e.g. ASTM F2924-12) for AM industry developments, process, calibration and testing [43] are imperative.

2.5. FEA of medical implants

2.5.1. Application of FEA

A CAD design is commonly tested through FEA in order to verify its structural strength and stiffness [44], provided the material properties of the analysed part are known. FEA makes it possible for designers to identify a component's weaknesses before manufacturing commences and allows the user to make changes or to modify the initial design in order to optimize it in terms of strength and materials used. This process is often referred to as the design loop and is used worldwide for obtaining an improved final design that can be used in a manufacturing process. A typical design loop in the AM industry is illustrated in Figure 2.7.

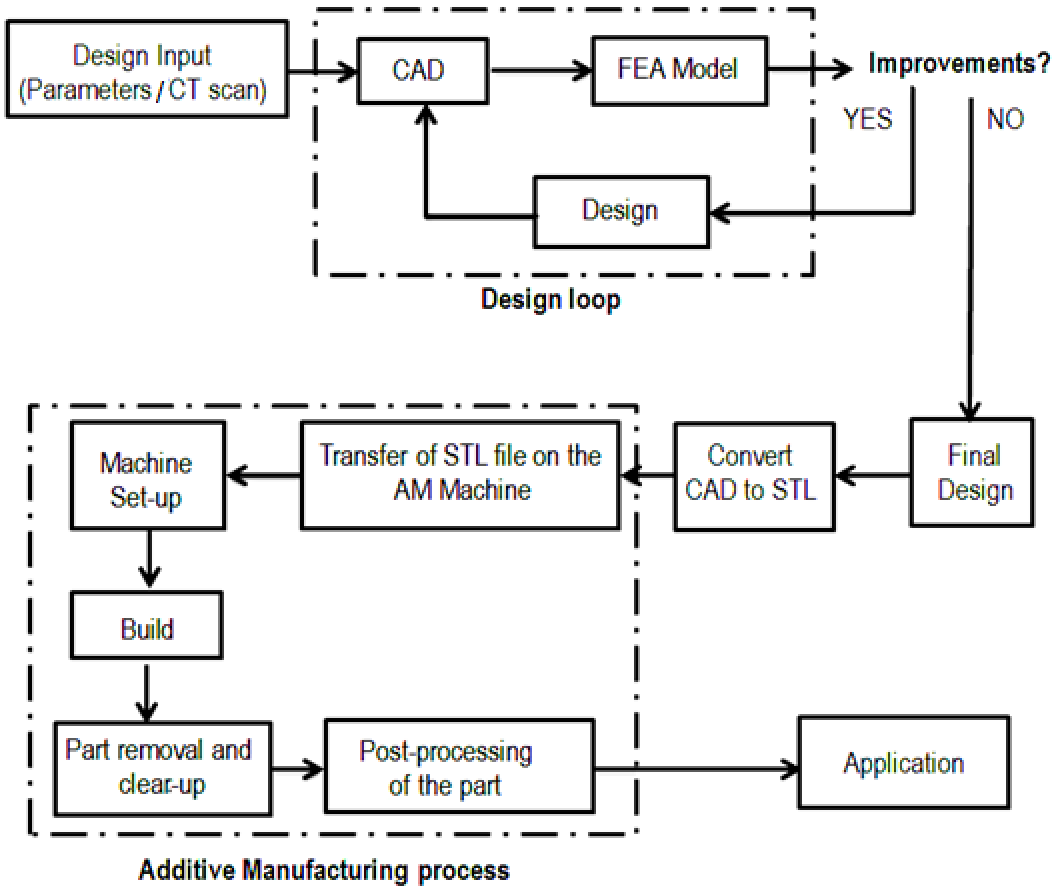


Figure 2.7: Computational design and additive manufacturing flow chart.

Finite element method (FEM) provides numerical solutions for complicated stress-strain problems that cannot be obtained routinely [45]. In essence, it is a numerical method for solving physical problems which are governed by differential or integral equations [46]. It is widely used in the analysis of solid, structures, heat transfer and fluid mechanics. Extensive research and publication have been done on FEM since the early 1960s [47]. In the field of biomechanical engineering, FEM is commonly used to simplify the analysis of the design of conventionally manufactured medical implants [48] and it has been shown that FEA reduces the product development time and expenses by obtaining a good design before manufacturing processes commence. In a similar way, FEA could be used as a valuable tool to qualify complex titanium medical implant designs for additive manufacturing. However, an FEA model requires experimental analyses to validate it [49]. In fact, the results of the final design are dependent on input information (parameters). If the inputs are inaccurate, then the results will be inaccurate [50]. Additionally, the material properties, boundary conditions and mesh size also influence the accuracy of FEA. Furthermore, it is clear from Figure 2.7 that if the final design is incorrect the process of AM will yield a defective or inferior product, which will lead to poor quality of the product. This is the rationale for the current study aimed at validating FEA modelling as a tool to predict the strain distribution of a Ti6Al4V medical implant produced by AM through physical experimentation.

2.5.2. Basic principles of FEM

The solution of an engineering system (general continuum problem) using the finite element method (FEM) always follow an orderly step-by-step process [51]. The first step is the discretisation of the continuum which refers to the division of a region into finite elements. This includes scalar parameters (such as number of nodes, number of elements etc.), material properties, coordinates of nodal points, connectivity array of finite elements, array of element types, array for description of displacement boundary conditions, as well as, array for description of surfaces and point loads. The process is executed by the pre-processor program to generate the finite element mesh for the whole system [51]. In Figure 2.8 the finite element types are illustrated with their typical applications.

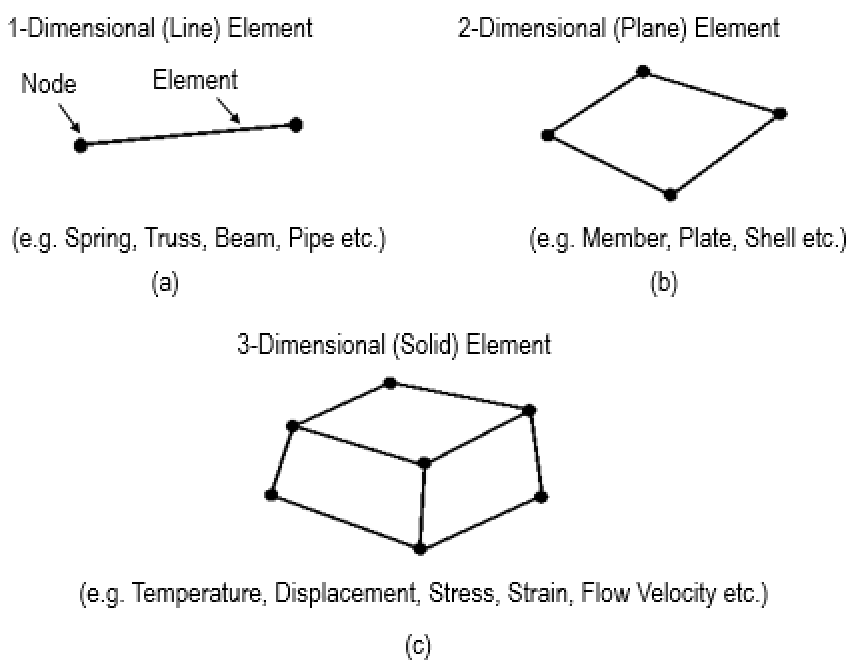


Figure 2.8: Illustration of some common finite element types with their typical applications with a line and dot represents element and node, respectively.

The second step is the selection of an interpolation function. In this case the variables are interpolated over the element. In many instances, a polynomial [52] is selected as the interpolation function. For the analysis of solid mechanics (or 3D mesh), such as medical implants, the second complete polynomial (ten-node tetrahedron or Tet 10 as it is called in programming) which is also known as a quadratic tetrahedron is commonly used, because it behaves significantly better than other polynomials such as a four-node (linear) tetrahedron. In addition, it retains the geometry favour in 3D mesh generation and allows the curve face and side [53]. In Figure 2.9 the illustration of quadratic tetrahedron elements is shown.

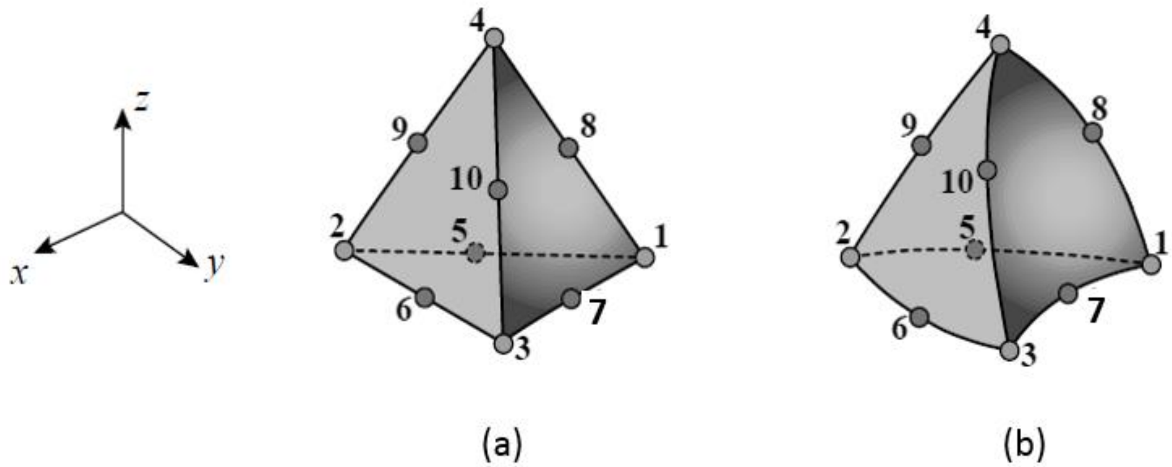


Figure 2.9: The quadratic (ten-node) tetrahedron (a) elements with planar faces and side nodes located at midpoints; (b) elements with curved faces and sides.

Such an element has four corner nodes with local number 1 through 4 and on its sides there are six nodes with local number 5 through 10. Nodes 5, 6, 7 are located on sides 1 - 2, 2 - 3 and 3 – 1, respectively. These side nodes do not necessarily lie on the midpoints of the sides but may deviate from these locations, subject to the Jacobian-determination (change of variables in multiple integral) constraints [47]. On the other hand, each element face in Figure 2.9 (a) is defined by six nodes which do not necessarily have to lie on the plane, but they should not deviate too much from it. This freedom allows the element to have curved sides and faces as indicated in Figure 2.9 (b).

For basic understanding of the element interpolation function, the linear shape function is discussed using one-dimensional element as shown in Figure 2.10 with three nodes.

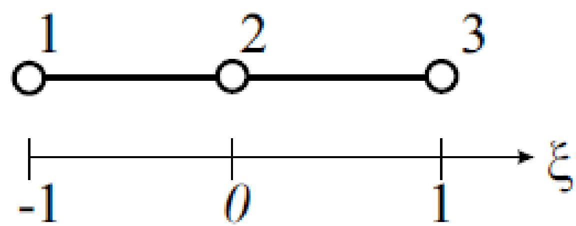


Figure 2.10: One-dimensional element with local coordinate system of -1 ≤ ξ (stretch of the element) ≤ 1.

With the shape function, any field inside the element is represented equation 2.1:

$$u(\xi) = \sum N_i u_i, \; i = 1, 2, 3 \quad (2.1)$$

Where N_i is called a shape function and represents an unknown function. Moreover, at the nodes the approximated function should be equal to its nodal values:

$u(-1) = u_1$

$u(0) = u_2$

$u(1) = u_3$

Since the element has three nodes [51]. Shape function 1 (N_1) can be written as follow:

$$N_1 = \alpha_1 + \alpha_2\xi + \alpha_3\xi^2 \quad (2.2)$$

α_i refers to an unknown coefficient which are defined from the system of equations shown below:

$N_1(-1) = \alpha_1 - \alpha_2 + \alpha_3 = 1$

$N_2(0) = \alpha_1 = 0$

$N_1(1) = \alpha_1 + \alpha_2 + \alpha_3 = 1$

The solutions are as follows: $\alpha_1 = 0, \; \alpha_2 = -\frac{1}{2}, \; \alpha_3 = \frac{1}{2}$. Consequently, the shape function N_1 is given by:

$$N_1 = -\frac{1}{2}\xi(1 - \xi) \quad (2.3)$$

Similarly, it is possible to obtain the shape functions N_2 and N_3 which are expressed by equation 2.4 and 2.5, respectively.

$$N_2 = 1 - \xi^2 \quad \text{(2.4)}$$

$$N_1 = \frac{1}{2}\xi(1 + \xi) \quad \text{(2.5)}$$

Finally, Figure 2.11 illustrates these shape functions.

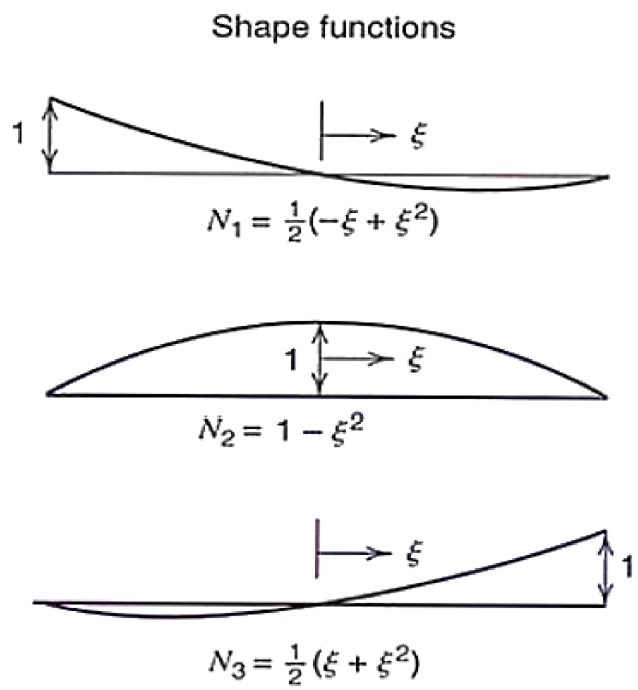


Figure 2.11: Illustration of the shape functions N_1, N_2, N_3 of the quadratic element [54].

The third step in FEM is to find the element properties. In this step the finite element matrix equations are established which refer to the nodal values of the unknown function related to other parameters. The stiffness matrix k^e of the element has to be derived. For example, when a uniaxial bar such as a strut is part of a structure and a force is applied on it, its ends will be able to move due to displacement of the structure and the deformation of the member. This may be modelled by a single element as shown in Figure 2.12. In the case where the spring element is used to represent a strut of length L and area A the spring stiffness will be given by:

$$k_1 = \frac{AE}{L} \qquad (2.6)$$

Where E is the Young's or elastic modulus of the material.

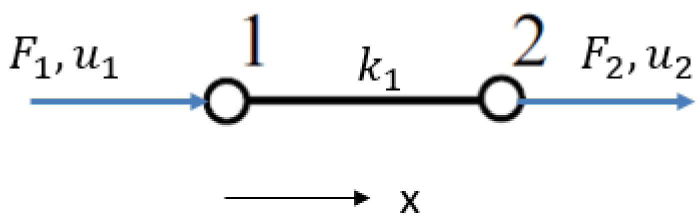


Figure 2.12: Simple illustration of single element.

For the simple illustration of a uniaxial element in Figure 2.12 using the sign convention that force F and displacement u are positive in the x direction. The force may be related to the displacement by the following equations:

$$F_1 = k_1(u_1 - u_2) \qquad (2.7)$$

$$F_2 = k_1(u_1 - u_2) \qquad (2.8)$$

The equation (2.7) and (2.8) may be written in matrix form as:

$$\begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} = \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix} \qquad (2.9)$$

In short form this can be expressed as:

$$\{F\} = [k^e]\{u\} \qquad (2.10)$$

Where k^e is the stiffness matrix of the elements. This is an important property of an element.

In structural engineering, analyses must satisfy three general analysis conditions. Firstly, the sum of forces and moments must be in an equilibrium state. Secondly, strain-displacement relations (also called compatibility of deformation) must be established: ensure that the displacement in a deformed continuous structure is free of voids or discontinuities. Finally, the stress strain relations (also known as constitutive relations) must be established. As for linear material, the generalization of Hooke's law states:

$$\{\sigma\} = [E]\{\varepsilon\} \quad (2.11)$$

Where σ and ε represent stress and strain, respectively. Additionally, this stress and strain are governed by equations 2.12 and 2.13, respectively which are acting in the x, y, z directions.

$$\{\sigma\} = \{\sigma_x \sigma_y \sigma_z \tau_{xy} \tau_{yz} \tau_{zx}\} \quad (2.12)$$

$$\{\varepsilon\} = \{\varepsilon_x \varepsilon_y \varepsilon_z \gamma_{xy} \gamma_{yz} \gamma_{zx}\} \quad (2.13)$$

$$[E] = 6\ by\ 6\ Matric\ of\ the\ elastic\ constant \quad (2.14)$$

Step four in FEM is to assemble the element equations in order to determine the global equation system for the whole solution region. The connectivity of the elements is used for the assembly process. For example, take a situation where the system consists of the two bar element as shown in Figure 2.13. The overall force in the system is obtained by adding all the forces acting at each node. The expression 2.15 shows the global system equation.

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} = \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} u_1 \\ u_2 \\ u_3 \end{Bmatrix} \quad (2.15)$$

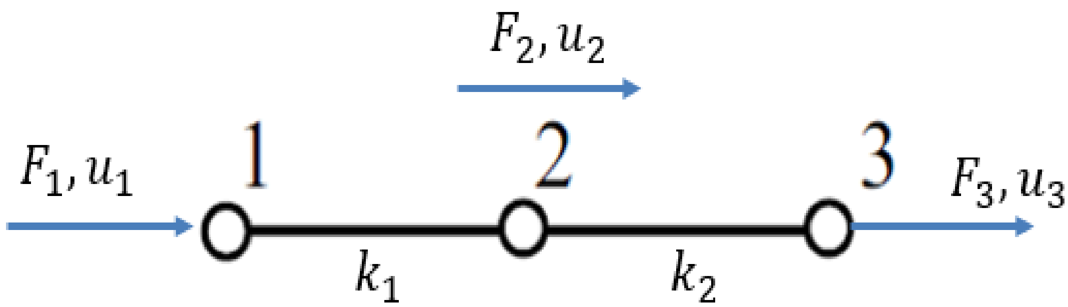


Figure 2.13: Two one-dimensional elements.

The fifth step is to solve the global equation system 2.15. To solve this equation, the boundary conditions must be applied. For example, take $u_1 = 0$ of the two element shown in Figure 2.14.

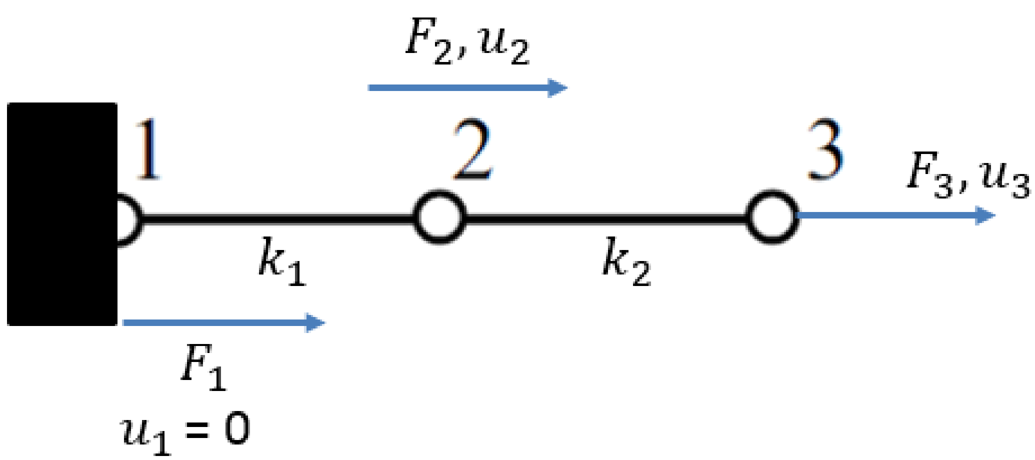


Figure 2.14: Two one-dimensional elements with the boundary condition.

In the global equation a boundary condition of $u_1 = 0$ is substituted. Consequently, the equation will be written as follow:

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \end{Bmatrix} = \begin{bmatrix} k_1 & -k_1 & 0 \\ -k_1 & k_1 + k_2 & -k_2 \\ 0 & -k_2 & k_2 \end{bmatrix} \begin{Bmatrix} 0 \\ u_2 \\ u_3 \end{Bmatrix} \quad \text{.......... (2.16)}$$

Then:

$$[K] = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \quad \text{.......... (2.17)}$$

Therefore, unique solution of force can be found:

$$F_1 = -k_1 u_2 \quad (2.18)$$

$$F_2 = k_1 u_2 + k_2 u_2 - k_2 u_3 \quad (2.19)$$

$$F_3 = k_2 u_3 - k_2 u_2 \quad (2.20)$$

The last step of FEM is to compute the additional results. In many cases the additional parameters need to be calculated. For instance, in mechanical engineering problems the stress-strain is of interest in addition to the displacement.

2.5.3. FEA validation through experimental measurement

Gröning et al. applied a new full strain measurement technique called digital speckle pattern interferometry (DSPI) to measure the strain on a loaded bone human mandible [55]. The aim was to validate the DSPI technique's results with FEA results. The results of the experiment were consistently reliable and corresponded well with the FEA. A few years later, Gröning et al. investigated in detail the DSPI to show that this technique can provide more comprehensive and accurate validation of FEA than traditional methods can [3]. The study was performed through quantifying and visualizing the variation in strain magnitude and orientation within and between repeated DSPI measurements and FEA results. The discrepancies between measured and computationally predicted strain were revealed through this exploitation. It was concluded that discrepancies were caused by the inaccuracies in the model's geometry and the degree of simplification of the modelled material.

However, traditional strain gauge measurements are still considered as an accurate system to validate FEA models. Various studies have been done to validate FEA by making use of strain gauges. In their studies, Erklig & Kütük published that their FEA was validated by installing strain gauges on a human metacarpal [56]. They investigated the effect of different loading conditions such as torsional, bending and static loading and compared the strain gauge measurements with those of a 3D FEA of the CAD model. They also conducted another study on a dental implant in which strain gauge measurement was performed with the aim to validate their FEA; significant differences in strain were recorded between strain gauge analysis and the 3D FEA. In their attempt to achieve better correlations, strain gauge measurements were performed on a simple cantilever beam. In this case the strain gauges were installed on the physical cantilever model at positions and orientations corresponding to an area where the strains were calculated in the FEA model. Their results from the cantilever experiment were compared with an FEA model and invaluable results were achieved. Therefore, by comparing the study performed on metacarpal and on the dental implant against the cantilever experiment, it was concluded that any inaccurate locations of strain gauges yielded deviations of up to 10%. Therefore, it is thought that validating FEA using an AM component with clearly marked locations and even surfaces for strain gauges' installation on the implant, could provide accurate results. The current study applies strain gauge measurements to validate an FEA model of a human mandible implant produced through AM.

2.6. Strain gauge measurement

2.6.1. Definition of strain

The deformation that a body experiences when a force is applied to it, is called strain (ε) which is measurable through strain gauges [57]. Strain is the ratio of the change in length over the total length and it is unit less. In Figure 2.15 the concept of strain is illustrated

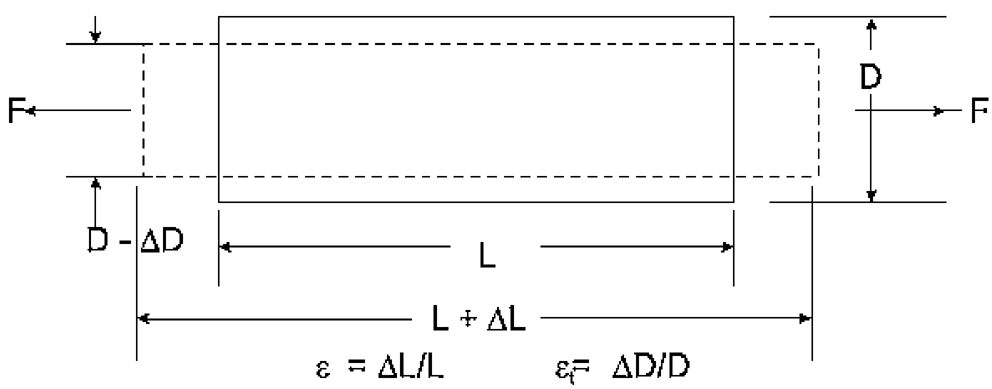


Figure 2.15: Illustration of strain where F = force, D = diameter of the sensing material (wire or foil), L = length of the sensing material. Strain is defined as ε = ΔD/D.

2.6.2. Strain gauge

A strain gauge is a device that measures precise deformation. In Figure 2.16 the typical strain gauge is shown. It is made-up of a very thin diameter metal wire or foil grid bonded on a non-conductor of electricity, called a carrier.

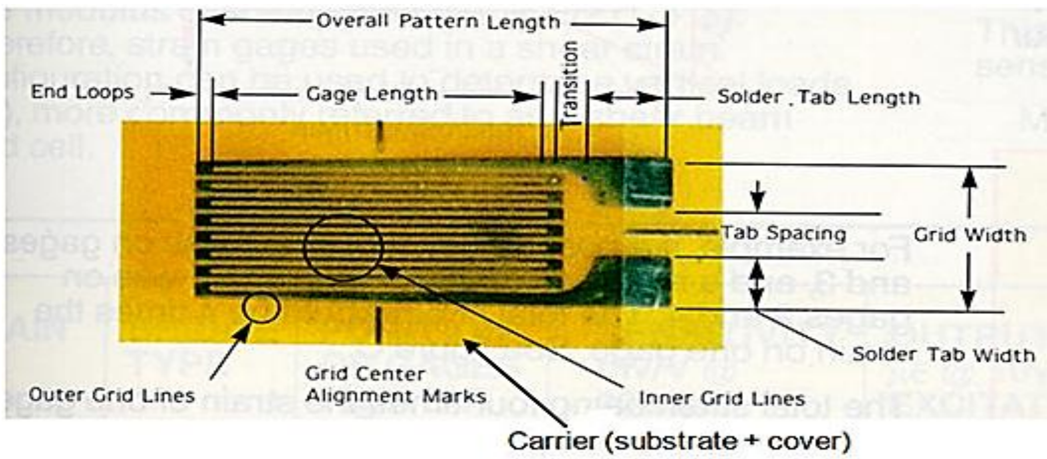


Figure 2.16: Typical metallic strain gauge [58]**.**

When a strain gauge is bonded onto a specimen's surface it is able to generate an electrical measure of strain in that specimen. As the wire is stretched with the specimen, the electrical resistance (R) changes because its length (L) increases and its cross-sectional area (A) is reduced [59]. This resistance is expressed by equation 2.1, where ρ represents the resistivity which is the measure of resistance to electrical conduction for a given material.

$$R = \frac{\rho L}{A} \qquad (2.1)$$

2.6.3. Strain gauge sensitivity

The strain gauge sensitivity or gauge factor (GF) is the proportionality factor between the relative electrical resistance changes ΔR/R and the strain, ε, to be measured [57]. The sensitivity of the strain gauge is expressed by equation 2.2.

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \qquad (2.2)$$

This strain gauge is designed to be sensitive in one direction (which is along the longitudinal direction) and to change its resistance only in response to the induced stress in the specimen to which it is bonded. However, transverse sensitivity could occur, but this sensitivity is reduced by extra material which is added on the ends of the grid loops and the grid lines are kept close to one another. On the other hand, the resistance of the strain gauge also changes with the change of temperature. This change in resistance with temperature of the bonded gauge is a function of the thermal expansion coefficient between the gauge and the specimen and of the thermal coefficient of the resistance of the gauge alloy [57].

2.6.4. Application of a strain gauge

A strain gauge must be properly bonded onto the surface of the specimen of which the strain is to be measured. It is important that the surface is initially well-prepared (free of pores, oil and cracks) before bonding. Proper bonding is achieved using recommended adhesives such as methylmetacrylate (X60), cyanoacrylate (Z70) for production of transducers that are of a medium accuracy and epoxy (X280, EP250 and EP310S) for high precision transducers. In addition, it is recommended that the bonding process be precisely done by a trained person [60]. Figure 2.17 illustrates schematically how a strain gauge is bonded to a specimen.

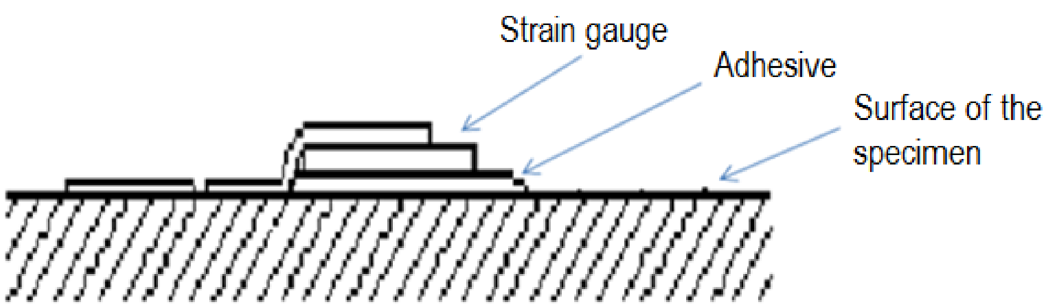


Figure 2.17: Illustration of a strain gauge bonded to a surface [60].

A microscopic change in resistance is impossible to measure with a simple ohmmeter. Therefore, strain gauges are almost always used with a Wheatstone bridge circuit. This circuit is mostly used in measuring equipment such as resistive-, inductive-, capacitive-, piezoelectric-, electromagnetic-, electrodynamic-, magnetoelastic-, galvanomagnetic-, vibrating-wire-, microresonator-, acoustic- and gyroscopic force transducers because of their reliability and accuracy [61]. This circuit is supplied by an excitation voltage (V_{ex}) which is multiplied by a small resistance ratio to determine the output voltage that is expressed in equation 2.3 [58].

$$V_o = [\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}]V_{ex} \quad (2.3)$$

Where R_1, R_2, R_3 and R_4 each represents a resistor in a typical Wheatstone bridge circuit shown in Figure 2.18.

In the basic Wheatstone bridge circuit configuration, shown in Figure 2.11(a), the resistances of the resistors in the circuit are equal in magnitude therefore the output voltage is zero. But if one resistor is replaced by a strain gauge to form a quarter bridge circuit (see Figure 2.11 (b)) which is bound to a loaded specimen, the output voltage can be determined by equation 2.4.

$$\frac{V_O}{V_{EX}} = \frac{GF.\varepsilon}{4}\left(\frac{1}{1+GF \text{ x} \frac{\varepsilon}{2}}\right) \quad (2.4)$$

Here GF and ε represent the gauge factor and strain, respectively. In addition, if two or all four resistors are replaced by a strain gauge, the circuit is called a half or full bridge circuit (see Figure 2.18 (c) and (d)), respectively. However, these circuits can be modified, depending on the different applications and accuracy of the required result, by the addition of an extra dummy gauge induced for temperature compensation.

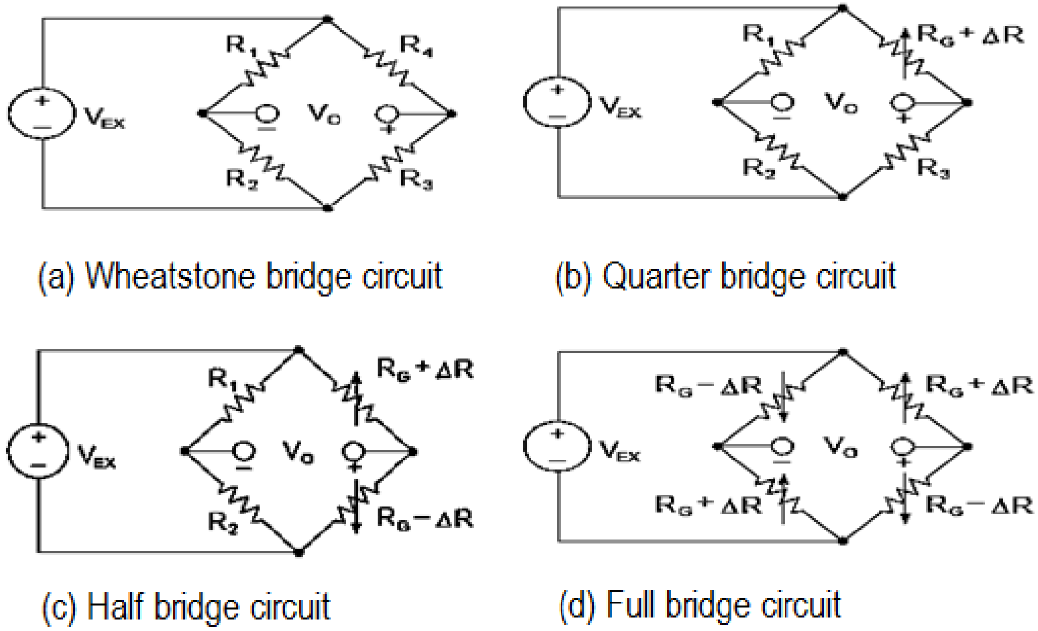


Figure 2.18: Typical Wheatstone Bridge circuits. ∆R and R_G represent the change in resistance and the gauge resistance, respectively [58].

Furthermore, the circuit is connected to an amplifier that will enhance the measured strain by enhancing the output voltage without changing it. As a result, the data recording or data acquisition (DAQ) system will be able to record the measured data. The DAQ provides a platform to measure data to be analysed and saves it on a personal computer (PC) or hard drive. The results can be displayed on a PC's monitor (see Figure 2.19) [62].

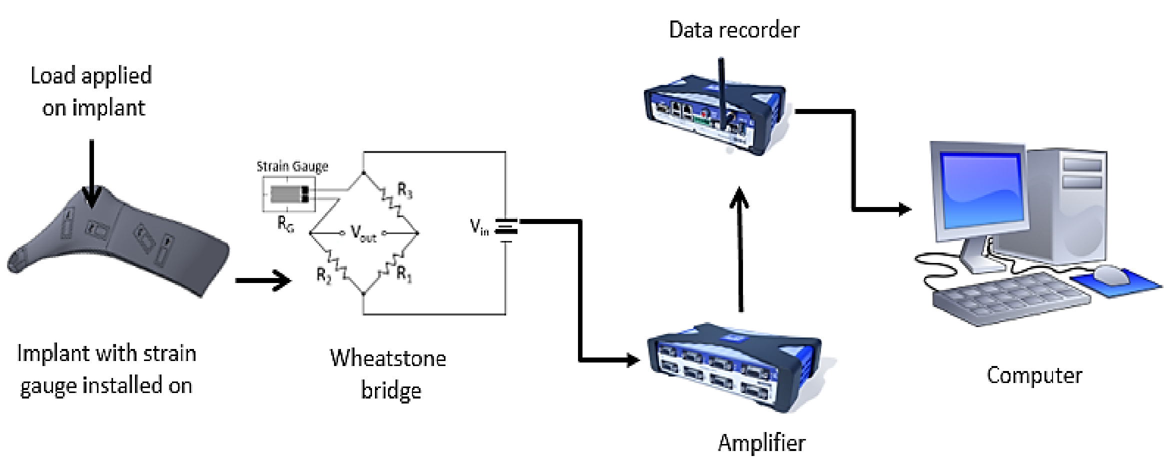


Figure 2.19: Process followed to record strain measurements with a strain gauge.

The measurement of strain using strain gauges is often done in the presence of electric and/or magnetic fields which can superimpose electrical noise on the measurement signal [63]. This noise can result in incorrect measurement of the strain. To avoid inaccurate results and incorrect interpretation of strain signals, the noise must be controlled. To control the noise, it is important to know the source. Any electrical device that generates, consumes or transmits power is a potential source for causing noise in a strain gauge circuit. The common source of electric noise includes alternating current power lines, relays, a soldering iron, fluorescent lamps, radio transmitters, etc. The electrical noise is categorised into two types which are electrostatic and magnetic. Unfortunately, these listed sources produce a combination of noise types, complicating the noise reduction problem.

The electrostatic fields are generated by the presence of voltage (V) with or without current flow [63]. Such an electrostatic field induces the noise in the strain gauge system and its effect is well defined by a capacitive coupling phenomenon. This has to do with the transfer of energy within an electrical network or between distance networks by means of displacement current between circuit nodes, induced by the electric field. In Figure 2.20 the electrostatic noise coupling is illustrated.

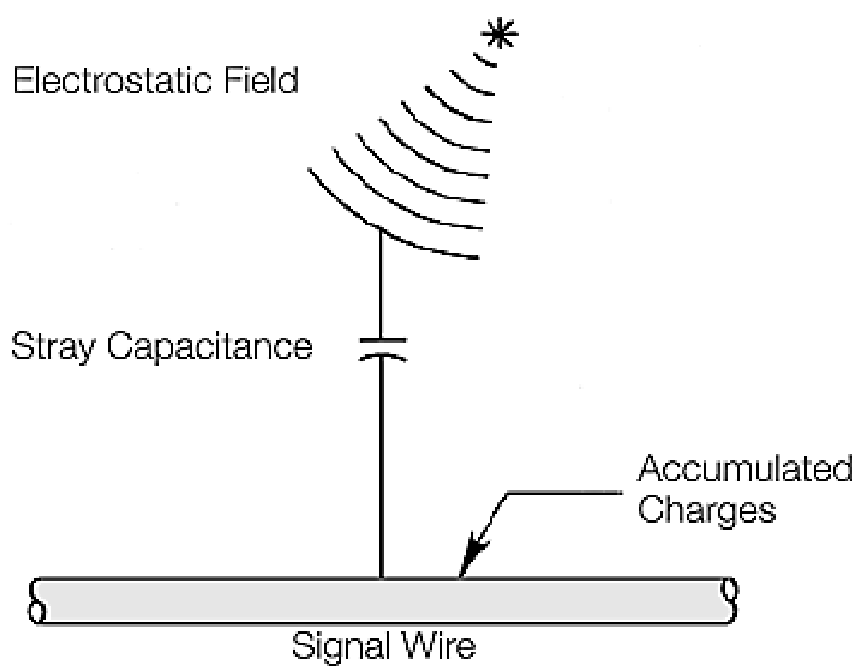


Figure 2.20: Electrostatic noise coupling.

To reduce the electrostatic noise a conductive shield is used as a barrier between the electrostatic field and the signal wire. The shield captures the charges that would otherwise reach the signal wiring and drains them off to a satisfactory ground. In Figure 2.21 this process is illustrated.

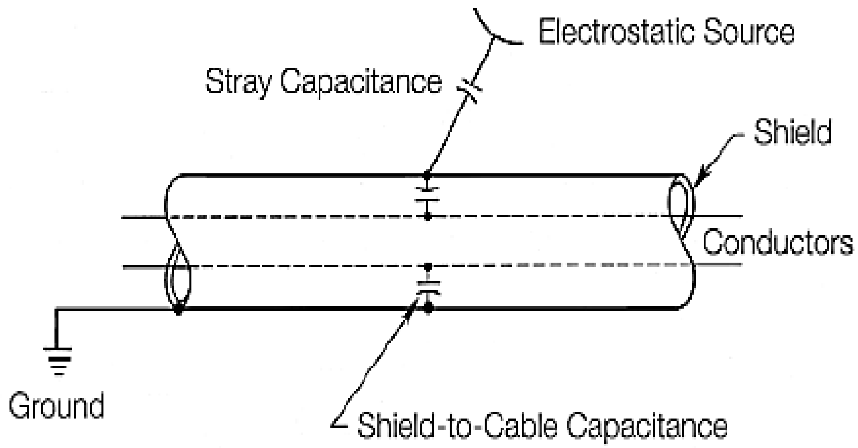


Figure 2.21: Illustration of electrostatic shielding.

On the other hand, a magnetic field is created either by the flow of electric current or by the presence of permanent magnetism. If the magnetic line of flux passes through the strain gauge signal wire electric noise is induced in the strain gauge circuit (see Figure 2.22).

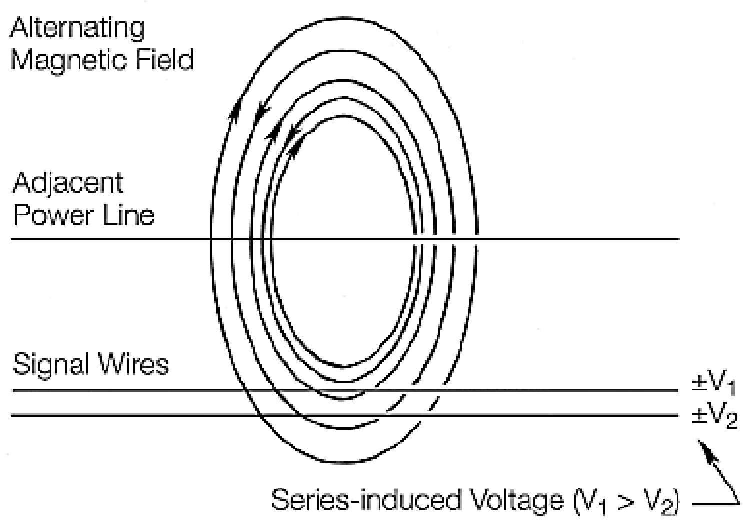


Figure 2.22: Electromagnetic noise coupling.

The most effective approach to minimize the electromagnetic noise in the strain measurement system is to induce the noise voltage equally in both sides of the amplifier. In Figure 2.23 the cancelation of the electromagnetic noise by the amplifier is illustrated. The bridge arrangement of all conventional strain gauge systems, such as quarter bridge (two or three lead wire), half bridge and full bridge, are designed to cancel the electric noise [63].

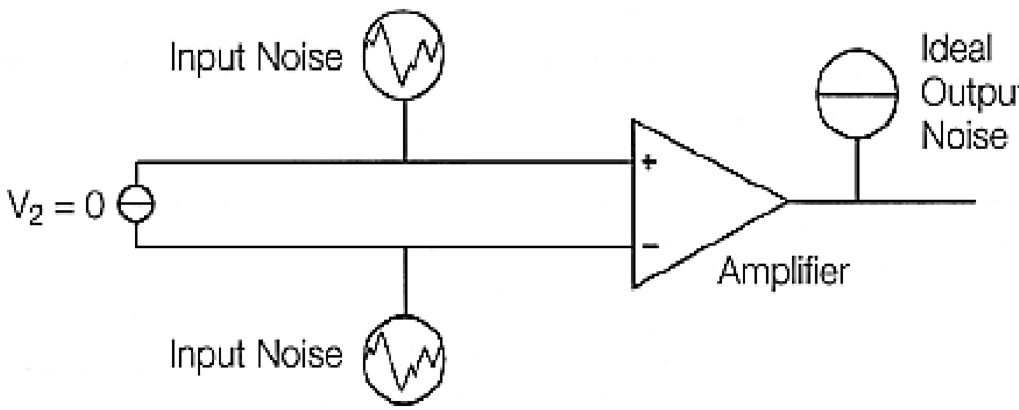


Figure 2.23: Cancellation of the electromagnetic noise by the amplifier.

This was the approach followed in the current study.

Chapter 3: Methodology

3.1. Approach

To establish confidence in FEA modelling, validation of such a model is essential, especially if the model is used to solve a complex mechanical system. Figure 3.1 provides a schematic overview of the research methodology followed in the attempt to establish such confidence.

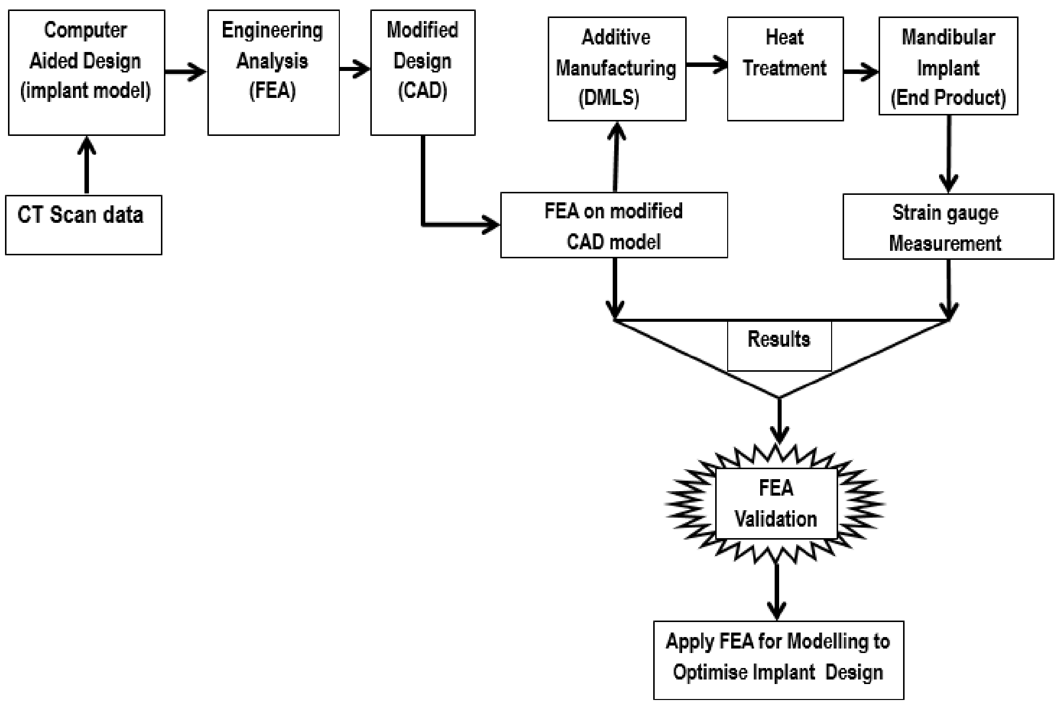


Figure 3.1: Overview of the research methodology used in an attempt to validate FEA through strain gauge measurements.

As shown in Figure 3.1, the mandibular implant CAD model was generated from CT scan data of a human mandible. This was done to achieve an implant model that resembled the original bone mandible as closely as possible. Therefore, it had to adhere to a number of requirements: firstly, to maintain the facial contour; secondly, to withstand all stresses induced during normal operation; thirdly, it had to consist of a biocompatible material and, most importantly, to maintain the mandibular functions.

Using this mandibular implant CAD model, an initial FEA was performed on the implant by applying a maximum static biting load. Consequently, from the generated results it was found necessary to modify the implant CAD model. These modifications were done to achieve a model that could be used for experimental strain gauge measurements. Such a model should consist of smooth surfaces to allow the installation of strain gauges and provide fixation positions so that boundary conditions that are applied on the FEA model can be realistically applied to the experimental setup. On application of the typical operational loads, sufficient strain had to be induced in the implant to be measured with strain gauges. Most importantly, the positions and orientations of the strain gauges had to be identified and permanently marked. This modified CAD model was used for the five final FEA simulations with different loads to be compared with the experimental strain gauge measurements.

Subsequently, the implant was additively manufactured in Ti6Al4V (ELI). A stress relieving heat treatment was performed on the AM implant to relieve the residual stresses that were locked in the implant due to the thermal gradients experienced during the AM process. Thereafter, the strain gauges were installed on the end product and the experimental strain gauge measurements were done under the same boundary conditions and loads that were used in the FEA simulations. Finally, the results from both the FEA simulations and the strain gauge measurements were compared.

3.2. Computational Analysis

3.2.1. Mandibular implant CAD model design

The design of a mandibular implant CAD model suitable for computational analysis and experimental validation was created using SOLIDWORKS® (2014-2015 student edition). The original model was designed to reconstruct a symmetrical half of an adult human mandible. The model was generated from the CT scan data of a patient and was made available for this study by the CRPM. In Figure 3.2 (a) and (c) this mandibular CAD model as produced from the CT data, is shown. From this CAD model a mandible implant was designed, which is shown in Figure 3.2 (b) and (d).

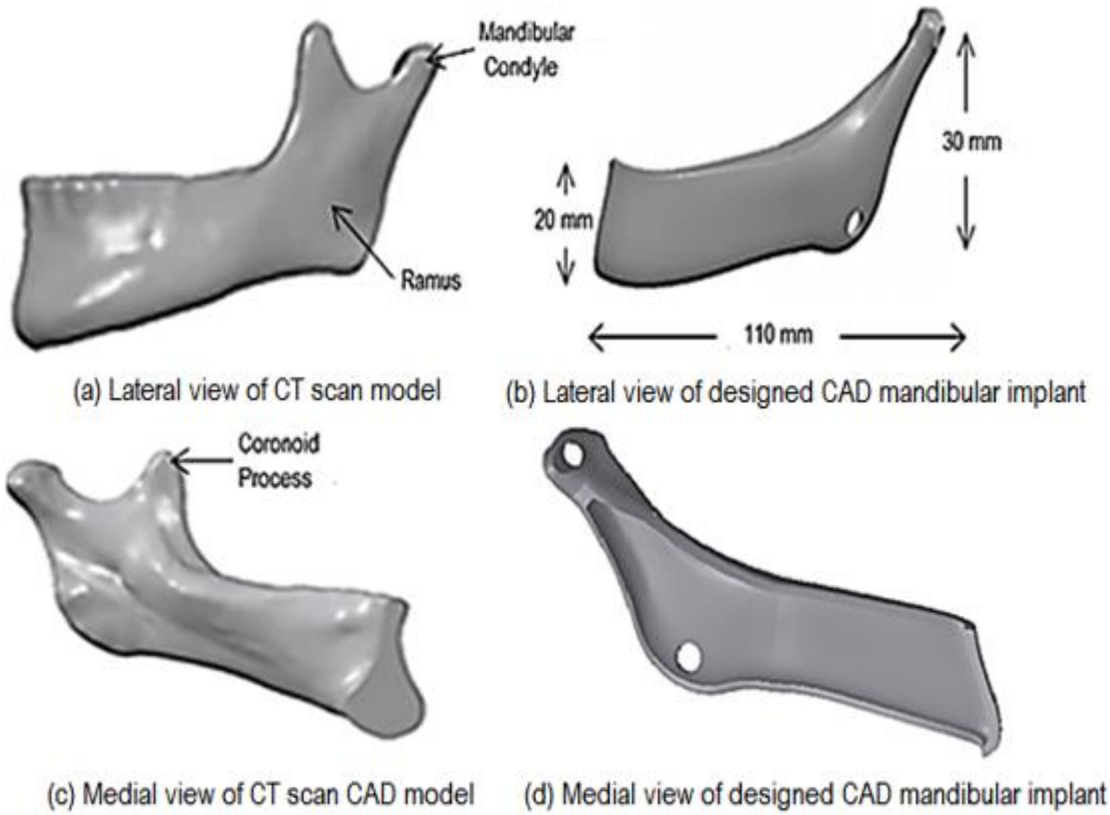


Figure 3.2: Lateral and medial views of the mandibular model obtained from CT scan data (a) and (c) provided as basis for the study and the designed mandibular implant CAD model (b) and (d).

The mandibular implant CAD model was designed in such a way that both its lateral and medial surfaces were made as smooth as possible to allow the proper installation of strain gauges. The mandibular condyle's dimension and shape on the designed implant was kept the same as the original CT model because, if it was to be used on a patient, it should be able to articulate with the temporal articulation surface of that specific patient. However, the coronoid process was cut out on the implant since this appeared to be common practice when designing mandibular implants [64][65].

Moreover, a hole was created at the ramus of the mandibular implant to represent the position of the attachment of the main mastication muscle known as the masseter muscle. Besides that, another hole was created on the implant's condyle for making it possible to apply the simplified mandible's boundary conditions both on the FEA and the experimental setup.

Another very important factor which was considered in the design of the implant was its geometric stiffness. To determine the thickness of the titanium implant that would give it properties equivalent to that of bone, some assumptions were made. Firstly, the implant with properties similar to the cortical bone of the mandible (elastic modulus E = 21 GPa [66] and thickness of 3.8 mm [67][68]) was treated as a simple supported beam under a bending load (F) of 1 026 N at its mid-span D. Secondly, the implant was taken as a rectangular beam with dimensions shown in Figure 3.3 (a) and loaded as in shown in (b).

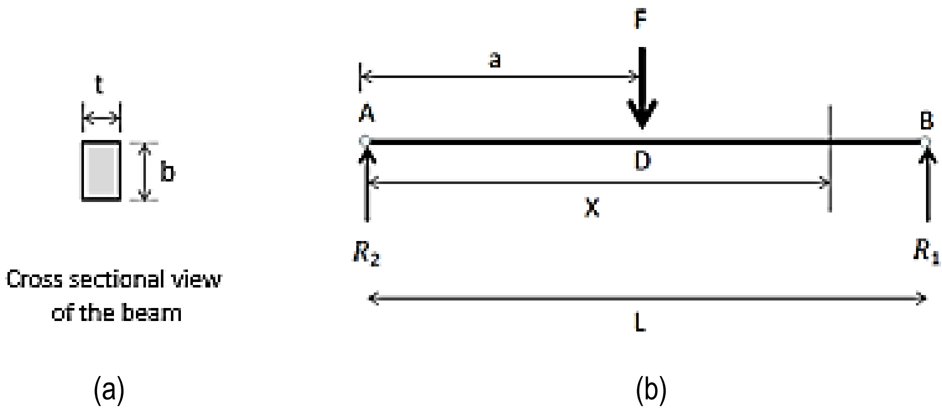


Figure 3.3: The beam representing the mandibular implant with (a) illustrating the beam cross sectional dimensions and (b) illustrating the loading condition.

Taking the moment about A, the reaction force, R_1, on the beam can be determined by making use of equation 3.1 or 3.2. in return the reaction force R_2 can be calculated by setting the sum of the static forces on the beam equal to zero (equation 3.4).

$\sum M_A \; taking \; clowice \; positive \; = 0$ .... (3.1)

$-R_1.L + F.x = 0$ .... (3.2)

$R_1 = \frac{F.x}{L}$ .... (3.3)

$R_2 = F - R_1$ .... (3.4)

Where L and x represent the total length of the beam and a distance along the beam length, respectively.

Therefore, by using the Macaulay's method (or double integration method) the bending moment M of the whole beam is given by:

$$M = R_1.x - F[x-a] \quad \text{......} (3.5)$$

Note that when x < a, the quantity in the square bracket would become negative and so $F[x-a]$ is taken as zero. Therefore, the moment of the beam is given by equation 3.6.

$$EI\frac{d^2y}{dx^2} = -M = -R_1.x - F[x-a] \quad \text{......} (3.6)$$

Where I is the second moment of area.

By integrating equation 3.6 the slope $\frac{dy}{dx}$ of the beam is achieved as expressed in equation (3.7).

$$\frac{dy}{dx} = \frac{1}{EA}\left(-\frac{R_1x^2}{2} + \frac{F}{2}[x-a]^2 + C\right) \quad \text{......} (3.7)$$

Where C is a constant value.

Similarly, by integrating the equation 3.7 the deflection y of the beam is obtained:

$$y = \frac{1}{EA}\left(-\frac{R_1x^3}{6} + \frac{F}{6}[x-a]^3 + Cx + C_1\right) \quad \text{......} (3.8)$$

When $x = 0, y = 0$ and since the term inside the square bracket is omitted, $C_1 = 0$. For $x = L, y = 0$. Then:

$$C = \frac{F.a}{6}(L-a)(2L-a) \quad \text{......} (3.9)$$

Substituting the value of C and R_1 in equation 3.8, equation 3.10 is obtained.

$$y = \frac{FL^3}{48EI} \quad (3.10)$$

Now for the same displacement, force, boundary conditions, width and length of the mandible bone the ratio between bone and titanium material properties was estimated using equation 3.11.

$$y_{titanium} = y_{bone} \quad (3.11)$$

$$\frac{FL^3}{48EI}\,titanium = \frac{FL^3}{48EI}\,bone \quad (3.12)$$

$$I_{titanium} = \frac{E_{bone}}{E_{titanium}} I_{bone} \quad (3.13)$$

Finally, the beam thickness, determined by using equation 3.14, can be used as the equivalent thickness of the titanium implant. To ensure confidence in the design and to achieve a robust implant a safety factor of 2.8 was used. See calculations in appendix 4.

$$t_{titanium} = \frac{12.I}{b^3} \text{ (safety factor)} \quad (3.14)$$

In general, the considerations during the medical implant design were to achieve a minimum weight and an economically effective implant, while still maintaining sufficient strength to ensure that it would not fail even under extreme load conditions.

3.2.2. Initial finite element analysis

The current study is based on a linear static analysis. Patran (2014 version) software was used for pre- and post-processing, whereas Nastran (2014 version) software was used as a solver. Firstly, the mandibular implant CAD model was imported into Patran software to create a quadratic tetrahedral (commonly known as Tet 10) solid mesh with a global element edge length of 2 mm. These meshes consist of linear and quadratic shape functions. Tet 10 (second complete-polynomial member) is significantly better for stress analysis in structure and solid mechanics such as a medical implant. However, at the area of strain gauge placement the mesh was refined because those were the specific areas where the strains were to be compared. To refine the mesh a uniform mesh seed was created around the gauge area to achieve a denser mesh. In Figure 3.4 the generated mesh on the implant is shown.

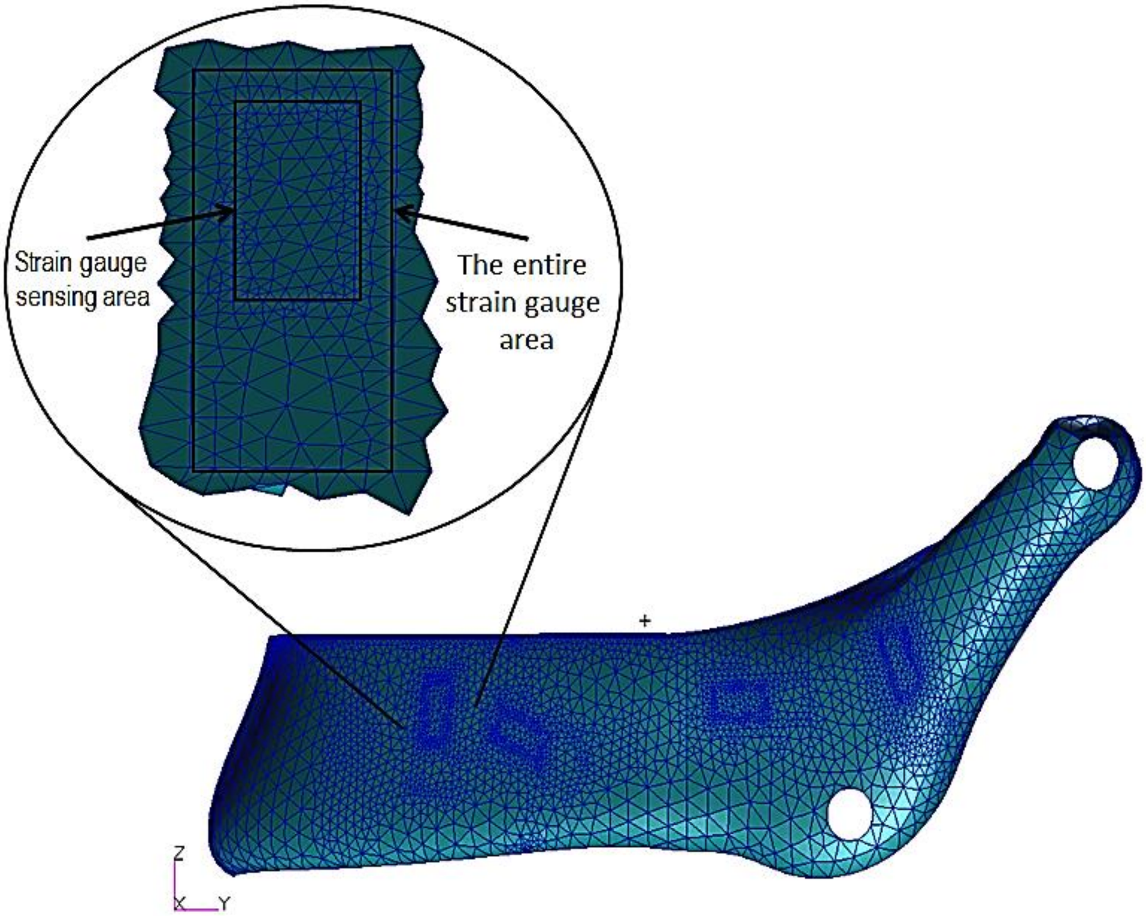


Figure 3.4: Quadratic tetrahedral solid mesh generated on the implant with mesh control at the areas of strain gauge attachment.

Secondly, the isotropic homogeneous material properties of Ti6Al4V (ELI) was applied on the implant. These annealed material properties as discussed in paragraph 2.4.2 were obtained following the procedure discussed in paragraph 3.2.2. In Table 3.1 the titanium material properties which were applied is shown.

Table 3.1: Ti6Al4V (ELI) material properties [40]**.**

Material	**Elastic Modulus (GPa)**	**Shear Modulus (GPa)**	**Poisson's ratio**	**Density (kg/m³)**
Ti6Al4V (ELI)	110	40.74	0.35	4400

Once the material properties were assigned the load and boundary conditions were set up. A local coordinate system was created at the centre of the cylinder through condyle **A** as shown in Figure 3.5. Furthermore, the condyle of the mandibular implant CAD model was fixed in such a way that it could rotate only about the local X – axis which is perpendicular to the Z-Y plane and passes through the centre of the hole. Besides that, the condyle was also restricted from translating in all directions. On the other side of the implant at section **B** the translation in the +Z direction as shown in Figure 3.5 was restricted. These boundary conditions were based on Koolstra's study of the human mastication system [28][69].

Both boundary conditions and loads were applied at the defined regions as illustrated in Figure 3.5. At the condyle **A** it was applied at the inner surface of the created hole. Additionally, at the front end **B**, the small top surface of the implant was set as the application region. As for the applied load, the top inner semi-circular surface of the hole in the ramus was set as the application region.

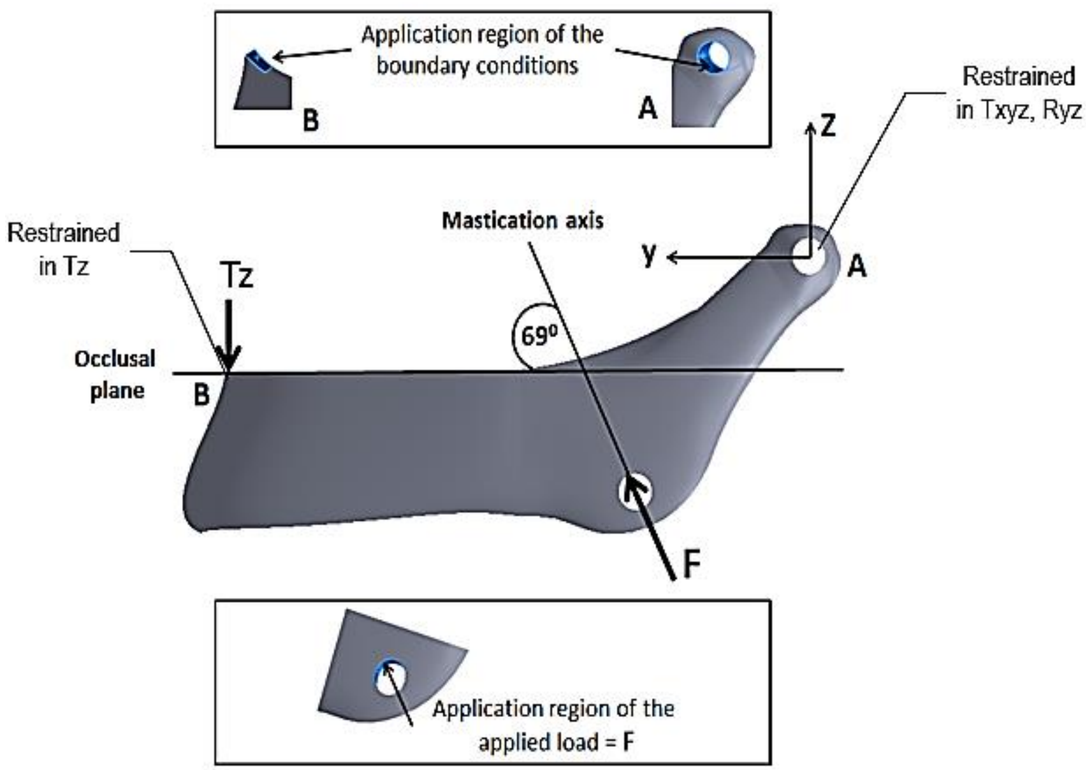


Figure 3.5: Experimental loading and boundary conditions of the mandibular implant. Where: T and R represent translation and rotation, respectively. F is the applied load.

The maximum load of 1 026 N was applied at an angle of 69^0 with regard to the occlusal plane, but parallel to the mastication axis of the implant CAD model. This angle was set based on the fact that both the masseter muscle and the mastication axis remain approximately 69^0 with regard to the occlusal plane, regardless of the inter-skeleton variations as described in section 2.3.2. The implant was designed to withstand the maximum biting load. The maximum force a person with healthy teeth can apply when biting is 2 091 N [31][30]. Therefore, the symmetrical half should withstand 1 026 N.

The outputs of the Patran software were sent to Nastran software and the results were sent back to Patran for interpretation. The interpretation of the results provided the data needed for the following modifications of the designed mandible implant CAD model.

3.2.3. Determination of strain gauge positions

Based on the initial FEA results, decisions were made regarding the areas in which the strain gauges should be installed on the experimental implant model. In essence, the main aim of the initial FEA was to identify positions in areas where strain gauges could be installed. However, care was taken not to position them close to the fixation and load application region, holes and sharp corners due to the fact that those were regions of stress concentration not representative of the general stress or strain distribution. In Figure 3.6 (a) and (b) the principal strain distributions obtained from the initial FEA simulation used to determine suitable positions for strain gauges, are shown.

By analysing the lateral view of the implant, it was found that high principal strains were attained at the ramus of the implant with gradual reduction towards the body of the implant. However, at the area close to the mental foramen (refer to Figure 2.2) the strains were found to be lower than at other regions of the implant. Similarly, the medial side of the implant experienced almost the same strain distribution as the lateral side as shown in Figure 3.6 (b).

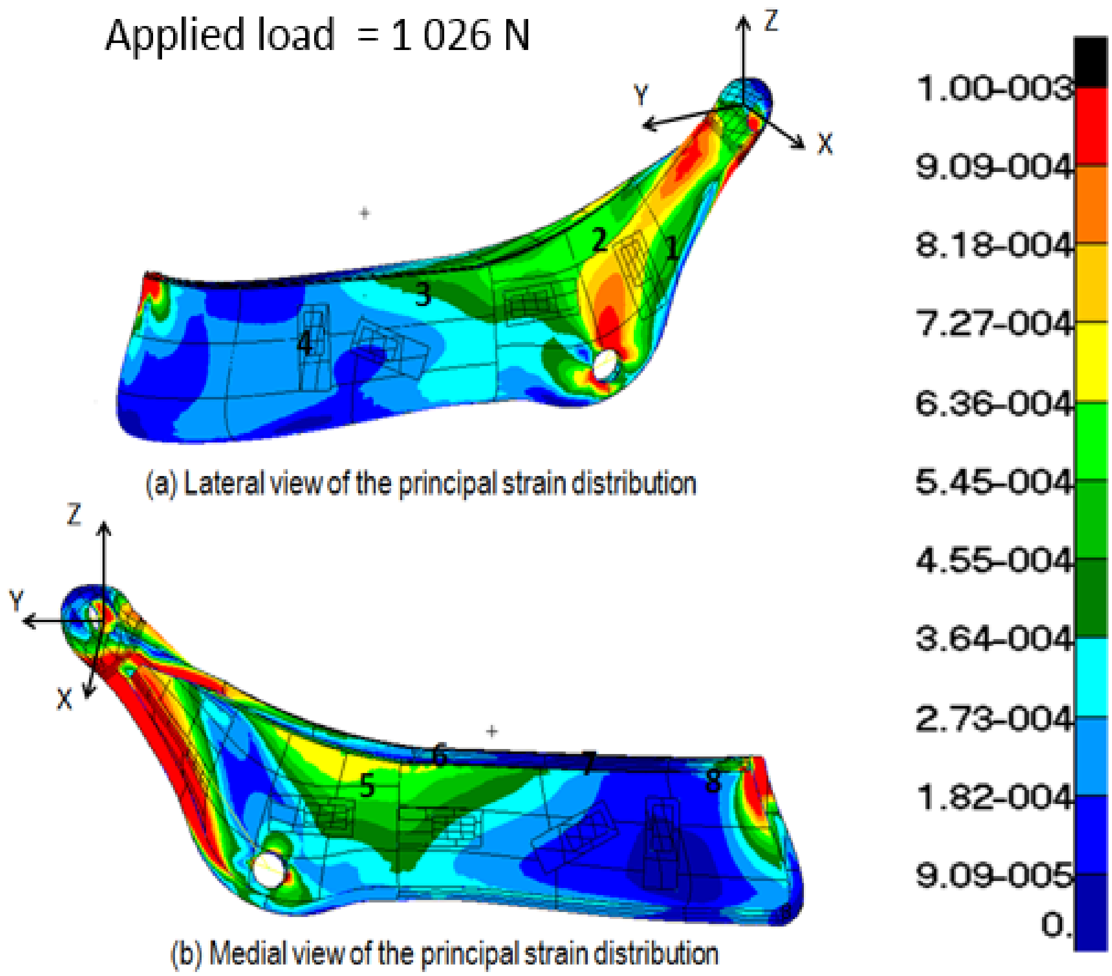


Figure 3.6: Lateral and medial views of the implant with principal strain distribution, at the applied load of 1 026 N.

Based on the initial FEA predictions shown in Figure 3.6, the strain gauge positions were identified and marked on the implant. Strain gauges 1 and 2 were positioned at the ramus and gauges 3 and 4 were placed on the lateral side of the body of the implant. Similarly, on the medial side of the implant strain gauge 5 was positioned at the ramus and 6, 7 and 8 on the body of the implant. These positions and orientations are shown in Figure 3.7.

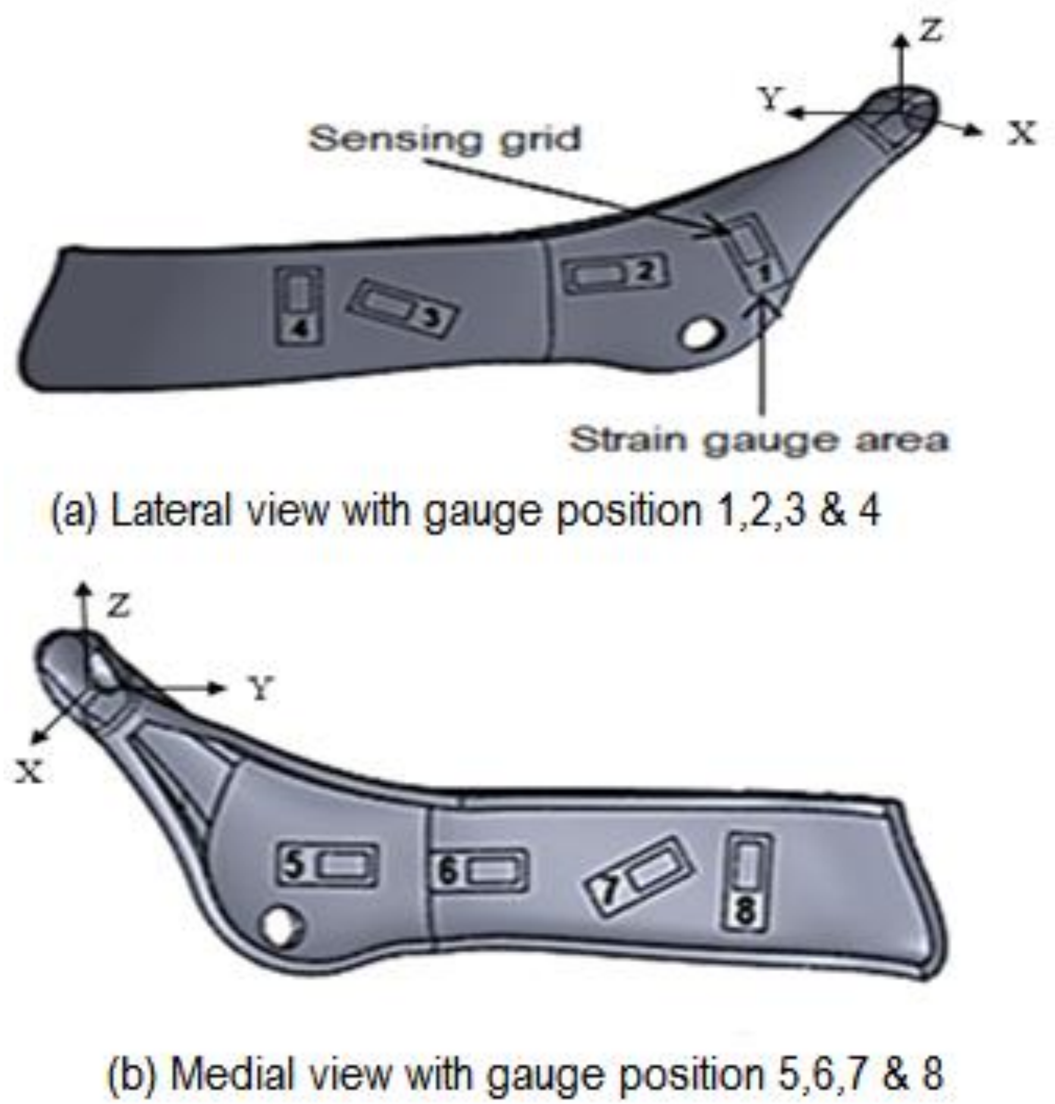


Figure 3.7: The positions and orientations of the strain gauges.

The directions, along which the gauge lengths of the strain gauges were aligned, were determined by plotting the marker vectors of the principal strain. Each strain gauge was installed along the direction of the Y-component of the principal strain vectors of the local coordinate system created in each gauge area. The benefit of this approach was that the calculated strains corresponded with the strains detected by the strain gauges. In Figure 3.8 the super positioned area of a strain gauge with the marker vectors illustrating the direction of the principal strain, is shown.

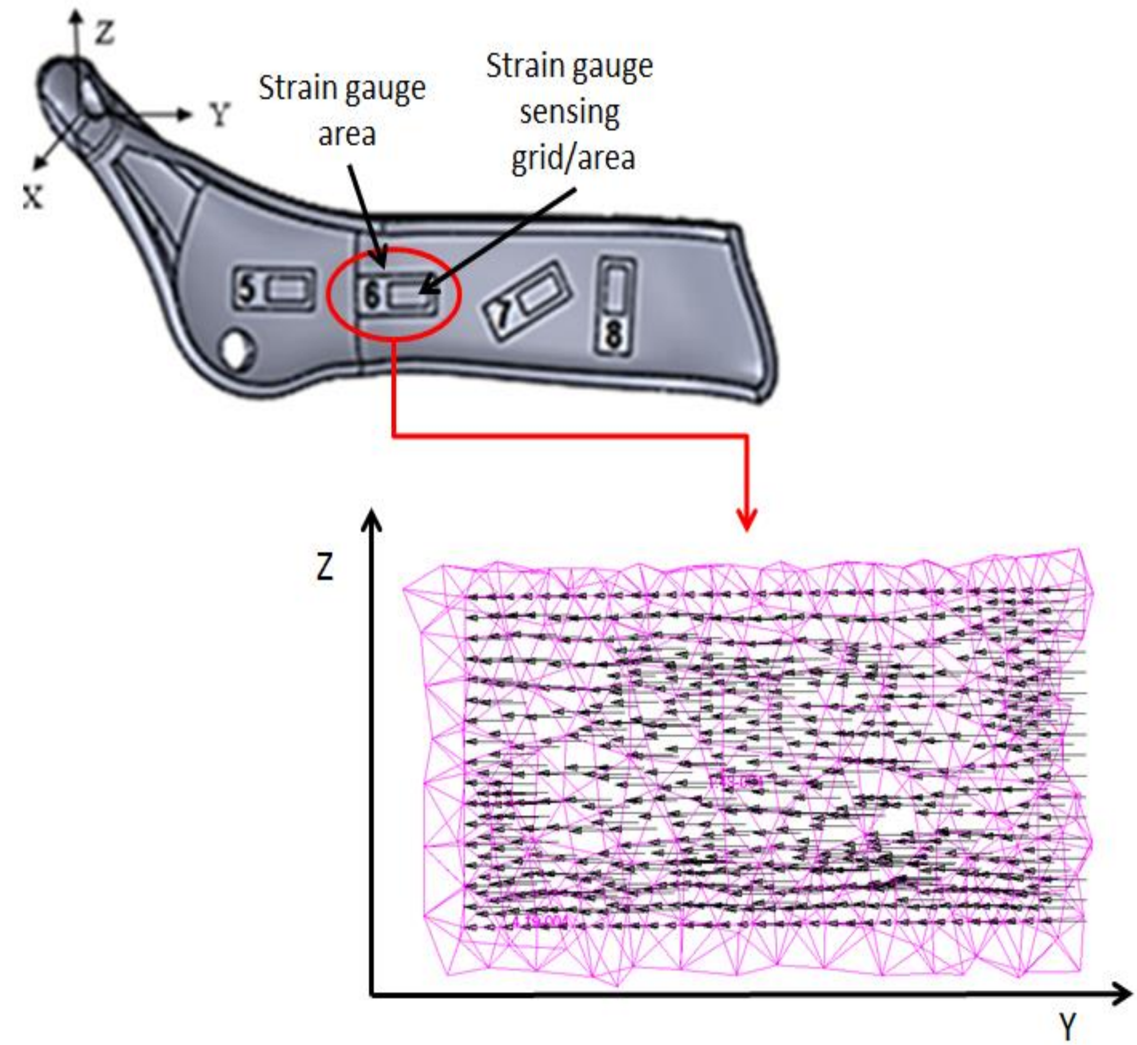


Figure 3.8: Superposition of the area of strain gauge 2 on the FEA mesh to align with the direction of the principal strain.

The areas identified for the strain gauges were marked through small ridges on the CAD model to be used for AM production of the experimental implant. This assisted with the positioning and alignment of the strain gauges on the experimental model during the gauge installation. The dimensions of the whole gauge are 5 mm x 12 mm and that of the sensing grid are 3 mm x 8 mm. In order to simplify FEA interpretation, the CAD surfaces were split on the periphery of the strain gauges, such that the nodes corresponding to the gauge sensing areas could be grouped separately.

An additional advantage of the initial FEA was to confirm that the implant would not fail when the typical maximum load was applied. For this the commonly used failure criteria of ductile materials (Von Mises failure criteria) were applied. According to these criteria, if the calculated Von Mises stress is greater than the yield stress of the material, failure occurs [70]. The maximum Von Mises stress found under the maximum loading of 1 026 N applicable to the mandible implant was 141 MPa. This clearly indicated that the implant would not fail under maximum load, because the maximum stress generated on the implant due to the applied force was much less than the yield stress of the Ti6Al4V (ELI) (see Table 2.1, which shows the variation of the yield stress from 795 to 875 MPa).

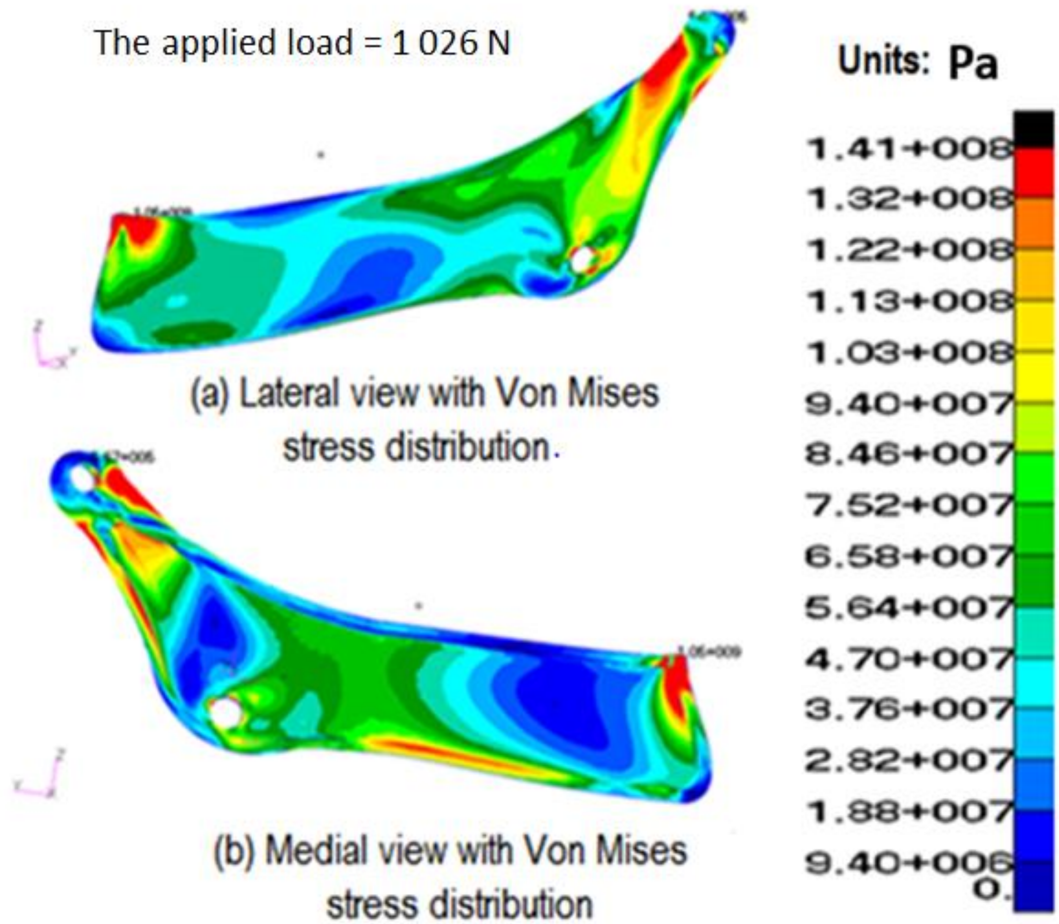
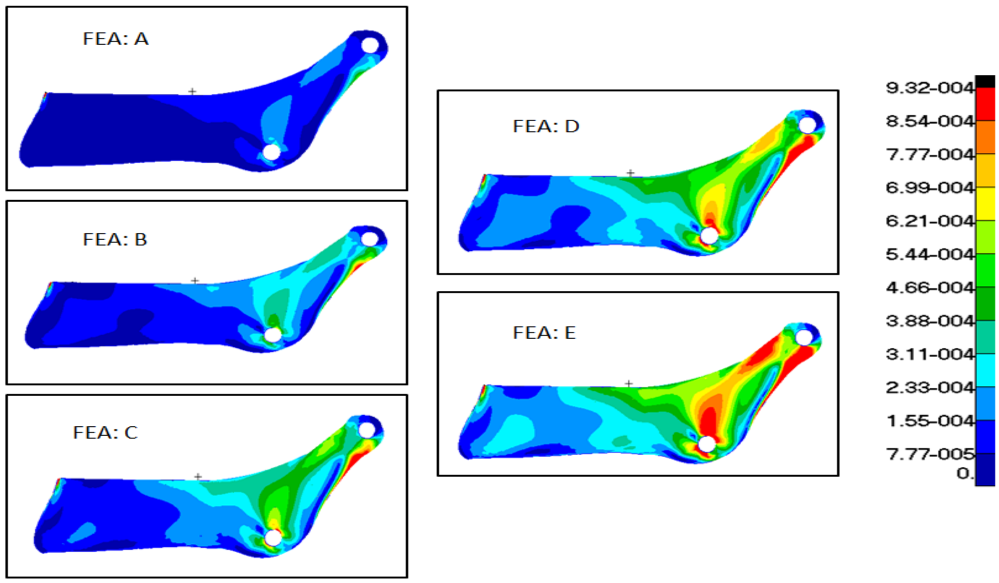


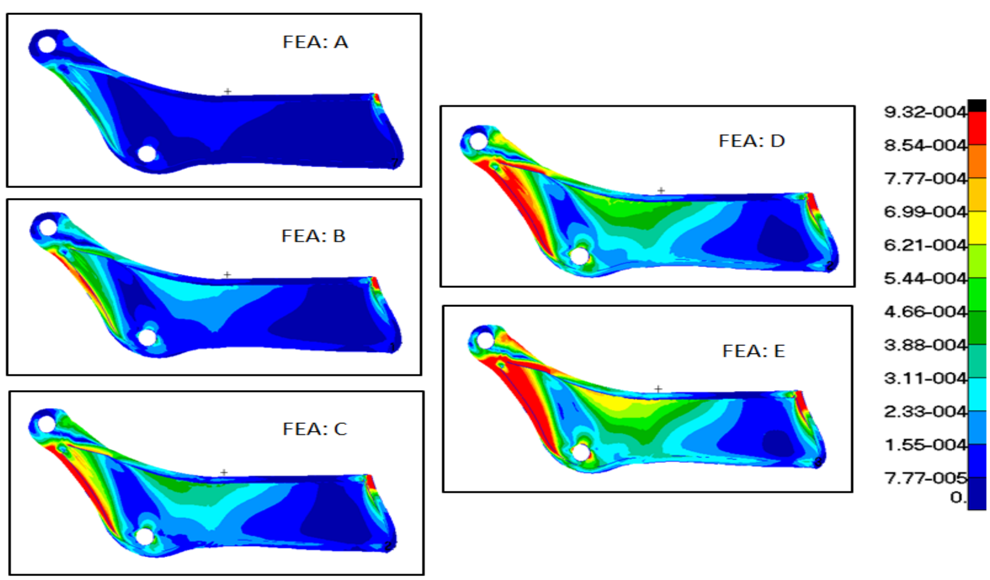
Figure 3.9: The lateral and medial views of the Von Mises stress distribution at the applied load of 1 026 N.

3.2.4. Final FEA on the mandibular implant

Finally, FEA was performed on the modified mandibular CAD model under different applied loads to determine the corresponding strain distributions. Because the muscles of mastication exert variable forces on the mandible to provide the different biting pressures, it was decided to simulate reality by performing the FEA simulations with different loads. Five FEA simulations were performed with different loads, namely, FEA: A = 215 N, FEA: B = 415 N, FEA: C = 620 N, FEA: D = 821 N and FEA: E = 1 026 N. For each load the mesh, boundary conditions and the material properties were kept constant.



(a) Lateral view



(b) Medial view

Figure 3.10: Lateral and medial view of the maximum principal strain distribution on the mandibular implant for different applied loads. FEA: A = 215 N, FEA: B = 415 N, FEA: C = 620 N, FEA: D = 821 N and 1 026 N.

In each strain gauge area, the Y-components of the principal strain were extracted from each node. Thereafter, the average strain values were calculated for all five FEAs.

3.3. Experimental Analysis

3.3.1. Additive manufacturing

DMLS was used to manufacture the experimental mandibular implant in Ti6Al4V at the CRPM. An EOSINT M280 machine with 200 Watt laser power and a powder layer thickness of 30 µm was used to execute the AM process. The implant was manufactured with the strain gauge positions and orientations marked with small indents on the boundaries of the strain gauges' positions.

The .stl file of the modified implant CAD model was imported in Magics® software to prepare the "building file". In this software the 3D CAD model was used to virtually orientate the implant geometry in the machine's building chamber and to add appropriate support structures as illustrated in Figure 3.11. These support structures are added in such a way that they can be easily removed from the implant after manufacturing. Additionally, supports are added to maintain the original geometry of the implant and to make it easy to remove the implant from the build platform.

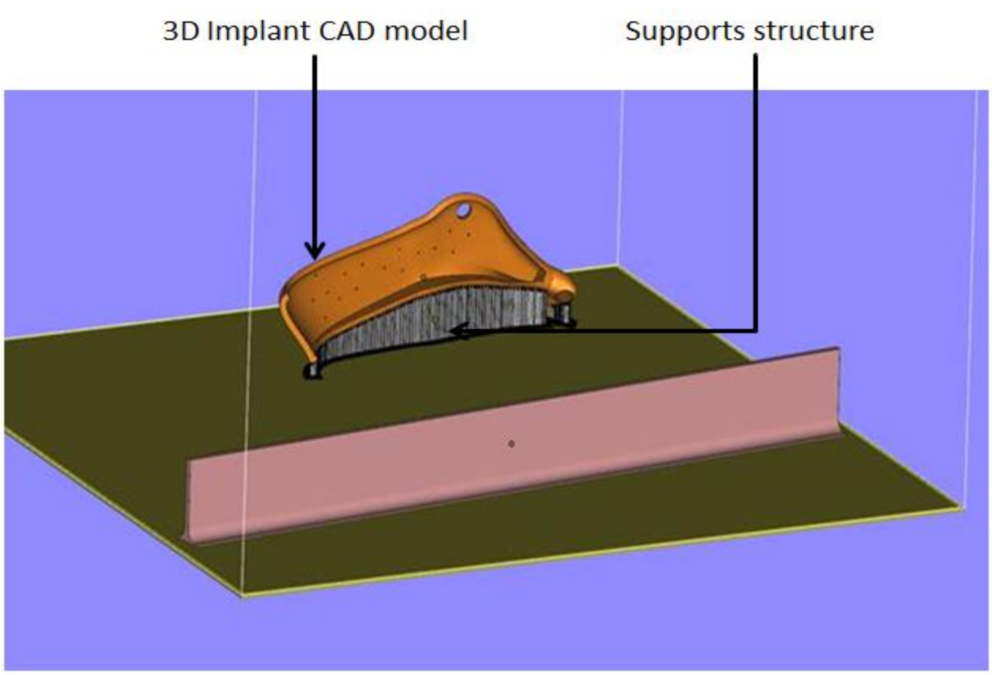


Figure 3.11: 3D Implant CAD model orientation with supports in the Magics® software.

Once the building file had been completed, it was sliced into two-dimensional layers. Subsequently, the sliced file was transferred to the machine for the building process to commence. The end product (experimental model) with all supports removed from it is shown in Figure 3.12.

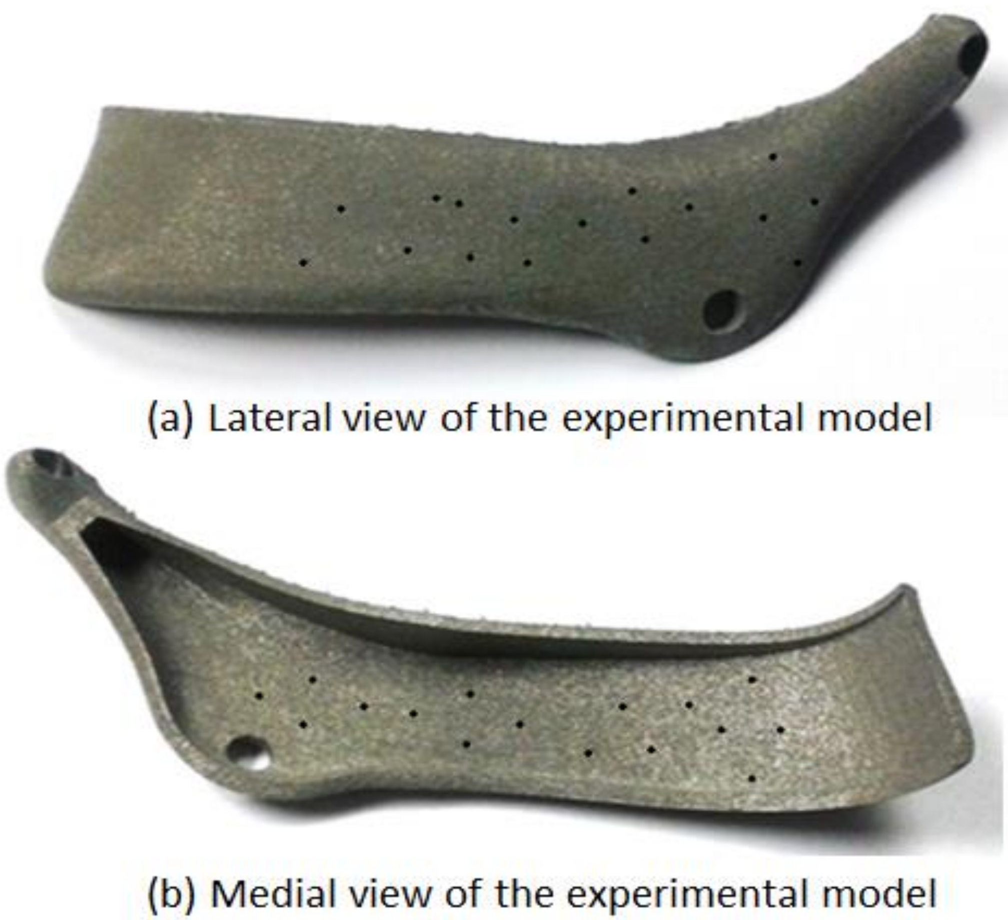


Figure 3.12: The experimental model manufactured through DMLS.

3.3.2. Residual stress relieving of the mandibular implant

A stress relieving heat treatment was performed on the implant to relieve the residual stress induced during the DMLS process. During this treatment the implant was heated in a furnace under a protective argon atmosphere at a temperature ramp up rate of 200 ^{0}C per hour until it reached 650^{0}C. Subsequently, it was kept at this temperature for 3 hours and then allowed to cool down slowly in the furnace. Thereafter, a beta annealing treatment was performed on the implant under vacuum at the CSIR. In this process the implant was heated over a ramp up time of 4 hours to 950 ^{0}C and furnace cooled to room temperature to allow alpha grain growth, resulting in increased ductility of the alloy.

Finally, the implant was heated to 950 ^{0}C, kept at this temperature for a period of 2 hours, and then furnace cooled to room temperature over 4 hours.

3.3.3. Preparation of selected surface for installation of the strain gauges

The first step prior to strain gauge application was to remove any oil, grease and organic contaminants that might be on the implant surface by using Hottinger Baldwin Messtechnik (HBM) reinigungsmittel 1 (RMS1) spray, which is a mixture of acetone and isopropanol. Secondly, the implant was abraded over and around the selected areas where strain gauges were to be installed using silicon-carbide paper of different grit sizes. Abrading was done by starting with a grit size of 80 followed by 180 and ended with 320. The abrading was done to achieve a root mean square surface roughness (Rq) of less than 3.2 μm. The SJ-210 Mitutoyo roughness measuring device was used to evaluate if the required surface roughness was achieved. In Figure 3.13 the implant with the roughness measurement device used is shown.

Figure 3.13: Root mean square (Rq) surface roughness of the implant as measured with SJ-210 roughness measuring device.

Before abrading was done on the implant, the roughness was found to be 13.054 μm while, in Table 3.2, the surface roughness of the implant after abrading for each strain gauge area is shown.

Table 3.2: The surface roughness of the implant after abrading for each strain gauge.

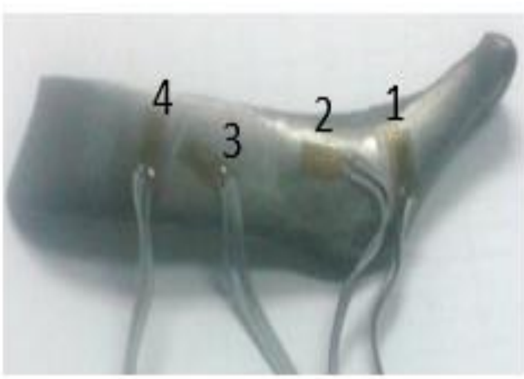
SG Area	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 7	SG 8
Rq (µm)	0.380	0.424	0.425	0.262	0.517	0.246	0.340	0.374

Finally, the RSM 1 was again applied to the implant and wiped with a single stroke of a clean paper towel. This final step was done several times till the towel appeared clean after a single wipe.

3.3.4. Strain gauge installation

Eight 350±0.3% ohms' strain gauges (6/350 LY41) were installed on the mandibular implant corresponding to the gauge locations and orientation marks manufactured with the implant. Initially, each strain gauge was placed on adhesive tape with its sensing side facing upwards. Thereafter, the gauge area was well cleaned using RMS1 cleaning agent before a very small drop of the HBM gauge adhesive (Z70) was applied on the implant where the strain gauge was to be installed. Immediately after that, the gauge was placed down on the marked position with its sensing side facing to the implant. Subsequently, uniform thumb pressure was applied on the gauge for fifteen minutes. Finally, 30 minutes was allowed for the adhesive to completely cure before carefully removing the adhesive tape.

Once the installation was done the three wire conductors were connected on the strain gauge solder tapes. In Figure 3.14 (a) and (b) the lateral and medial views of the implant with the installed strain gauges are shown.



(a)

(b)

Figure 3.14: Physical implant with strain gauges installed on and three wire configurations connected to all strain gauge.

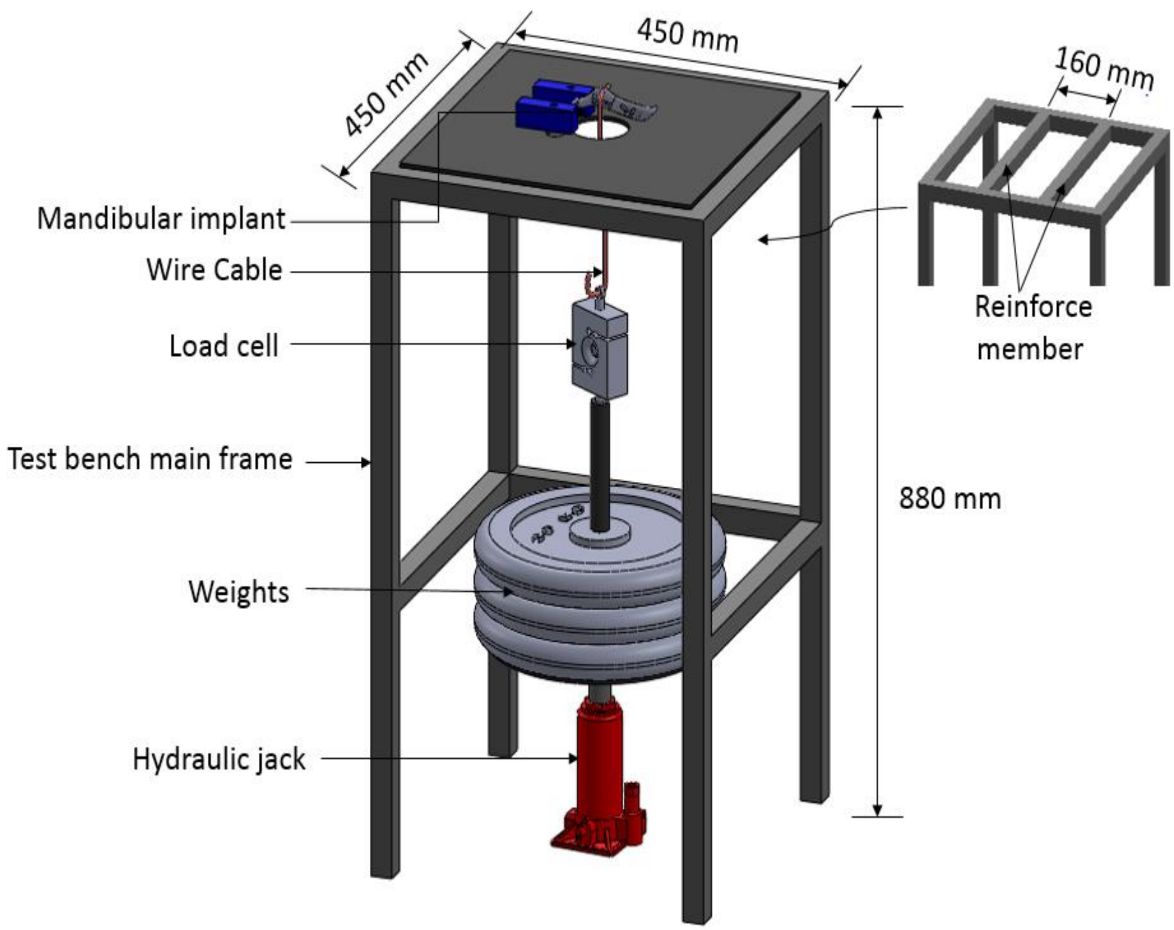
3.3.5. Experimental test bench and data recording

The strain gauges which were installed on the implant were connected to the quarter bridge circuits (1-SCM-SG120) by a 3 wire configuration. Thereafter, each circuit was connected to the specific channel on the Quantum X Universal Amplifier (MX840 8 channel amplifier), which was connected to the Quantum X Data Recorder (CX 22W) with the specifications indicated in appendix 1 and 2, respectively. The technical specifications of the strain gauges, quarter bridge and load cell used in this study are indicated in Table 3.3.

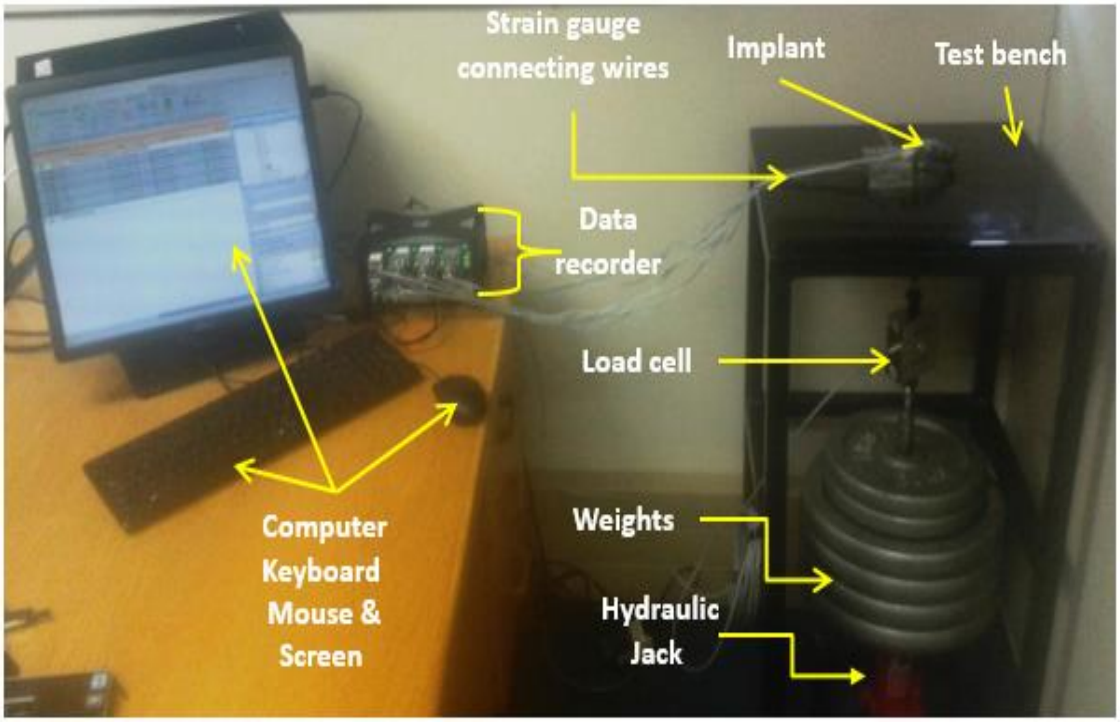
Table 3.3: The technical specifications of all components used during experimentation.

Strain Gauge (6/350 LY41)	
Resistance (R)	350 Ohm ± 0.30 %
Gauge factor (GF)	2.03 ± 1.0 %
Transverse sensitivity	-0.4 %
Temperature coefficient	0 ± 0 [10^{-6} / ºC]
Quarter Bridge Circuit (SCM –SG 350 for connection of strain gauge with 350 Ohm)	
SG connection	Quarter bridge, Three wire
Bridge excitation voltage, max	DC 50V; AC 2.5 V
Impedance	350 Ohm
Degree of protection	IP20
Operation temperature range	-20 ºC …+65 ºC
Storage temperature range	-40 ºC …+75 ºC
Cable length to the quarter bridge, max	30 m
Vibration 30 min	50 g
Impact 6 ms	350 g
Build-in shunt that can additionally be connected via software	86.6 kOhm (approx. 1 mV/V with 350 Ohm)
Zero error (with 2 m cable to strain gauge)	0.2 mV/V
Addition influence of the ambient temperature on the zero point. 350 Ohm	0.003 mV/V per 10 K
Data Recorder CX22W (See Appendix 1)	
Universal Amplifier MX840A (See Appendix 2)	
Load Cell / Force Transducer S9M/50kg (See Appendix 3)	

The experimental test bench was designed in such a way that the boundary conditions applicable to the loading and testing of the mandibular implant corresponded with the FEA model. To achieve this, the test bench was designed and constructed not to buckle as the load was applied. The bench was made from mild steel with 30 mm X 30 mm X 2 mm square tubing reinforced by 5 mm thick plate at the top. In Figure 3.15 (a) and (b) the engineering drawing and the picture of the experimental test bench is illustrated, respectively.



(a) Engineering drawing of the experimental test bench.



(b) The experimental test bench illustrating the connection of its different components.

Figure 3.15: The experimental test bench with (a) engineering drawing and (b) picture of the experimental test bench.

The implant's condyle was connected by a 5 mm diameter mild steel pin in a way that it formed a hinge about an axis perpendicular to the Z-Y plane by passing through point A as shown in Figure 3.16.

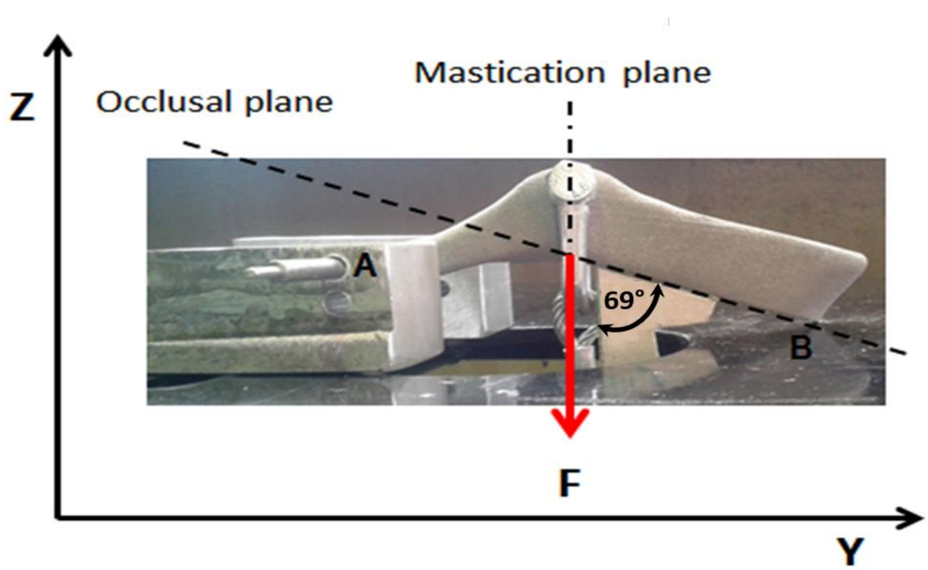


Figure 3.16: Experimental test bench used to achieve the load and boundary conditions.

Moreover, the condyle was restricted to translate in all directions by two aluminium blocks mounted on each side of it. On the other side of the implant at position **B** the implant rested on the test bench's platform in such a way that only one direction was prohibited, namely translation in the negative Z direction.

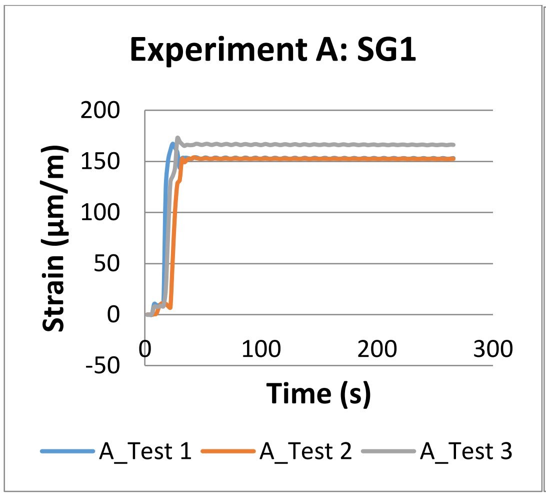
A U-bolt was inserted through the hole at the ramus of the mandibular implant. Loads were applied onto the U-bolt by utilising a hanger with masses connected via a cable. The mass was initially supported by the hydraulic jack and the implant was experiencing no load. As the jack was slowly lowered below the load the implant began to gradually experience loading until the jack was completely removed from the load. The load was applied to represent the effect of contraction of the masseter muscle. Once the load was applied on the implant, the strain values were captured with Catman® software. Five experiments were performed at different loads, namely experiment A = 215 N, experiment B = 415 N, experiment C = 620 N, experiment D = 821 N and experiment E = 1 026 N. In each experiment three tests were performed and from these tests the average strain value was computed and saved for comparison with the FEA results.

3.3.6. Measurement system analysis

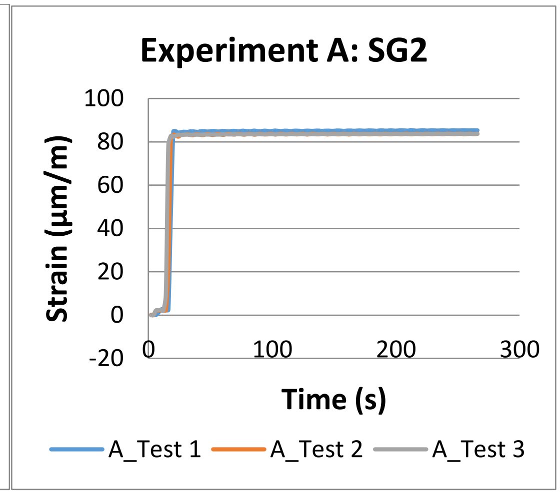
The system allowed data from a number of strain gauges to be collected simultaneously. On application of the load on the implant each gauge started to record the data at a frequency of 0.5 Hz. This implied that for a single test each gauge recorded 133 data points over a period of 266 seconds. Based on the collected data the standard deviation of the measurement system was calculated. This deviation was computed based on the data recorded after the stable region of the strain was reached (after 33 data points were recorded). In Table 3.3 the minimum, maximum, mean, standard deviations and confidence interval strain of the recorded data for the selected measurement system in experiment A are shown.

The standard deviation was found to be very small in all strain gauges, with the exception of gauge 7. The strain value measured with gauge 7 was also much higher than any of the others, which indicated that it was not measuring correctly. It was, therefore, decided not to use data from this gauge in subsequent experiments.

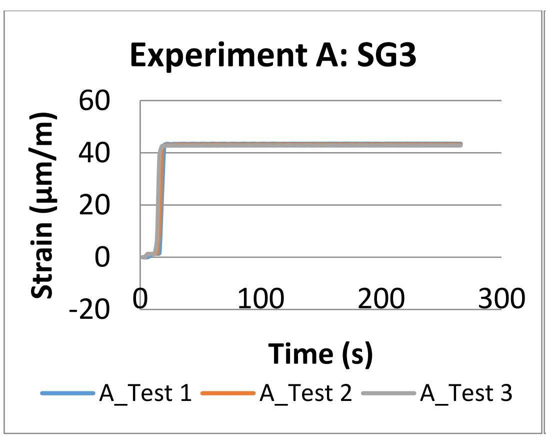
Each test in each experiment was repeated three times to determine the repeatability of the measurements. In Figure 3.17 the repeatability of the all gauges is illustrated for Experiment A with a load of 215 N. Clearly, the initial part of the graph represents a transitional region when the load takes 66 seconds to reach the stable region of strain. Only values obtained after 66 seconds were used for validation purposes.



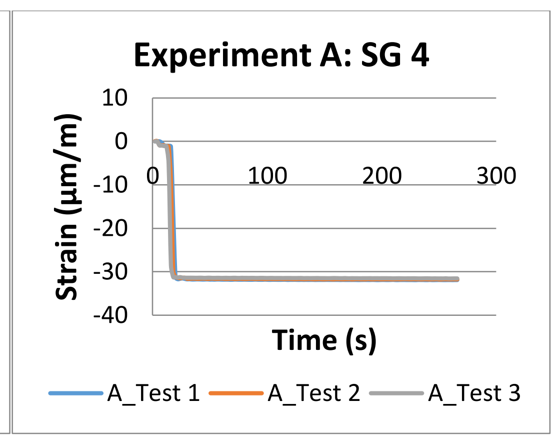
(a) Strain gauge 1



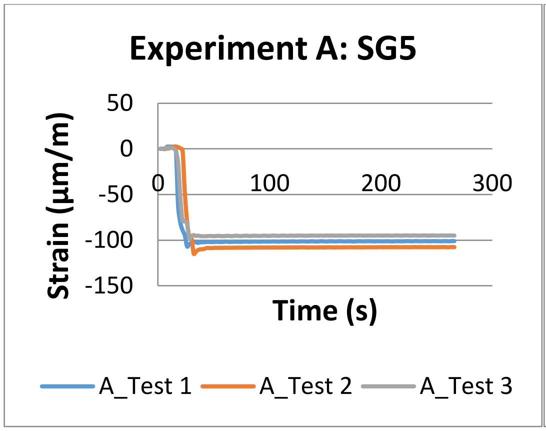
(b) Strain gauge 2



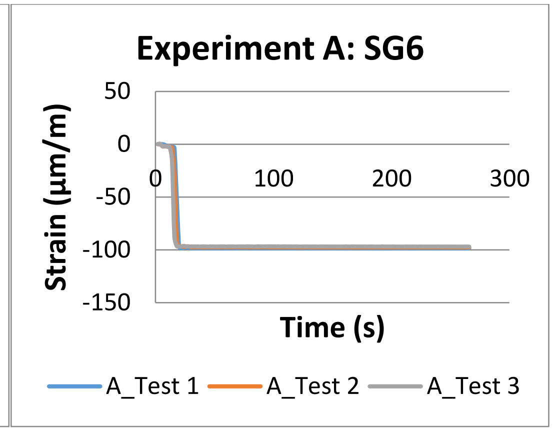
(c) Strain gauge 3



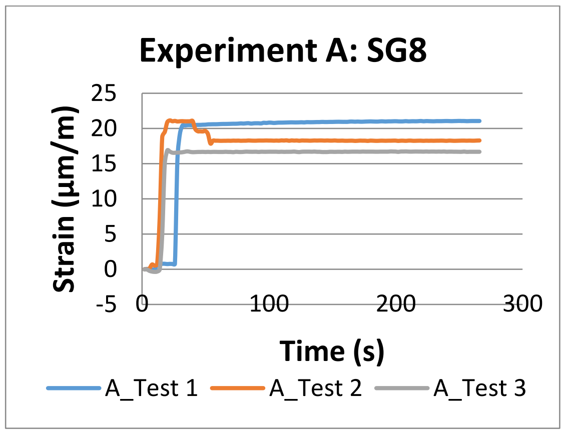
(d) Strain gauge 4



(e) Strain gauge 5



(f) Strain gauge 6



(g) Strain gauge 8

Figure 3.17: Graphical representation of strain against time for all strain gauges in experiment A.

The curves of the three tests have the same pattern for all strain gauges. This signifies a level of repeatability in all the strain gauge results. Nonetheless, by evaluating Figure 3.17 in detail, there are very small deviations on the repeatability of the measurements. Therefore, it was found necessary to quantify the repeatability by determining the confidence interval of the measured strain value for each strain gauge in experiment A. The confidence intervals were obtained using equation 3.15. A level of confidence of 90% was decided on. Such confidence was based on the fact that the percentage error between FEA and strain gauge should be within 10%, refer to the paragraph 2.5.3. Resulting from this, the critical value z was found to be 1.6 using a standard statistics table for normal distribution. In appendix 5 the detailed calculation of the critical value and the standard statistic table are shown.

$$90\%\ Confidence\ interval = \overline{x} \pm z\frac{s}{\sqrt{n}} \quad (3.15)$$

Where $\overline{x}$ is the mean/average value, s is the standard deviations and n is the number of samples.

Table 3.4: The minimum, maximum, mean, standard deviations and confidence interval strain of the recorded data with the selected measurement system for experiment A is documented.

	Experiment A						
	SG 1	**SG 2**	**SG 3**	**SG 4**	**SG 5**	**SG 6**	**SG 8**
Samples	133	133	133	133	133	133	133
Units	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)
Min	156.83	83.97	43.11	-31.74	-101.84	-97.71	18.53
Max	157.84	84.27	43.15	-31.62	-101.04	-97.53	18.69
Mean	157.21	84.13	43.13	-31.69	-101.32	-97.63	18.64
STD	0.26	0.08	0.01	0.04	0.18	0.05	0.04
Confidence interval	157.21 ±0.036	84.13 ±0.011	43.13 ±0.0014	-31.69 ±0.005	-101.32 ±0.02	-97.63 ±0.007	18.64 ±0.005

Chapter 4: Results and Discussions

4.1. Introduction

In this chapter the FEA results, experimental data and the comparison between FEA and experimental data are presented and discussed. This is followed by a general discussion of the results.

4.2. Finite element analysis results

Extracting the FEA strain values from the software for each strain gauge area on the surface of the implant was the main requirement for acquiring computational data suitable for validation of the FEA. The detailed FEA results for all the nodes under each strain gauge area are documented in Appendix 6. Table 4.1 summarises the FEA strain values found for the range of loads in the areas where the strain gauges were attached.

Table 4.1: Average strain magnitudes over strain gauge areas for the different applied loads in (µm/m).

FEA Results	FEA: A	FEA: B	FEA: C	FEA: D	FEA: E
Applied Load (N)	215	415	620	821	1 026
SG1	148.87	288.07	430.53	569.81	711.60
SG2	88.17	170.62	255.00	337.49	421.47
SG3	39.70	76.82	114.80	151.94	189.75
SG4	-28.94	-57.99	-83.69	-110.76	-138.32
SG5	-102.92	-199.15	-297.65	-393.93	-491.95
SG6	-97.21	-188.10	-281.13	-372.07	-464.65
SG8	17.97	33.99	50.80	67.23	83.96

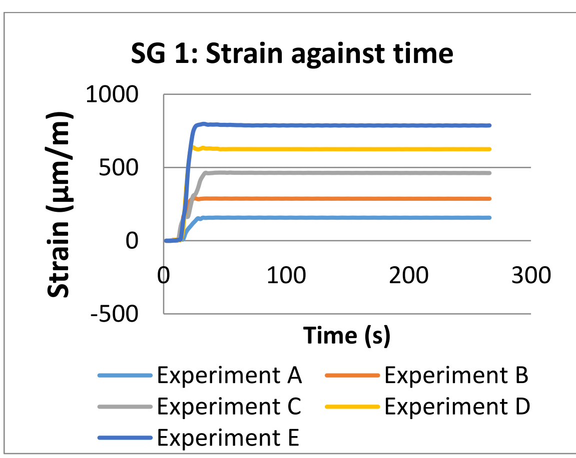
4.3. Experimental results

For all five experiments mentioned in 3.2.4 the average strain values of the three measurement tests were calculated for each strain gauge in each experiment. For FEA validation purpose, it was necessary to determine the specific strain value from the three tests that represent the specific area in which the strain gauge was installed. Therefore, the mean values of all average values of all the strain gauge measurements were computed. In Appendix 7 all the data for each strain gauge is documented. The mean values of the measured strain for the different applied loads are shown in Table 4.2.

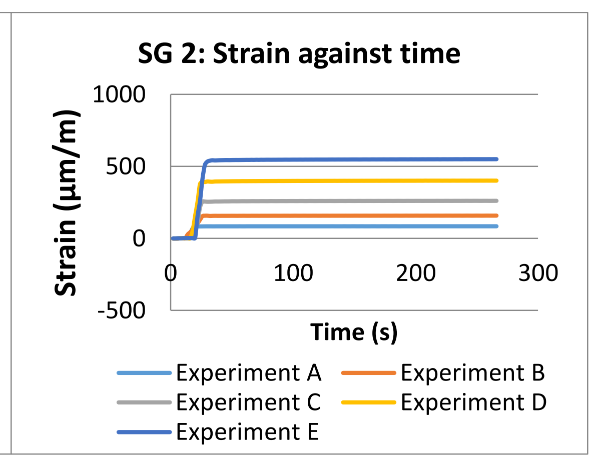
Table 4.2: The experimental strain magnitude for the different applied loads measured in (µm/m).

Experimental Results	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Applied Load (N)	215	415	620	821	1 026
SG1	157.21±0.036	286.88±0.040	462.62±0.063	625.66±0.017	787.97±0.078
SG2	84.13±0.011	158.22±0.035	260.98±0.091	401.06±0.130	550.19±0.182
SG3	43.13±0.001	77.86±0.008	108.79±0.007	140.58±0.016	184.34±0.019
SG4	-31.69±0.005	-63.00±0.014	-86.91±0.022	-114.40±0.026	-149.08±0.032
SG5	-101.32±0.024	-210.12±0.043	-307.87±0.049	-400.45±0.101	-494.18±0.106
SG6	-97.63±0.007	-199.46±0.004	-304.95±0.024	-431.33±0.038	-605.21±0.048
SG8	18.64±0.005	33.48±0.003	51.47±0.009	70.05±0.047	92.60±0.014

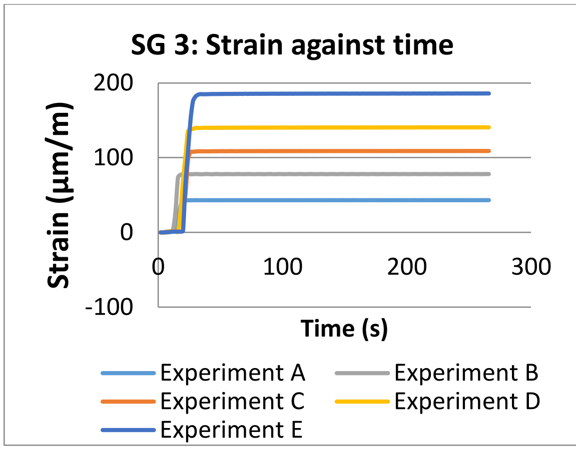
Furthermore, to interpret the strain distribution from experimental data tabulated in Table 4.2 the strain values were plotted against time for different loads on a single Cartesian plane. In Figure 4.1 the graphical representation of all strain gauges for all experiments and different loads is illustrated.



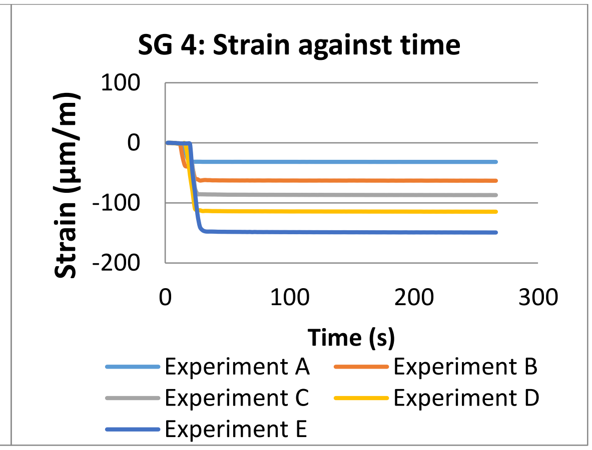
(a) Strain gauge 1



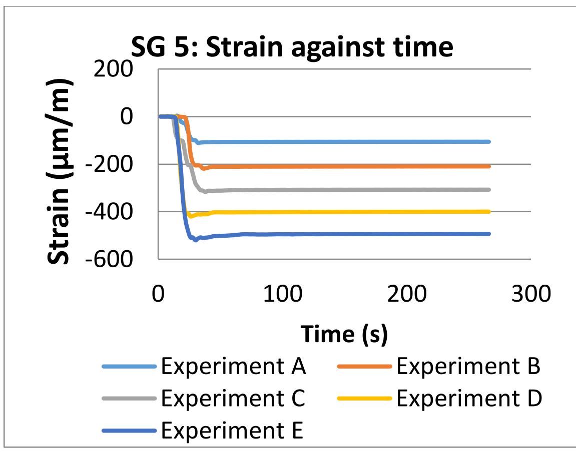
(b) Strain gauge 2



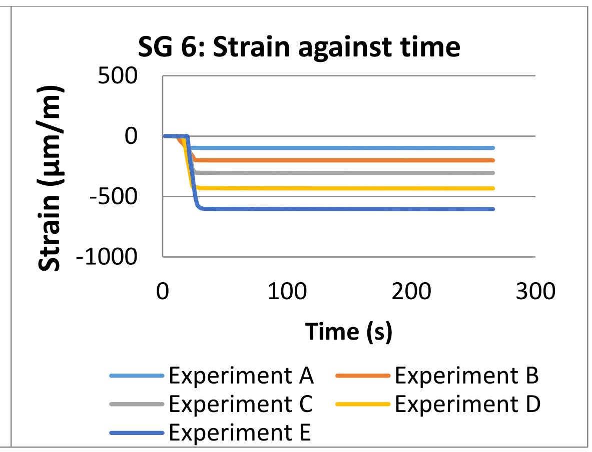
(c) Strain gauge 3



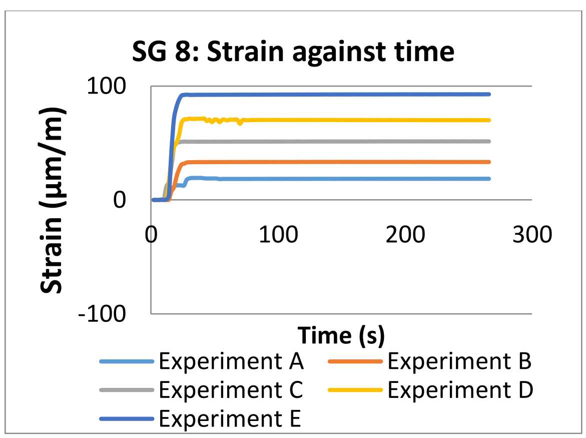
(d) Strain gauge 4



(e) Strain gauge 5



(f) Strain gauge 6



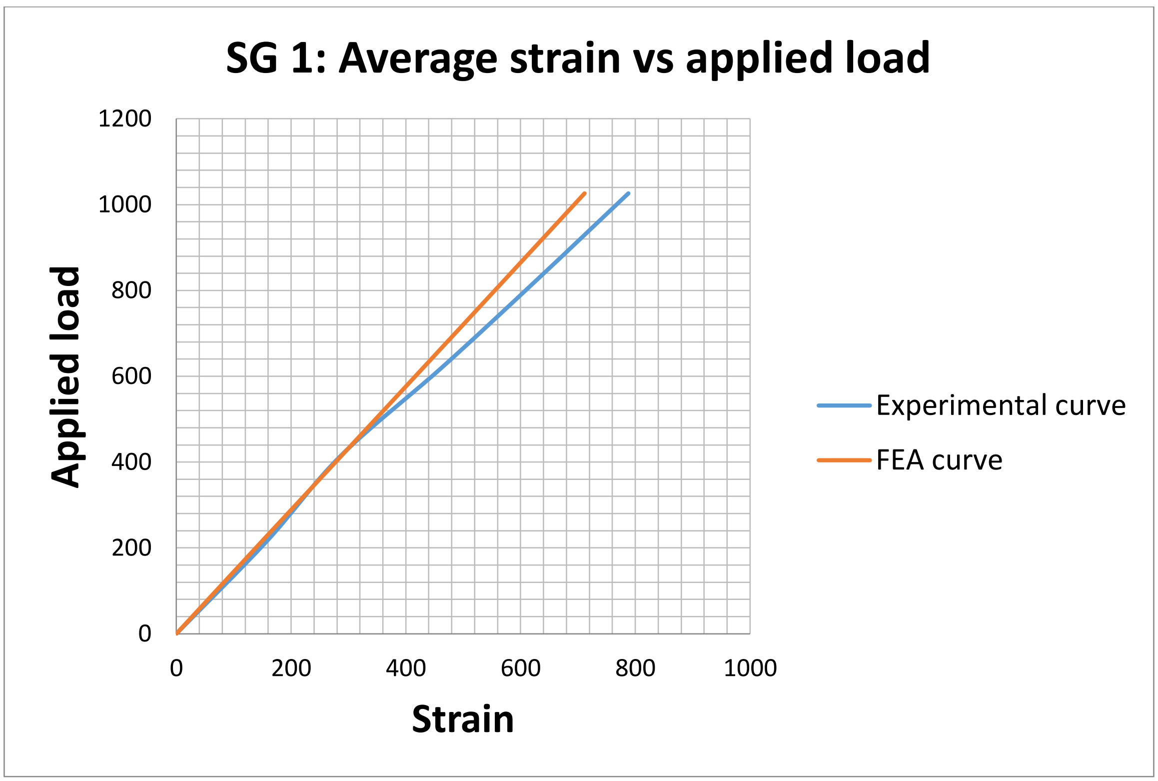
(h) Strain gauge 8

Figure 4.1: Graphical representation of all strain gauge results for all experiments to illustrate the relationship between strain and applied load.

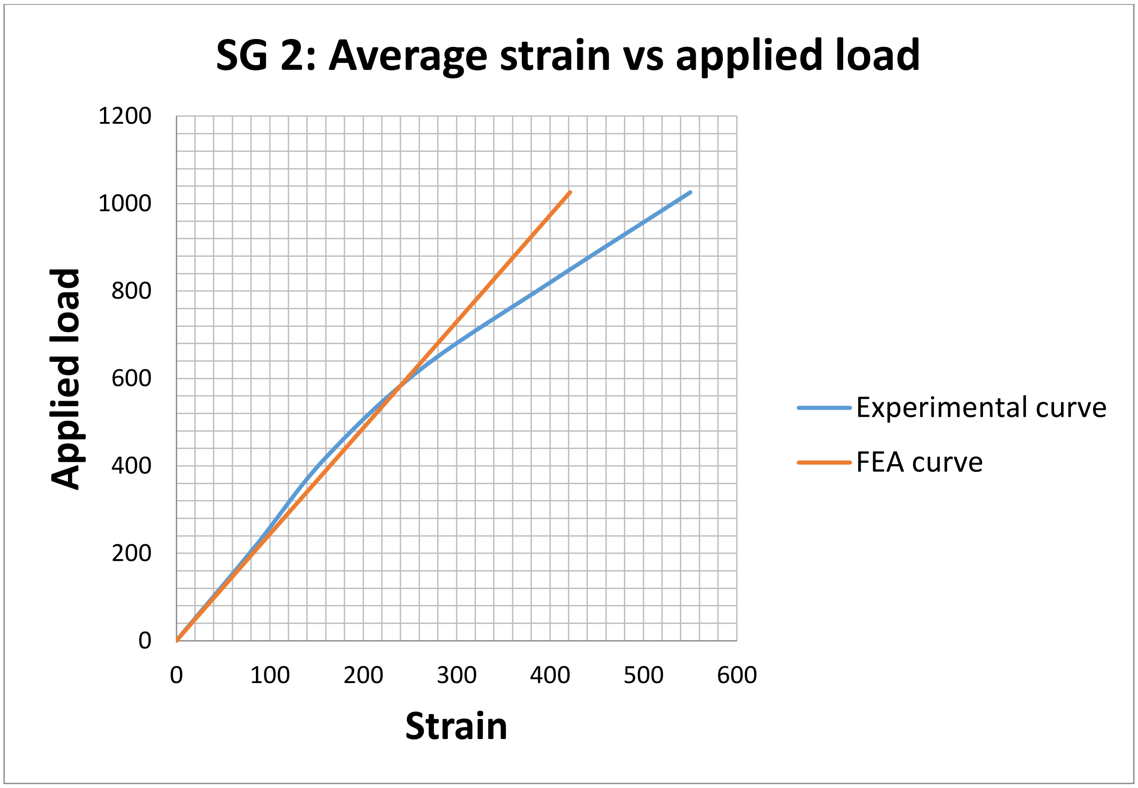
In the same way, as it was observed from the FEA results, the experimental results presented in Figure 4.1 also illustrate that there is a direct relationship between the applied load and the strain induced in the implant.

4.4. Comparison of FEA and strain gauge results

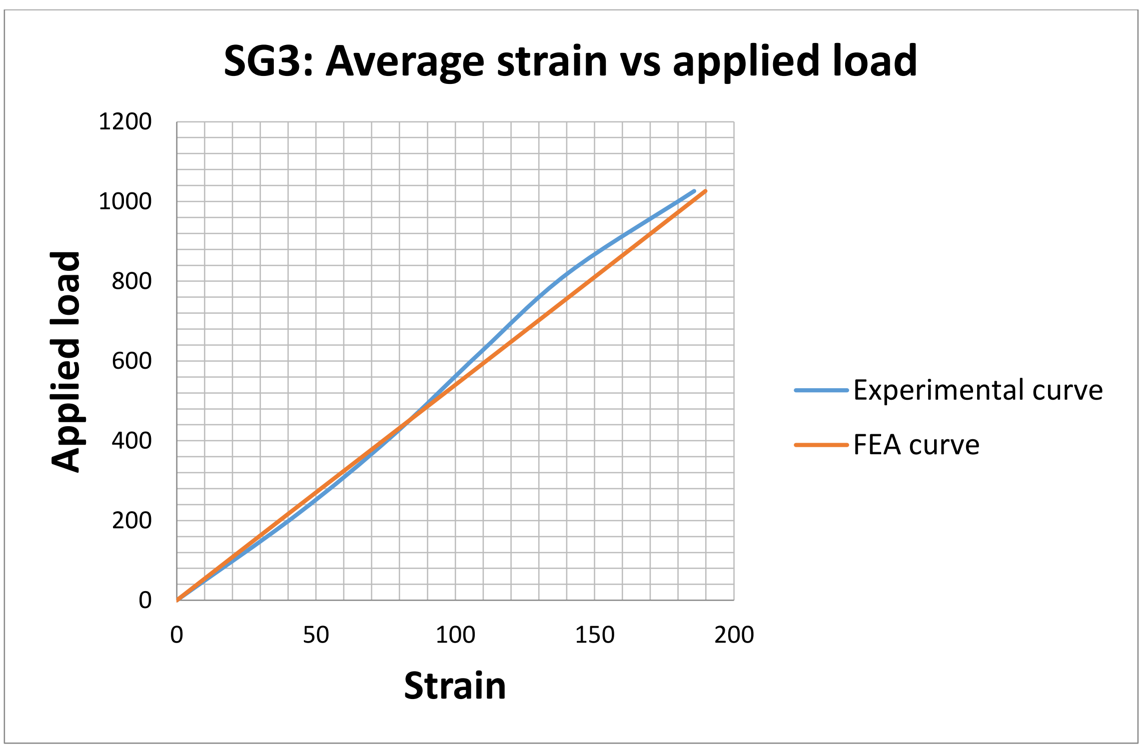
The FEA strain values were compared with the experimental strain values for different loads for all the strain gauges. Figures 4.2 (a) to (g) illustrate the correlation between the FEA and the experimental values for different experiments. Figure 4.2 clearly shows that there is generally a very good correlation between the experimental and FEA results, with the exception of strain gauges 2 and 6 at high loads.



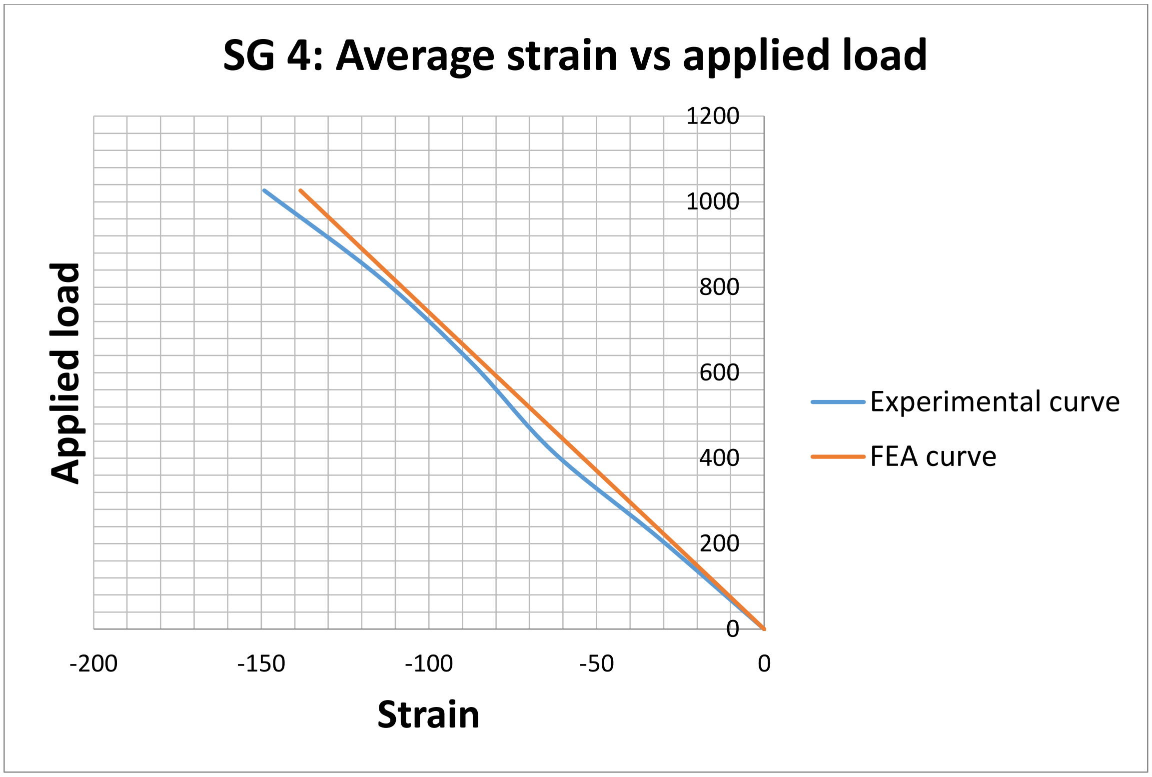
(a) Strain gauge 1



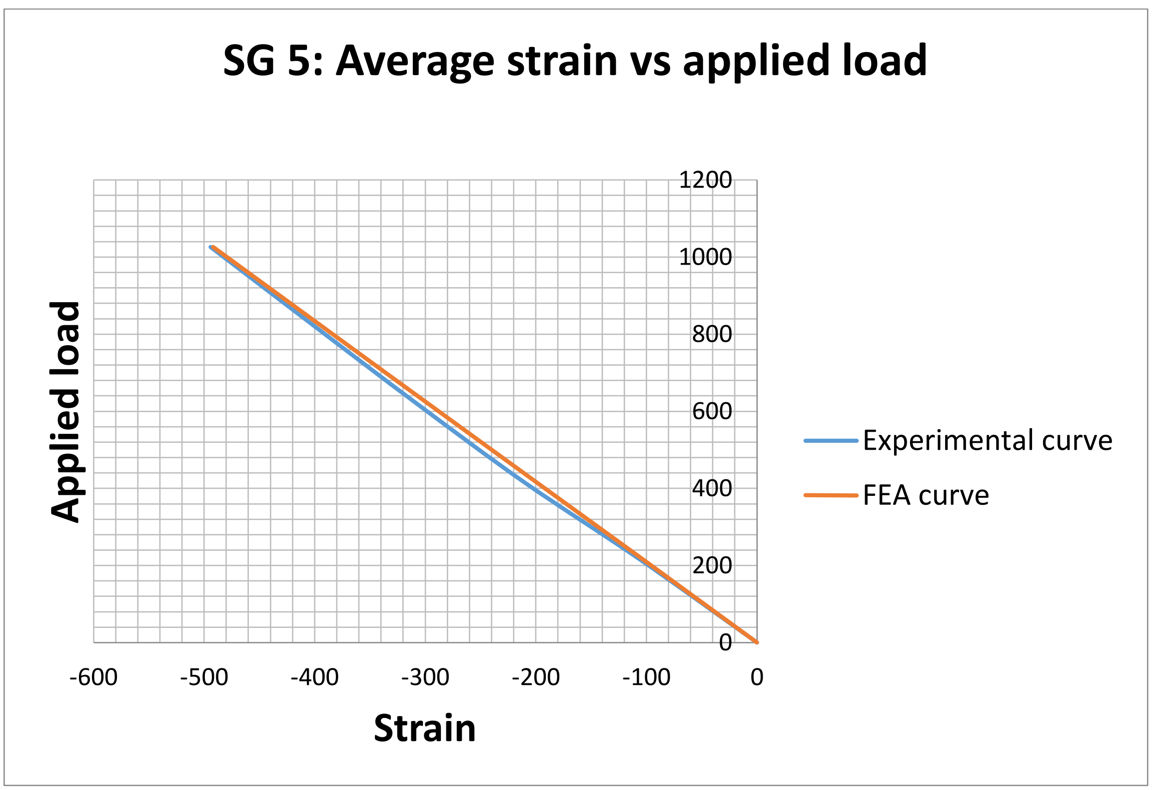
(b) Strain gauge 2



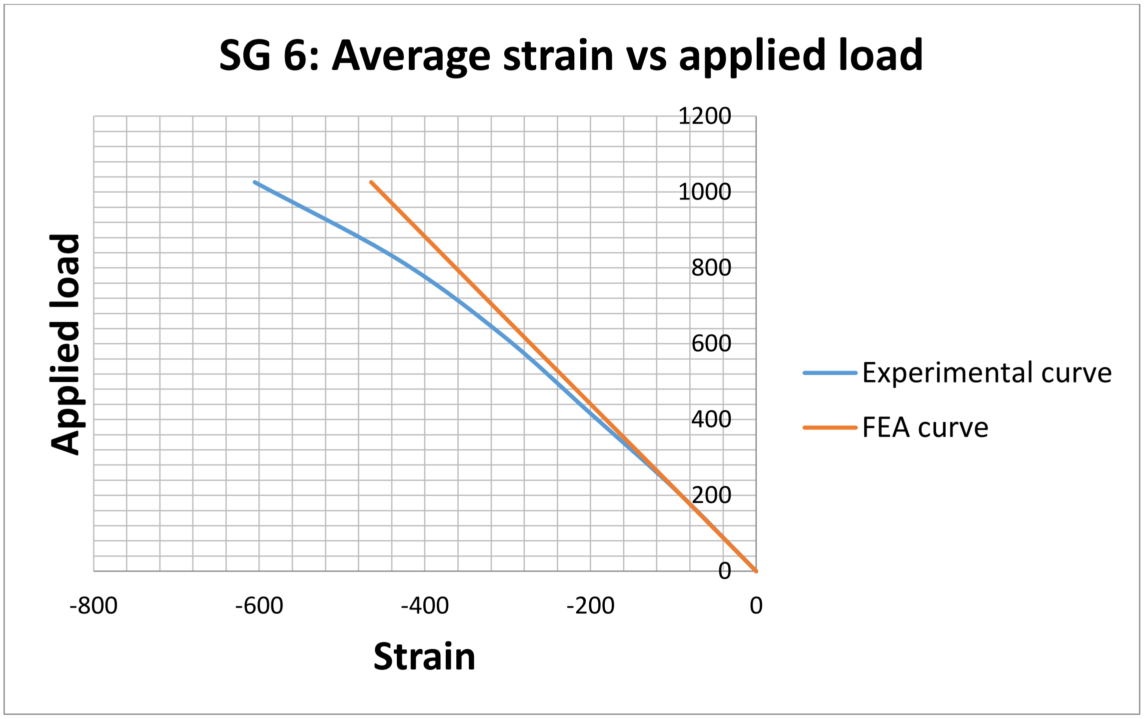
(c) Strain gauge 3



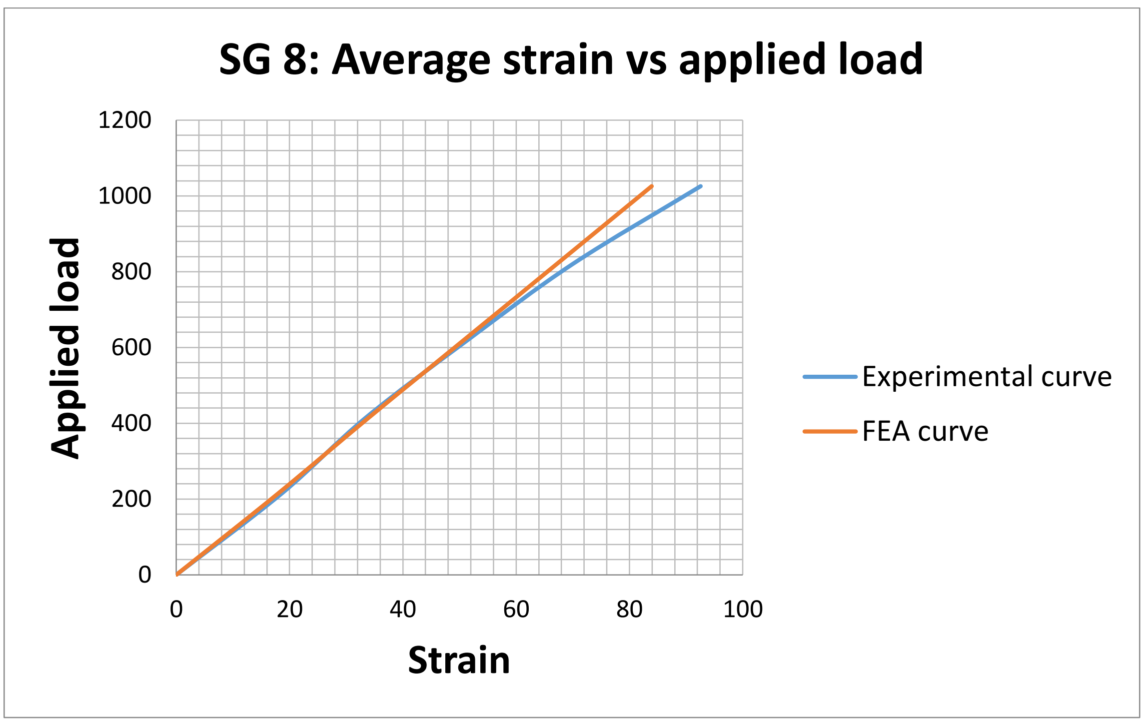
(d) Strain gauge 4



(e) Strain gauge 5



(f) Strain gauge 6



(g) Strain gauge 8

Figure 4.2: Illustration of the accuracy between the FEA and the experimental values for the different strain gauges.

The percentage difference of the FEA results from the experimental results was calculated for each strain gauge, using equation 4.1.

$$\% \, Difference = \left(\frac{Experimental\ Strain\ Value - FEA\ Strain\ Value}{Experimental\ Strain\ Value}\right) 100 \text{..............................(4.1)}$$

In Table 4.3 the FEA and experimental results, as well as the percentage difference between these, are tabulated. In the table, the number of FEA nodes used for calculating the strain for each strain measurement area is also documented.

Table 4.3: Comparison of experimental results versus FEA strain results (µm/m).

	Loads (N)	SG 1	SG 2	SG 3	SG 4	SG 5	SG 6	SG 8
Nodes		177	181	169	193	193	173	177
				Experiment A				
FEA Strain	215	148.87	88.17	39.70	-28.94	-102.92	-97.21	17.97
Experimental strain		157.21 ±0.036	84.13 ±0.011	43.13 ±0.001	-31.69 ±0.005	-101.32 ±0.024	-97.63 ±0.007	18.64 ±0.005
% Difference		**5.31%**	**-4.80%**	**7.95%**	**8.68%**	**-1.58%**	**0.43%**	**3.59%**
				Experiment B				
FEA Strain	415	288.07	170.62	76.82	-57.99	-199.15	-188.10	33.99
Experimental strain		286.88 ±0.040	158.22 ±0.035	77.86 ±0.008	-63.00 ±0.014	-210.12 ±0.043	-199.46 ±0.004	33.48 ±0.003
% Difference		**-0.41%**	**-7.84%**	**1.34%**	**8.64%**	**5.22%**	**5.70%**	**-1.52%**
				Experiment C				
FEA Strain	620	430.53	255.00	114.80	-83.69	-297.65	-281.13	50.80
Experimental strain		462.62 ±0.063	260.98 ±0.091	108.79 ±0.007	-86.91 ±0.022	-307.87 ±0.049	-304.95 ±0.024	51.47 ±0.009
% Difference		**6.94%**	**2.29%**	**-5.52%**	**3.70%**	**3.32%**	**7.81%**	**1.30%**
				Experiment D				
FEA Strain	821							
Experimental strain		625.66 ±0.017	401.06 ±0.130	140.58 ±0.016	-114.40 ±0.026	-400.45 ±0.101	-431.33 ±0.038	70.05 ±0.047
% Difference		**8.93%**	**15.85%**	**-8.08%**	**3.18%**	**1.63%**	**13.75%**	**4.03%**
				Experiment E				
FEA Strain	1026	711.60	421.47	189.75	-138.32	-491.95	-464.65	83.96
Experimental strain		787.97 ±0.078	550.19 ±0.182	184.34 ±0.019	-149.08 ±0.032	-494.18 ±0.106	-605.21 ±0.048	92.60 ±0.014
% Difference		**9.69%**	**23.40%**	**-2.17%**	**7.22%**	**0.75%**	**23.22%**	**9.33%**

For the lower loads the correlation between the FEA and strain gauge measurements was found to be mostly within 10%. However, at high loads, for strain gauges 2 and 6, the percentage differences were found to be more than 10%. This is also clear in Figures 4.2 (b) and (f). This is attributed to some shear strain induced in the implant under high loads due to deflection or slight bending of the implant. Such bending results from the geometry of the implant (see Figure 3.2 (b) and (d)). The shear strain due to the shear force component that results from bending is small relative to the normal strain [71]. Its effect is more significant when the ratio of the dimension of the implant's cross section to the length is small and when the applied load is relatively high. In this study strain gauge areas 2 and 6 were placed very close to the position of the applied load. Therefore, the detectable shear strain effect was higher in areas 2 and 6 than the in the other gauge areas. This type of strain gauge cannot differentiate between the principal strain and the shear strain component and just detects an increased strain value. This could be the explanation for the deviations between the FEA and strain gauge measurements.

4.5. General discussion of the results

A mandibular implant that allowed the strain distribution to be determined with FEA and strain gauge measurements, was successfully designed. The design was made possible through SolidWorks® software. Thereafter, the linear static strain distribution was determined using Patran/Nastran software. Finally, the strain gauge measurement was successfully executed by the Quantum X data acquisition system with Catman® software.

The strain distribution at selected areas in the mandible was predicted under selected static load conditions using FEA. The surface nodes on the selected areas of the implant were grouped. Thereafter, the strain magnitudes of the grouped nodes were calculated using linear static FEA. Subsequently, the strain gauge measurements performed on the additively manufactured implant on the selected areas were compared with the FEA results. From the results obtained it can be said that satisfactory correlation was found between the FEA results and the experimental results from strain gauge measurements.

Furthermore, it is clear that FEA models of medical implants designed for production through AM can be accurately achieved provided the methodology followed in this study is applied in conjunction with the existing design process discussed in section 2.4.1. By combining the design flow chart with the methodology chart the validation chart shown in Figure 4.6 was attained.

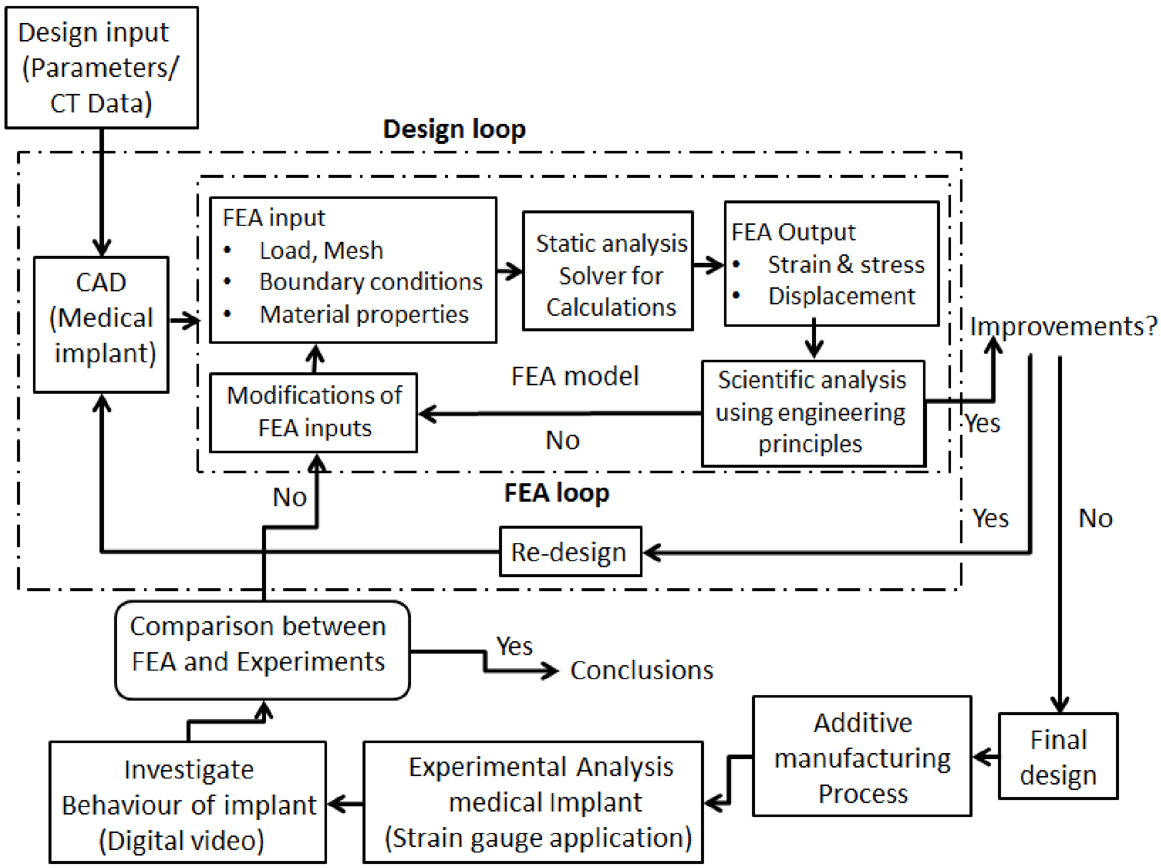


Figure 4.3: Recommended FEA validation chart for medical implants produced through AM.

The CT scan data provide accurate input for the CAD of the medical implant. The reconstruction of a part of the skeleton and the best CAD model for validation can be accurately achieved. The FEA loop begins with the FEA inputs (mesh, loads, boundary conditions, and material properties) which should resemble experimental models as closely as possible. Once the results are generated by the solver, it is highly recommended that the results should be scientifically analysed using engineering principles. Should there be an unacceptable mismatch the FEA inputs should be modified. However, if there is a match the results can be used in the design loop to evaluate whether the required mechanical properties are achieved before the final implant design is approved.

Chapter 5: Conclusions and Future Work

5.1. Conclusions

Validation of FEA depends on a proper resemblance between FEA and the experimental setup. Therefore, the FEA should be integrated well within the computational design process of the medical implant. This is achieved if the FEA loop is well integrated in the design loop. The correlation between the FEA and strain gauge measurements was found to be 90% or better. Therefore, the study confirmed that FEA of Ti6Al4V (ELI) medical implants designed for AM can be validated through using strain gauge measurements.

This study has confirmed that the ability to deliver medical implants that consistently comply with the required physical and mechanical properties required for normal activities of a patient can be achieved through the integration of FEA in the design process. The data collected in this research were found sufficient to validate FEA models of Ti6Al4V (ELI) medical implants produced through additive manufacturing using the EOSINT M 280 machine with standard parameters. Therefore, FEA can be confidently used as a design tool to predict the stress/strain distribution in titanium AM medical implants, provided that the loading conditions represent the loads that the implant will be subjected to. For a mandible implant, the facial contour of the patient can be restored, while ensuring sufficient mechanical strength.

From the results obtained, it can be stated that the aim of this study, namely to establish confidence in FEA as a powerful design tool during design for AM by validating an FEA model of a mandibular implant produced by AM in Ti6Al4V (ELI) through experimental strain gauge measurements, was achieved. This makes FEA a powerful tool for prediction of stress and strain distributions during the design of complex medical implants to be produced through AM.

5.2. Future Work

In this study FEA was validated to generate accurate results for linear static analyses of medical implants for AM. However, there is also a case to be made for nonlinear analyses where applicable. Consequently, there is an opportunity for future validation of FEA of medical implants produced through AM under nonlinear conditions.

Another potential topic for future research could be validation of FEA of a Ti6Al4V (ELI) medical implant for additive manufacturing through direct image correlation or digital speckle pattern interferometry.

List of References

[1] C. R. F. Azevedo, "Failure analysis of a commercially pure titanium plate for osteosynthesis," *Engineering Failure Analysis*, vol. 10, no. 2, pp. 153–164, 2003.

[2] M. Kromka and G. Milewski, "Experimental and numerical approach to chosen types of mandibular fractures cured by means of miniplate osteosynthesis," *Acta of Bioengineering and Biomechanics*, vol. 9, no. 2, pp. 49–54, 2007.

[3] F. Gröning, J. a Bright, M. J. Fagan, and P. O'Higgins, "Improving the validation of finite element models with quantitative full-field strain comparisons.," *Journal of biomechanics*, vol. 45, no. 8, pp. 1498–506, May 2012.

[4] A. Kumar, K. G. Svensson, L. Baad-Hansen, M. Trulsson, F. Isidor, and P. Svensson, "Optimization of jaw muscle activity and fine motor control during repeated biting tasks.," *Archives of oral biology*, vol. 59, no. 12, pp. 1342–51, Dec. 2014.

[5] A. G. Hannam, "Structure and Function in the Human Jaw," in *Auditory-Visual speech processing*, 2005, p. 151.

[6] H. Greyling, W. B. Du Preez, D. De Beer, and A. Uys, "Collaborative Program in Additive Manufacturing to the Department of Science and Technology, focus area: Additive Manufacturing," pp. 1–30, 2014.

[7] D. Manfredi, F. Calignano, M. Krishnan, R. Canali, E. P. Ambrosio, S. Biamino, D. Ugues, M. Pavese, and P. Fino, "Additive Manufacturing of Al Alloys and Aluminium Matrix Composites (AMCs)," in *Light Metal Alloys Applications*, 2014, pp. 3–34.

[8] A. R. Chowdhury, A. Kashi, and S. Saha, "A comparison of stress distributions for different surgical procedures, screw dimensions and orientations for a Temporomandibular joint implant," *Journal of Biomechanics*, vol. 44, no. 14, pp. 2584–2587, 2011.

[9] O. L. a Harrysson, O. Cansizoglu, D. J. Marcellin-Little, D. R. Cormier, and H. a. West, "Direct metal fabrication of titanium implants with tailored materials and mechanical properties using electron beam melting technology," *Materials Science and Engineering C*, vol. 28, no. 3, pp. 366–373, 2008.

[10] S. Sharma, K. Lammin, and P. Kay, "(i) Introduction and follow-up of new implants," *Orthopaedics and Trauma*, vol. 26, no. 4, pp. 231–261, 2012.

[11] W. Wang and C. Wang, *The Design and Manufacture of Medical Devices*. Woodhead Publishing

Limited, 2012.

[12] ASTM International, “F2792-12a - Standard Terminology for Additive Manufacturing Technologies,” 2013.

[13] S. Mellor, L. Hao, and D. Zhang, “Additive manufacturing: A framework for implementation,” *International Journal of Production Economics*, vol. 149, pp. 194–201, Mar. 2014.

[14] H. Shulman and C. Hoag, “Introduction to Additive Manufacturing, Ceramic Industry,” 2012.

[15] M. Ruffo, C. Tuck, and R. J. M. Hague, “Cost estimation for rapid manufacturing - laser sintering production for low to medium volumes,” *Journal of Engineering Manufacture*, vol. 220, no. 9, pp. 1417–1427, 2006.

[16] W. B. Du Preez, D. De Beer, O. Damm, D. Dimitrov, T. Becker, H. Greyling, M. Vermeulen, R. Knutsen, and P. Mendonides, “Qualification of Additive Manufacturing of Ti6Al4V for Medical Implants and Aerospace Components, Proposed Business Plan for 2014/15 to 2017/18 to the Depatrment of Science and Technology, Focus Area: Additive Manufacturing of metals and Non-metals,” 2014.

[17] M. Shellabear and O. Nyrhilä, “DMLS – Development History and State of the Art.” 2004.

[18] B. a. James and R. a. Sire, “Fatigue-life assessment and validation techniques for metallic vascular implants,” *Biomaterials*, vol. 31, no. 2, pp. 181–186, 2010.

[19] W. Xiaoquing and C. Kevin, “Residual Stress in Metal Parts Produced by Powder-Bed Additive Manufacturing Processes,” *Journal of Chemical Information and Modeling*, vol. 53, no. 9, pp. 1689–1699, 2013.

[20] J. Klopper, “An investigation into the effect of weld induced residual stresses on the structural behaviour of built-up 3CR12 columns,” 2010.

[21] E. R. Denlinger, J. C. Heigel, P. Michaleris, and T. a. Palmer, “Effect of inter-layer dwell time on distortion and residual stress in additive manufacturing of titanium and nickel alloys,” *Journal of Materials Processing Technology*, vol. 215, pp. 123–131, Jan. 2015.

[22] J. Matthew and J. Donachie, “Heat treating titanium and its alloys,” 2001.

[23] T. J. Pillai, T. S. Devi, and C. K. Devi, “Studies on Human Mandibles,” vol. 13, no. 1, pp. 8–15, 2014.

[24] V. K. Nirmale, U. W. Mane, S. B. Sukre, and C. V Diwan, “Morphological Features of Human Mandible,” *international Journal of Recent Trand in Science and Technology*, vol. 3, no. 2, pp. 38–43, 2012.

[25] G. Pileicikiene and A. Surna, “The Human Masticatory System From A Biomechanical Perspective : A Review,” *Baltic Dental and Maxillofacial Journal*, vol. 6, no. 3, pp. 81–84, 2004.

[26] M. Yaşar İşcan, *Color atlas of anatomy: A photographic study of the human body*, vol. 61, no. 2–3. 1993.

[27] A. Fallis, *University Physics with Modern Physics*, 13th ed., vol. 53, no. 9. Jim Smith, 2013.

[28] J. Koolstra, “Dynamics of the Human Mastication System,” *International and American Associationf or Dental Research*, vol. 13, no. 4, pp. 266–376, 2012.

[29] K. Saladin and L. Miller, *Anatomy & physiology*. 1998.

[30] Y. Hattori, C. Satoh, T. Kunieda, R. Endoh, H. Hisamatsu, and M. Watanabe, “Bite forces and their resultants during forceful intercuspal clenching in humans.,” *Journal of biomechanics*, vol. 42, no. 10, pp. 1533–8, Jul. 2009.

[31] C. Meyer, J. Kahn, P. Boutemy, A. Wilk, S. Head, and P. A. Wilk, “Determination of the external forces applied to the mandible during various static chewing tasks,” *Journal of Cranio-Maxillofacial Surgery*, vol. 26, no. 5, pp. 331–341, 1998.

[32] U. Santana-Mora, A. Martínez-Ínsua, U. Santana-Penín, A. P. Del Palomar, J. C. Banzo, and M. J. Mora, “Muscular activity during isometric incisal biting.,” *Journal of biomechanics*, vol. 47, no. 16, pp. 3891–7, Dec. 2014.

[33] H. J. Schindler, S. Rues, J. C. Türp, K. Schweizerhof, and J. Lenz, “Jaw clenching: muscle and joint forces, optimization strategies.,” *Journal of dental research*, vol. 86, no. 9, pp. 843–847, 2007.

[34] M. Sato, M. Motoyoshi, M. Hirabayashi, K. Hosoi, N. Mitsui, and N. Shimizu, “Inclination of the occlusal plane is associated with the direction of the masticatory movement path,” *European Journal of Orthodontics*, vol. 29, no. 1, pp. 21–25, 2007.

[35] N. N. Hung, “Basic Knowledge of Bone Grafting,” *In tech*, 2012.

[36] S. Singare, L. Dichen, L. Bingheng, L. Yanpu, G. Zhenyu, and L. Yaxiong, “Design and fabrication of custom mandible titanium tray based on rapid prototyping,” *Medical Engineering and Physics*, vol. 26, no. 8, pp. 671–676, 2004.

[37] T. Kero, A. Pettersson, J. Fäldt, M. Andersson, L. Gillot, B. Cannas, K. Näsström, and R. Söderberg, “Virtual variation simulation of CAD/CAM template-guided surgeries performed on human cadavers: Part II,” *Journal of Prosthetic Dentistry*, vol. 104, no. 1, pp. 48–55, 2010.

[38] A. Tarsitano, S. Mazzoni, R. Cipriani, R. Scotti, C. Marchetti, and L. Ciocca, “The CAD-CAM

technique for mandibular reconstruction: An 18 patients oncological case-series," *Journal of Cranio-Maxillofacial Surgery*, vol. 42, no. 7, pp. 1460–1464, 2014.

[39] L. S. Bertol, W. K. Júnior, F. P. Da Silva, and C. Aumund-Kopp, "Medical design: Direct metal laser sintering of Ti-6Al-4V," *Materials and Design*, vol. 31, no. 8, pp. 3982–3988, 2010.

[40] K. Wang, "The use of titanium for medical applications in the USA," vol. 213, pp. 8–11, 1996.

[41] Arcam, "Implants for surgery Metallic materials Part 3: Wrought titanium 6-aluminium 4-vanadium alloy," 2016.

[42] Y. Okazaki, "Corrosion resistance and corrosion fatigue strength of new titanium alloys for medical implants without V and Al," vol. 213, pp. 138–147, 1996.

[43] W. Gao, Y. Zhang, D. Ramanujan, K. Ramani, Y. Chen, C. B. Williams, C. C. L. Wang, Y. C. Shin, S. Zhang, and P. D. Zavattieri, "The status, challenges, and future of additive manufacturing in engineering," *Computer-Aided Design*, vol. 69, pp. 65–89, 2015.

[44] L. Podshivalov, C. M. Gomes, A. Zocca, J. Guenster, P. Bar-Yoseph, and A. Fischer, "Design, Analysis and Additive Manufacturing of Porous Structures for Biocompatible Micro-Scale Scaffolds," *Procedia CIRP*, vol. 5, pp. 247–252, 2013.

[45] D. Roylance, "Finite Element Analysis Department of Materials Science and engineering, Massachusetts Institute of Technology Cambridge, MA 02139," 2001.

[46] G. P. Nikishkov, "Introduction To the Finite Element Method," 2004.

[47] K.-J. Bathe, *Finite element procedures. Second edition*. 2006.

[48] J. Wieding, R. Souffrant, W. Mittelmeier, and R. Bader, "Medical Engineering & Physics Finite element analysis on the biomechanical stability of open porous titanium scaffolds for large segmental bone defects under physiological load conditions," *Medical Engineering and Physics*, vol. 35, no. 4, pp. 422–432, 2013.

[49] R. Tiossi, M. a a Vasco, L. Lin, H. J. Conrad, O. L. Bezzon, R. F. Ribeiro, and A. S. L. Fok, "Validation of finite element models for strain analysis of implant-supported prostheses using digital image correlation.," *Dental materials : official publication of the Academy of Dental Materials*, vol. 29, no. 7, pp. 788–96, Jul. 2013.

[50] S. Moaveni, "Finite Element Analysis, Theory and application with ANSYS, .pdf." p. 560, 1999.

[51] R. Singiresu, *The finite element method in engineering*. 2005.

[52] D. E. Dobbs, M. Fontana, and S. Frisch, "Polynomial function," 2009.

[53] B. Wilson, "Chapter 1. Introduction," *The Biogeography of the Australian North West Shelf:*

Environmental Change and Life's Response.

[54] D. W. Pepper and J. C. Heinrich, "The Finite Element Method : Basic Concepts and Applications." pp. 1–24, 1992.

[55] F. Gröning, J. Liu, M. J. Fagan, and P. O'Higgins, "Validating a voxel-based finite element model of a human mandible using digital speckle pattern interferometry.," *Journal of biomechanics*, vol. 42, no. 9, pp. 1224–9, Jun. 2009.

[56] A. Erklig and M. A. Kütük, "Experimental Finite Element Approach for Stress Analysis," *Journal of Engineering*, vol. 2014, 2014.

[57] J. Bradley, "Tech notes: Practical Strain Gage," 1994.

[58] N. Instruments, "National Instruments, Application Note 078, Strain Gauge Measurement – A Tutorial," 1998.

[59] D. Roylance, "Experimental Strain Analysis Strain gages," 2001.

[60] K. Hoffmann, *Practical hints for the installation of strain gages*. 1996.

[61] D. M. Ştefănescu and M. A. Anghel, "Electrical methods for force measurement – A brief survey," *Measurement*, vol. 46, no. 2, pp. 949–959, Feb. 2013.

[62] C.-H. Pi and K.-S. Chen, "A strain-sensing based scheme for indoor localization: Analysis, algorithm, and demonstration," *Measurement*, vol. 51, pp. 224–235, 2014.

[63] M.-M. Vishay Precision Group, "Noise Control in Strain Gage Measurements Strain Gages and Instruments, Tech Note TN-501-2," *Micro-Measur*, pp. 1–8, 2013.

[64] M. Qin, Y. Liu, L. Wang, J. He, M. Xuan, C. Hua, D. Li, Z. Jin, and X. Wang, "Design and optimization of the fixing plate for customized mandible implants," *Journal of Cranio-Maxillofacial Surgery*, vol. 43, no. 7, pp. 1296–1302, 2015.

[65] W. Dongmei, W. Chengtao, Z. Xiujuan, and X. Liqun, "Design and biomechanical evaluation of a custom lateral mandible titanium prosthesis.," *Conference proceedings : Annual International Conference of the IEEE Engineering in Medicine and Biology Society IEEE Engineering in Medicine and Biology Society Conference*, vol. 6, pp. 6188–6191, 2005.

[66] G. Odin, C. Savoldelli, P. Bouchard, Y. Tillier, G. Odin, C. Savoldelli, P. Bouchard, and Y. T. Determination, "Determination of Young ' s modulus of mandibular bone using inverse analysis," 2012.

[67] A. C. De Souza Fernandes, S. De Quadros Uzeda-Gonzalez, M. L. Mascarenhas, L. A. MacHado, and M. De Moraes, "Direct and tomographic dimensional analysis of the inter-

radicular distance and thickness of the vestibular cortical bone in the parasymphyseal region of adult human mandibles," *British Journal of Oral and Maxillofacial Surgery*, vol. 50, no. 4, pp. 350–355, 2012.

[68] S. M. Gonzalez, "Cortical bone thickness in the maxilla and mandible for mini-implant placement," *ProQuest Dissertations and Theses*, p. 76, 2008.

[69] J. . Koolstra and T. M. G. . van Eijden, "A method to predict muscle control in the kinematically and mechanically indeterminate human masticatory system," *Journal of Biomechanics*, vol. 34, no. 9, pp. 1179–1188, 2001.

[70] T. L. Anderson, *Fracture Mechanics: Fundamentals and Applications, Third Edition*. 2005.

[71] R. Pavazza, A. Matoković, and M. Vukasović, "Bending of thin-walled beams of open section with influence of shear-Part II: Application," *Thin-Walled Structures*, vol. 116, no. August 2016, pp. 369–386, 2016.

[72] D. Kremelberg, *Practical Statistics: A Quick and Easy Guide to IBM® SPSS® Statistics, STATA, and other STatistical Software*. SAGE Publications,Inc, 2011.

Appendix 1: Universal Amplifier Specifications (MX840A)

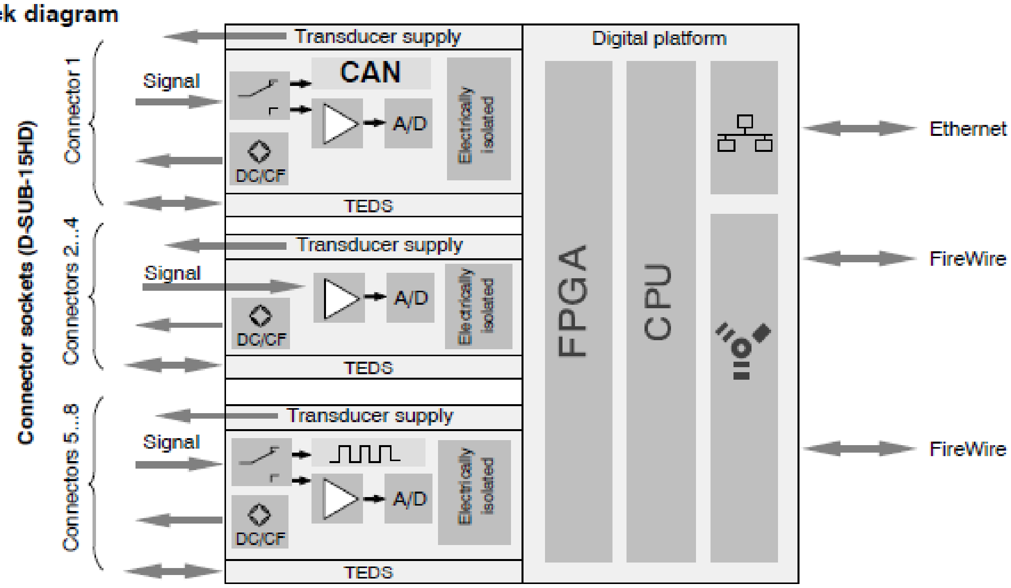
QUANTUM X
MX840A
Universal amplifier

Data Sheet

Special features

- 8 individually configurable inputs (electrically isolated)
- Connection of more than 12 transducers technologies
- Data rate: up to 19,200 Hz
- 24–bit A/D converter per channel for synchronous, parallel measurements
- Active low pass filter
- TEDS support
- Supply voltage (DC): 10 V ... 30 V
- Supply voltage for active transducers (DC): 5 V ... 24 V

Block diagram



B2924-1.1 en

HBM

Specifications MX840A

General specifications		
Inputs	Number	8, electrically isolated from each other and from the supply voltage[1]
Transducer technologies		Strain gage full and half bridge, inductive full and half bridge, piezoresistive full bridge, potentiometric transducers, three voltage ranges, current; resistance (e. g. PTC, NTC, KTY); resistance thermometer (PT100, PT1000); thermocouples (K, N, E, T, S, ...) with cold junction in the plug (1−THERMO−MXBOARD). Frequency, pulse counting, SSI, incremental rotary encoder (connectors 5−8 only) CAN (ISO 11898; connector 1 only)
A/D converter		24 Bit Delta Sigma converter
Data rate	Hz	0.1 ... 19200, adjustable for each channel
Active low-pass filter (Bessel/Butterworth, can be switched off)	Hz	0.01 ... 3200 (−3 dB)
Transducer identification (TEDS, IEEE 1451.4) max. distance of the TEDS module	m	100
Transducer connection		D-SUB-15HD
Supply voltage range (DC)	V	10 ... 30 (24 V nominal (rated) voltage)
Supply voltage interruption		max. 5 ms at 24 V
Power consumption without adjustable transducer excitation with adjustable transducer excitation	 W W	 < 9 < 12
Transducer Excitation (active transducers) Adjustable supply voltage (DC) Maximum output power	 V W	 5 ... 24; adjustable for each channel 0.7 each channel / a total of 2
Ethernet (data link) Protocol/addressing Connection Max. cable length to module	 − − m	10Base-T / 100Base-TX TCP/IP (direct IP address or DHCP) 8P8C plug (RJ-45) with twisted pair cable (CAT-5) 100
FireWire (module synchronization, data link, optional supply voltage) Baud rate Max. current from module to module Max. cable length between the nodes Max. number of modules connected in series (daisy chain) Max. number of modules in a FireWire system (including hubs[2], backplane) Max. number of hops[3]	 MBaud A m − − −	IEEE 1394b (HBM modules only) 400 (approx. 50 MByte/s) 1.5 5 12 (=11 Hops) 24 14
Nominal (rated) temperature range	°C [°F]	−20 ... +60 [−4 ... +140]
Operating temperature range (no dewing allowed/module not dew-point proof)	°C [°F]	−20 ... +65 [−4 ... +149]
Storage temperature range	°C [°F]	−40 ... +75 [−40 ... +167]
Rel. humidity at 31 °C	%	80 (non condensing) lin. reduction to 50 % at 40 °C
Protection class (up to 2000 m height, degree of contamination 2)		III
Degree of protection		IP20 per EN 60529
Mechanical tests[4] Vibration (30 min) Shock (6 ms)	 m/s^2 m/s^2	 50 350
EMC requirements		per EN 61326
Max. input voltage at transducer socket to ground (Pin 6) PIN 1, 2, 3, 4, 5, 7, 8, 10, 13, 15 PIN 14 (voltage)	 V V	 5.5 (no transients) 60 (no transients)/typ. 500
Dimensions, horizontal (W x H x D)	mm	52.5 x 200 x 124 (with case protection) 44 x 174 x 124 (without case protection)
Weight, approx.	g	980

1) When the variable transducer supply is used, there is no electrical isolation from the supply voltage.
2) Hub: FireWire node or distributor
3) Hop: Transition from module to module or signal conditioning / distribution via FireWire (hub, backplane)
4) Mechanical stress is tested according to European Standard EN60068−2−6 for vibrations and EN60068−2−27 for shock. The equipment is subjected to an acceleration of 50 m/s^2 in a frequency range of 5...65 Hz in all 3 axes. Duration of this vibration test: 30min per axis. The shock test is performed with a nominal acceleration of 350 m/s^2 for 6 ms, half sine pulse shape, with 3 shocks in each of the 6 possible directions.

Specifications MX840A (Continued)

5 mV/V CF strain gage full bridge with 1 V or 2.5 V excitation (AC, effective)		
Accuracy class		0.05
Carrier frequency (sine)	Hz	4800 ±1.5
Bridge excitation voltage (effective)	V	1 and 2.5 (± 5 %)
Transducers that can be connected		strain gage full bridges
Permissible cable length between MX840A and transducer	m	100
Measuring ranges at 2.5 V excitation at 1 V excitation	 mV/V mV/V	 ± 5 ± 10
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance at 2.5 V excitation at 1 V excitation	 Ω Ω	 300 ... 1000 80 ... 1000
Noise at 25 °C and 2.5 V excitation (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 0.2 < 0.5 < 1 < 4
Linearity error	%	< 0.02 of full scale
Zero drift (2.5 V excitation)	% / 10 K	0.02 of full scale
Full-scale drift (2.5 V excitation)	% / 10 K	< 0.05 of measurement value

5 mV/V CF strain gage half bridge with 1 V or 2.5 V excitation (AC, effective)		
Accuracy class		0.1
Carrier frequency (sine)	Hz	4800 ±1.5
Bridge excitation voltage (effective)	V	1 and 2.5 (± 5 %)
Transducers that can be connected		strain gage half bridges
Permissible cable length between MX840A and transducer	m	100
Measuring ranges at 2.5 V excitation at 1 V excitation	 mV/V mV/V	 ± 5 ± 10
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance at 2.5 V excitation at 1 V excitation	 Ω Ω	 300 ... 1000 80 ... 1000
Noise at 25 °C and 2.5 V excitation (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 0.5 < 0.7 < 1 < 4
Linearity error	%	< 0.02 of full scale
Zero drift (2.5 V excitation)	% / 10 K	0.1 of full scale
Full-scale drift (2.5 V excitation)	% / 10 K	< 0.1 of measurement value

Specifications MX840A (Continued)

100 mV/V DC piezoresistive strain gage full bridge with 2.5 V (DC) excitation		
Accuracy class		0.05
Excitation voltage (DC)	V	2.5 ± 5%
Transducers that can be connected		piezoresistive strain gage full bridges
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV/V	± 100
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Transducer impedance	Ω	300 ... 1000
Noise at 25 °C (peak to peak)		
with filter 1 Hz Bessel	µV/V	< 4
with filter 10 Hz Bessel	µV/V	< 6
with filter 100 Hz Bessel	µV/V	< 15
with filter 1 kHz Bessel	µV/V	< 80
Linearity error	%	< 0.02 of full scale
Zero drift	% / 10 K	< 0.02 of full scale
Full-scale drift	% / 10 K	< 0.05 of measurement value

1000 mV/V DC piezoresistive strain gage full bridge with 2.5 V (DC) excitation		
Accuracy class		0.05
Bridge excitation voltage (DC)	V	2.5 ± 5%
Transducers that can be connected		piezoresistive strain gage full bridges
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV/V	± 1000
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Transducer impedance	Ω	300 ... 1000
Noise at 25 °C (peak to peak)		
with filter 1 Hz Bessel	µV/V	< 40
with filter 10 Hz Bessel	µV/V	< 100
with filter 100 Hz Bessel	µV/V	< 200
with filter 1 kHz Bessel	µV/V	< 700
Linearity error	%	< 0.02 of full scale
Zero drift	% / 10 K	< 0.02 of full scale
Full-scale drift	% / 10 K	< 0.05 of measurement value

Specifications MX840A (Continued)

100 mV/V CF inductive full bridge with 1 V or 2.5 V excitation (AC, effective)		
Accuracy class		0.05
Carrier frequency (sine)	Hz	4800 ±1.5
Bridge excitation voltage (effective)	V	1 and 2.5 (± 5 %)
Transducers that can be connected		inductive full bridges
Permissible cable length between MX840A and transducer	m	100
Measuring ranges at 2.5 V excitation at 1 V excitation	 mV/V mV/V	 ± 100 ± 300
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance at 2.5 V excitation at 1 V excitation	 Ω Ω	 300 ... 1000 80 ... 1000
Noise at 25 °C and 2.5 V excitation (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 3 < 5 < 15 < 50
Linearity error	%	< 0.02 of full scale
Zero drift (2.5 V excitation)	% / 10 K	< 0.02 of full scale
Full-scale drift (2.5 V excitation)	% / 10 K	< 0.05 of measurement value

1000 mV/V CF inductive full bridge with 1 V excitation (AC, effective)		
Accuracy class		0.1
Carrier frequency (sine)	Hz	4800 ±1.5
Bridge excitation voltage (effective)	V	1 (± 5 %)
Transducers that can be connected		inductive full bridges
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV/V	± 1000
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance	Ω	80 ... 1000
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 40 < 100 < 500 < 1200
Linearity error	%	< 0.02 of full scale
Zero drift	% / 10 K	< 0.02 of full scale
Full-scale drift	% / 10 K	< 0.1 of measurement value

Specifications MX840A (Continued)

100 mV/V CF inductive half bridge with 1 V or 2.5 V excitation (AC, effective)		
Accuracy class		0.1
Carrier frequency (sine)	Hz	4800 ± 1.5
Bridge excitation voltage (effective)	V	1 and 2.5 (± 5 %)
Transducers that can be connected		inductive half bridges
Permissible cable length between MX840A and transducer	m	100
Measuring ranges at 2.5 V excitation at 1 V excitation	 mV/V mV/V	 ± 100 ± 300
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance at 2.5 V excitation at 1 V excitation	 Ω Ω	 300 ... 1000 80 ... 1000
Noise at 25 °C and 2.5 V excitation (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 3 < 5 < 15 < 50
Linearity error	%	< 0.02 of full scale
Zero drift (2.5 V excitation)	% / 10 K	< 0.1 of full scale
Full-scale drift (2.5 V excitation)	% / 10 K	< 0.1 of measurement value

LVDT		
Accuracy class		0.1
Carrier frequency (sine)	Hz	4800 ± 1.5
Bridge excitation voltage (effective)	V	1 (± 5 %)
Transducers that can be connected		LVDT
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV/V	± 3000
Measurement frequency range (–3 dB)	kHz	0 ... 1.6
Transducer impedance	mH	4 ... 33
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 40 < 100 < 500 < 1200
Linearity error	%	< 0.02 of full scale
Zero drift	% / 10 K	< 0.1 of full scale
Full-scale drift	% / 10 K	< 0.1 of measurement value

Specifications MX840A (Continued)

Potentiometric transducer		
Accuracy class		0.1
Excitation voltage (DC)	V	2.5 (± 5 %)
Transducers that can be connected		potentiometric transducers
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV/V	± 500
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Transducer impedance	Ω	300 ... 5000
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV/V µV/V µV/V µV/V	 < 40 < 100 < 200 < 700
Linearity error	%	< 0.02 of full scale
Zero drift (1 V excitation)	% / 10 K	< 0.1 of full scale
Full-scale drift (1 V excitation)	% / 10 K	< 0.1 of measurement value

10 V DC voltage		
Accuracy class		0.05
Transducers that can be connected		voltage generator up to ±10 V
Permissible cable length between MX840A and transducer	m	100
Measuring range	V	± 10
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Internal resistance of the voltage source	Ω	< 500
Internal impedance, typ.	MΩ	1
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV µV µV µV	 < 150 < 300 < 600 < 3000
Linearity error	%	< 0.02 of full scale
Common-mode rejection with DC common mode with 50 Hz common mode, typ.	 dB dB	 > 100 75
Maximum common-mode voltage (to housing and supply ground)	V	± 60
Zero drift	% / 10 K	< 0.02 of full scale
Full-scale drift	% / 10 K	< 0.05 of measurement value

Specifications MX840A (Continued)

60 V DC voltage		
Accuracy class		0.05
Transducers that can be connected		voltage generator up to ± 60 V
Permissible cable length between MX840A and transducer	m	100
Measuring range	V	± 60
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Internal resistance of the voltage source	Ω	< 500
Input impedance, typ.	MΩ	1
Noise at 25 °C (peak to peak) with filter 1Hz Bessel with filter 10Hz Bessel with filter 100Hz Bessel with filter 1kHz Bessel	 µV µV µV µV	 < 150 < 300 < 600 < 3000
Linearity error	%	< 0.02 of full scale
Common-mode rejection with DC common mode with 50 Hz common mode, typ.	 dB dB	 > 100 75
Maximum common-mode voltage (to housing and supply ground)	V	± 60
Zero drift	% / 10 K	< 0.02 of full scale
Full-scale drift	% / 10 K	< 0.05 of measurement value

100 mV DC voltage		
Accuracy class		0.1
Transducers that can be connected		voltage generator
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV	± 300
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Input impedance	MΩ	> 20
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µV µV µV µV	 < 5 < 100 < 1000 < 1500
Linearity error	%	< 0.03 of full scale
Common-mode rejection with DC common mode with 50 Hz common mode, typ.	 dB dB	 > 90 75
Maximum common-mode voltage (to housing and supply ground)	V	± 30
Zero drift	% / 10 K	< 0.1 of full scale
Full-scale drift	% / 10 K	< 0.1 of measurement value

Specifications MX840A (Continued)

20 mA DC current		
Accuracy class		0.05
Transducers that can be connected		transducers with current output (0 ... 20 mA or 4 ... 20 mA)
Permissible cable length between MX840A and transducer	m	100
Measuring range	mA	± 30
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Measurement resistance value, typ.	Ω	10
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 µA µA µA µA	 < 1 < 1.5 < 15 < 40
Linearity error	%	< 0.02 of full scale
Common-mode rejection with DC common mode with 50 Hz common mode, typ.	 dB dB	 > 100 75
Maximum common-mode voltage (to housing and supply ground)	V	± 30
Zero drift	% / 10 K	< 0.05 of full scale
Full-scale drift	% / 10 K	< 0.05 of measurement value

Resistance		
Accuracy class		0.1
Transducers that can be connected		PTC, NTC, KTY, TT-3, resistances generally (connection with 4 wire configuration)
Permissible cable length between MX840A and transducer	m	100
Measuring ranges	Ω	0 ... 5000
Speisestrom	mA	0.4 ... 0.8
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 K K K K	 < 0.5 < 1 < 2 < 6
Linearity error	%	< ± 0.02 of full scale
Zero drift	%/10K	<0.02 of full scale
Full-scale drift	% / 10 K	<0.1 of measurement value

Resistance thermometer (PT100, PT1000)		
Accuracy class		0.1
Transducers that can be connected		PT100, PT1000 (connection with 4 wire configuration)
Permissible cable length between MX840A and transducer	m	100
Linearization range	°C [°F]	–200 ... +848 [–328 ... +1558.4]
Measurement frequency range (–3 dB)	kHz	0 ... 3.2
Noise at 25 °C (peak to peak) with filter 1 Hz Bessel with filter 10 Hz Bessel with filter 100 Hz Bessel with filter 1 kHz Bessel	 K K K K	 < 0.1 < 0.2 < 0.5 < 1.5
Linearity error	K	< ± 0.3
Zero drift with PT100 with PT1000	 K / 10 K K / 10 K	 <0.2 <0.1
Full-scale drift with PT100 with PT1000	 K / 10 K K / 10 K	 <0.5 <1

Specifications MX840A (Continued)

Thermocouples[5]		
Transducers that can be connected		Thermocouples (type B, E, J, K, N, R, S, T)
Permissible cable length between MX840A and transducer	m	100
Measuring range	mV	±100
Linearization ranges Type B (Pt-30 % Rh and Pt-6 % Rh) Type E (Ni-Cr and Cu-Ni) Type J (Fe and Cu-Ni) Type K (Ni-Cr and Ni-Al) Type N (Ni-14,2 % Cr and Ni-4,4 % Si-0,1 % Mg) Type R (Pt-13 % Rh and Pt) Type S (Pt-10 % Rh and Pt) Type T (Cu and Cu-Ni)	 °C [°F] °C [°F] °C [°F] °C [°F] °C [°F] °C [°F] °C [°F] °C [°F]	 +100 ... +1820 [+212 ... +3308] −200 ... +900 [−328 ... +1652] −210 ... +1200 [−346 ... +2192] −270 ... +1372 [−454 ... +2501.6] −270 ... +1300 [−454 ... +2372] −50 ... +1768 [−58 ... +3214.4] −50 ... +1768 [−58 ... +3214.4] −270 ... +400 [−454 ... +752]
Transducer impedance	Ω	< 500
Measurement frequency range (−3 dB)	kHz	0 ... 3.2
Noise at 25 °C and Type K (peak to peak) with Filter 1 Hz Bessel with Filter 10 Hz Bessel with Filter 100 Hz Bessel with Filter 1 kHz Bessel	 K K K K	 0.05 0.1 0.5 1
Zero error Type E, J, K, T Type N, R, S Type B	 K K K	 < ±0.3 < ±3 < ±30
Linearity error Type E, J, K, T Type N, R, S Type B	 K K K	 < ±0.3 < ±3 < ±30
Max. error of the cold junction	K	< ±0.5
Total error limit Type E, J, K, T Type N, R, S Type B	 K K K	 ±1 ±6.5 ±60
Temperature drift (type K)	K/10 °C	< ±1
Cold junction 1−THERMO−MXBOARD Nominal (rated) temperature range Operating temperature range Storage temperature range	 °C [°F] °C [°F] °C [°F]	 −20 ... +60 [−4 ... +140] −20 ... +65 [−4 ... +149] −40 ... +75 [−40 ... +167]

[5] The external cold junction is required for connecting thermocouples to the MX840A (Order no.: 1−THERMO−MXBOARD).

Specifications MX840A (Continued)

Frequency or pulse counting (connections 5 ... 8)		
Accuracy class		0.01
Transducers that can be connected		HBM-torque transducers, Frequency signal sources (square), incremental encoder, pulse counters, SSI transducers
Permissible cable length between MX840A and transducer	m	50
Signals F_1 (±) F_2 (±) Zero index (±)		Frequency or pulse signal Direction of rotation signal shifted by ± 90° to F_1 Zero position signal
Input level with differential operation Low level High level		Differential inputs (RS422): Signal (+) < Signal (–) –200 mV Differential inputs (RS422): Signal (+) > Signal (–) +200 mV
Input level with unipolar operation Low level High level	V V	<1.5 > 3.5
Maximum input voltage at transducer socket to ground (pin 6)	V	5.5 (no transients)
Measuring ranges Frequency Pulse counting	Hz pulses/s	0.1 ... 1,000,000 0 ... 1,000,000
Input impedance, typ.	kΩ	10
Temperature drift	%/10K	< 0,01 of measurement value
SSI mode (differentially) Shift clock Word length Code Input level Low level High level Signals Data Shift clock	 kHz Bit	 100, 200, 500, 1000 12–31 dual or gray Differential inputs (RS422): Signal (+) < Signal (–) –200 mV Differential inputs (RS422): Signal (+) > Signal (–) +200 mV Data+, Data– (RS-422) Clk+, Clk– (RS-422)

Digital control output (Triggering shunt calibration, reset of external charge amplifiers)		
Output type		open collector
Reference potential		Pin 6 (ground)
High level Output unloaded, typ. I_{out} = 5 mA	 V V	 5 > 4.5
Leakage current (high impedance output)	µA	< 1
Permissible load impedance	kΩ	> 1

CAN (connection 1/read only)						
Supported protocols		CAN 2.0A, CAN 2.0B				
Number of CAN ports		1 (connection 1)				
Bus link		two wire, according to ISO11898				
Baud rates and permissible cable lengths	kBit/s m	1000, 25,	500, 100,	250, 250,	125, 500,	100 600
Sampling rate	signals/s	max. 10,000				
CAN signals		≤ 128				
CAN signal types		standard, mode-dependent, mode-signal				

Appendix 2: Data Recorder Specifications (CX22W)

Data Sheet

QUANTUMX

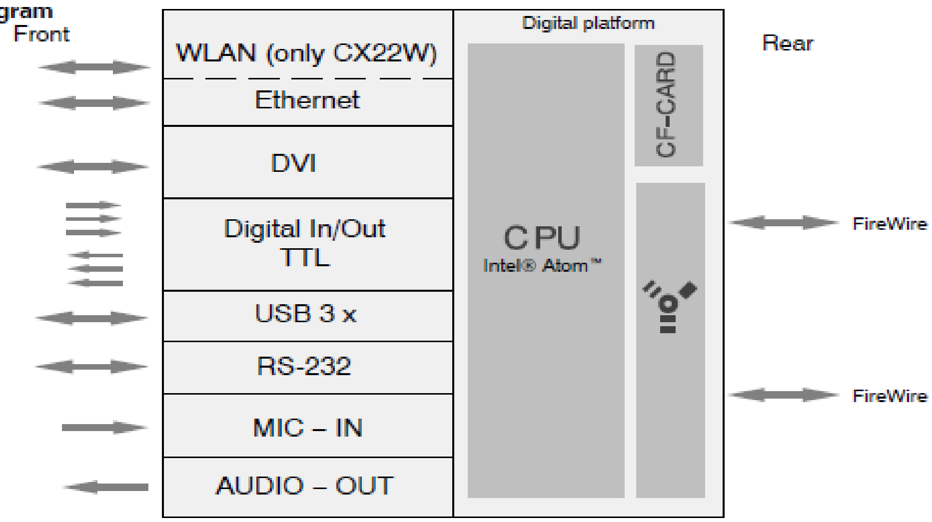
CX22W / CX22

Data recorder

Special features

- Stand-alone data acquisition: exchangeable CF–CARD
- Connection of QuantumX modules
- Easy system configuration: trigger, computation, virtual channels, signal analysis
- Many interfaces: LAN, WLAN, USB, Digital I/O
- Touchscreen connection (optional): DVI / USB
- Supply voltage (DC): 10 V ... 30 V no fan

Block diagram



B3191-1.0 en

HBM

Specifications

Devices that can be connected		QuantumX MGCplus [2]
Number of channels FireWire (QuantumX) Ethernet NTP (QuantumX, MGCplus Cp42, Interrogator)		384 (24 modules x 16 Channels) 400
Synchronization options		FireWire (only QuantumX, automatica, recommended) Ethernet / NTP (QuantumX / MGCplus CP42)
System configuration / Data access		Remote access or via "QuantumX Network Assistant" software Direct connection to a PC (Ethernet or WLAN) or via network (DHCP) Data access via Windows Explorer
Channel configuration		Manually via integrated sensor database (all typical transducers, HBM sensors, CAN–dbc import, open, expandable) Automatically via TEDS (integrated editor)
Data recording / Start of recording		After switching on the operating voltage Triggered (pre–trigger) to measurement signal, message, digital input Via software (remote access or direct connection of peripheral devices), time
Number of sample rates		3 different data rates and groups (depending on measurement module)
Formula editor (calculation channels)		Arithmetic, exponent, root, root mean square value, logic, trigonometry, integral/differential, exponential, logarithm, limit values (connect digital output, play audio file via external speaker, entry in log file), software filters (moving averages, Bessel, Butterworth), experimental stress analysis using SG
Trigger signals		Analog, bus signal, computed signals, digital input (0/1)
Trigger type		Edge (rising, falling), level (above, below)
End of recording		Switch off, manual, triggered (post), time, number of measured values
Scope of recording		Selected signals, meta data (sensors, measurement configuration, test parameters), statistics log
Recording mode		Standard Time interval (periodic file creation, without data loss) Long–term measurement (time, cycle with counter/cycle time/peak–valley) Peak values (interval) Ring buffer (up to 10 minutes)
Sequences		10 sequential recording configurations (measurement jobs), repetitions
Storage formats		HBM catman® (bin) ASCII (asc, replay with MX878) Microsoft Excel® (xls, xlsx, xlsb) MTS (RPC III) MathWorks MATLAB™ (mat) HBM nCode (dac) Vector (MDF 4.0) NI DIAdem (dac)
Automation		Key scripting (Visual Basic for application)
Data storage		Exchangeable CF card, USB stick, external USB hard disk
Display or remote control		
Online display **Recommended display**		Freely configurable display and control panels in full screen mode 1024 x 768 pixels DVI digital [1]
Display elements		Numeric display, line recorder (y–t, x–y, y–f / FFT), spreadsheet, indicator, bar graph, LED, polar diagram, switch (button), checkbox, selection box, background image, text
Keypad		Control via function keys

[1] DVI–2–VGA adapter does not work

[2] QuantumX and MGCplus CP42 can be synchronized via Ethernet NTP. The CX22(–W) can be used as NTP Master.

Specifications

Protection		
System change		Enhanced Write Filter (EWF) needs to be opened to save changes.
General specifications		
Operating system		WindowsXP embedded
Prozessor		Intel Atom, 1.33 GHz with 533 MHz FSB
Internal storage medium	GB	8, two partitions
Exchangeable memory Version Formfactor Memory capacity, max. Recording rate, max. Measured value / Signal	 GByte Values/s Byte	CompactFlash 4.1 CompactFlash type 1 128 800000 4
Starting time, approx.	sec	45
Interfaces (number)[1]		Ethernet (1) WLAN (1) FireWire (2) USB2.0 (3) RS232(1) DVI (1) Digital I/O (6)
Supply voltage range (DC)	V	10 ... 30, nominal (rated) voltage 24V
Power consumption (at 24V)	W	< 12, no rotating parts (fans), no noise
Ethernet (Konfiguration des Datenrekorders) Protocol/addressing Connection Max. cable length to module **WLAN** (data recorder configuration) WLAN standard Data transfer rate Security protocols Straight line range Frequency carrier, Country/Region Antenna	 m MBit m	10Base–T / 100Base–TX / 1000Base–TX TCP/IP (direct IP address or DHCP) 8P8C plug (RJ-45) with twisted pair cable (CAT-5) 100 IEEE 802.11 n/h and IEEE 802.11 b/g, Adhoc-support 54 WEP, WPA, WPA2, TKIP, AES 200 (IEEE 802.11n) 2.4 GHz Standard SMA socket, Typ RF Coax
FireWire (module synchronization, data link, optional supply voltage) Baud rate Max. current from module to module Max. cable length between the nodes Max. number of modules connected in series (daisy chain) Max. number of modules in a FireWire system (including hubs[2]), backplane) max. chain of hops[3])	 MBaud A m	IEEE 1394b (HBM modules only) 400 (approx. 50 MByte/s) 1.5 5 12 (=11 hops) 24 14
USB Version / Connector Cable length, max.	 m	 2.0/Standard Highspeed (Host) compatible with Version 1.1 5
RS-232-C Connector Baud rate, max. Devices	 kBaud	 DSUB 9–pin 115 e.g. GPS (NMEA)
DVI Type		 Digital, connecting LCD monitor

[1]) Rack installation not possible
[2]) Hub: FireWire node or distributor
[3]) Hop: Transition from module to module/signal conditioning

Specifications

Protection class (up to 2000 m height, degree of contamination 2)		III
Line out / voice output		Jack, 3.5 mm
Degree of protection		IP20
Mechanical tests[1] Vibration (30 min) Shock (6 ms)	 m/s^2 m/s^2	 50 350
EMC requirements		according to EN61326
Nominal (rated) temperature range	°C [°F]	−20 °C ... +60 °C [−4 ... +140]
Operating temperature range (no dewing allowed/module not dew-point proof)	°C [°F]	−20 °C ... +65 °C [−4 ... +149]
Storage temperature range	°C [°F]	−40 °C ... +75 °C [−40 ... +167]
Rel. humidity at 31 °C	%	80 (non condensing) lin. reduction to 50 % at 40 °C
Weight, approx.	g	1200
Dimensions, horizontal (H x W x D)	mm	52.5 x 200 x 122 (with case protection) 44 x 174 x 119 (without case protection)
Real Time Clock		
Clock drift		max. 1.2 minutes per month
Time buffering		CMOS Batterie
Time zone (factory settings)		UTC (Universal Time, Coordinated)
Digital I/Os		
Number of inputs/outputs		6 3 inputs (clamps 1, 2, 3) 3 outpust (clamps 4, 5, 6)
Type of connection		screw terminals Plug: MC 1,5/7−ST−3,5 (Phoenixcontact)
LEDs (number) output state		 3
Cable length (max.)	m	3
Cable type (required with interference)		shielded
Input signal range TTL Max. permissible input level Input level High Input level Low Internal pullup resistors	 V V V kOhm	 −0.5 ... 5.5 4 0.7 100
Output signal range TTL Output High Output Low Output current max.	 V V mA	 4 0.7 1

[1] Mechanical stress is tested according to European Standard EN60068−2−6 for vibrations and EN60068−2−27 for shock. The equipment is subjected to an acceleration of 25 m/s^2 in a frequency range of 5...65 Hz in all 3 axes. Duration of this vibration test: 30min per axis. The shock test is performed with a nominal acceleration of 200 m/s^2 for 11 ms, half sine pulse shape, with shocks in each of the 6 possible directions.

Appendix 3: Load Cell / Force Transducer Specifications

S9M

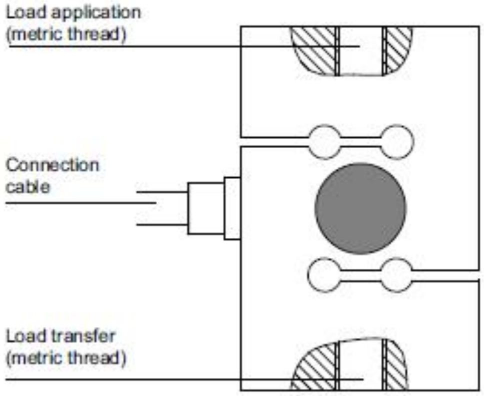
Force Transducer

Special features

- Tensile/compressive force transducer
- Accuracy class 0.02
- Hermetically encapsulated (IP68)
- Rust-resistant materials
- Available in different cable lengths and with connector mounted on request
- TEDS on request

Data sheet

Principle of the S9M force transducer

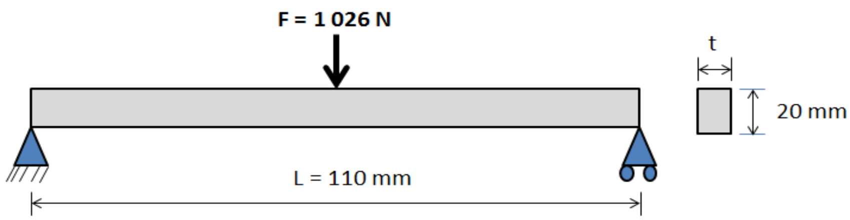


Design 5 kN ... 50 kN

Specifications

Type			S9M						
Nominal (rated) force:	F_{nom}	kN	0.5	1	2	5	10	20	50
Accuracy									
Accuracy class			0.02						
Relative reproducibility and repeatability errors without rotation	b_{rg}	%	0.02						
Rel. reversibility error	v		0.02						
Non-linearity	d_{lin}		0.02						
Relative creep	d_{crf+E}		0.02						
Temperature effect on sensitivity	TC_S	%/10K	0.02						
Temperature effect on zero signal	TC_0		0.02						
Electrical characteristics									
Nominal (rated) sensitivity	C_{nom}	mV/V	2						
Relative zero signal error	$d_{s,0}$	%	5						
Sensitivity error	d_c		0.25						
Tensile/compressive sensitivity variation	d_{zd}		0.1						
Input resistance	R_i	Ω	389 ±15						
Output resistance	R_o		350 ±1.5						
Insulation resistance	R_{is}	Giga Ω	>2						
Operating range of the excitation voltage	$B_{u,gt}$	V	0.5….12						
Reference excitation voltage	U_{ref}		5						
Connection			6-wire circuit						
Temperature									
Reference temperature	T_{ref}	°C	+23						
Nominal temperature range	$B_{t,nom}$		-10…+70						
Operating temperature range	$B_{t,g}$		-30…+85						
Storage temperature range	$B_{t,S}$		-30…+85						
Characteristic mechanical quantities									
Maximum operating force	F_G	% of F_{nom}	150						
Force limit	F_L		150						
Breaking force	F_B		200			300			200
Limit torque	$M_{G, perm}$	Nm	25		50	90		150	
Static lateral limit force	F_q	% of F_{nom}	10						
Nominal (rated) displacement	s_{nom}	mm	0.35	0.4	0.35	0.1	0.2	0.2	0.4
Fundamental frequency	f_G	kHz	0.6	0.9	1	1.7	2.1	2.3	2.5
Relative permissible oscillatory stress	F_{rb}	% of F_{nom}	100						70
General information									
Degree of protection per EN 60529			IP68 (test condition 1 m water column / 100 hours)						
Spring element material			Stainless steel in accordance with EN 10088-1						
Measuring point protection			Hermetically welded enclosure						
Cable			6-wire cable, PVC insulation						
Cable length	m		7.6 m (standard), also available: 1.5 m; 3 m and 6 m						

Appendix 4: Equivalent Implant Thickness



Determination of the thickness of the titanium implant that would give it properties equivalent to that of the bone is illustrated in this appendix. The main aim was to obtain the implant with similar performance as the bone of the mandible. Since the nature of the mandibular implant is complex, some assumptions were made. First, the implant with properties similar to the cortical bone of the mandible (elastic modulus E = 21 GPa [66] and thickness of 3.8 mm [67][68] was treated as a simple supported beam under bending load (F) of 1 026 N at its mid-span. Secondly, the implant was taken as a rectangular beam with the length and width equivalent to the designed implant.

Second moment of area for the beam with mandible dimensions:

$$I = \frac{tb^3}{12}$$

$$= \frac{0.0038(0.02)^3}{12}$$

$$= 2.5x10^{-9}\ m^4$$

Deflection of the beam with material property of mandible:

$$y = \frac{FL^3}{48EI}$$

$$= \frac{1\,026(0.11)^3}{48(21x10^9)(2.533x10^{-9})}$$

$$= 0.535x10^{-3}\ m$$

For the same deflection and the applied load, the calculation of the beam's second moment of area with the material property of (Ti6AL4V) was performed:

$$I = \frac{FL^3}{48yE}$$

$$= \frac{1\,026(0.11)^3}{48(0.533x10^{-3})(110x10^9)}$$

$$= 0.483x10^{-9}\ m^4$$

Finally, the thickness of the titanium implant that would give it properties equivalent to that of the bone was determined:

$$Thickness\ of\ of\ titanium = \frac{12.I}{h^3}$$

$$= \frac{12(0.483x10^{-9})}{0.02^3}$$

$$= 0.725x10^{-3}\ m$$

For this study a safety factor of 2.8 was decided on and this results in:

$$Thickness\ of\ titanium = 0.725\ mm\ x\ 2.8 = 2\ mm$$

Calculation results:

Bone properties	E = 21 GPA	$y = 0.535$	Thickness = 3.8 mm
Titanium properties	E = 110 GPa	$y = 0.535$	Thickness = 0.725

Appendix 5: Statistic Formulation & Table [72]

Determination of the critical value z

$$Alpha = 1 - 90\%\ confidence\ level$$
$$= 1 - \frac{90\%}{100}$$
$$= 0.1$$

- Where alpha refers to significance level, the probability of making a type I error.
- In statistical hypothesis testing, a type I error is the incorrect rejection of a true null hypothesis (a "false positive"), while a type II error is incorrectly retaining a false null hypothesis (a "false negative").
- A hypothesis test is a statistical test that is used to determine whether there is enough evidence in a sample of data to infer that a certain condition is true for the entire population.

$$Critical\ probability = 1 - \frac{alpha}{2}$$
$$= 1 - \frac{0.1}{2}$$
$$= 0.95$$

The critical value of 1.6 was determined using the standards statistic table by following this three steps:

1. The left most column tells you how many standard deviations above the mean to 1 decimal place.
2. The top row gives the second decimal place.
3. The intersection of a row and column gives the probability.

Confidence interval calculation

$$confidence\ interval = \overline{x} \pm z\frac{s}{\sqrt{n}}$$

$$= 157.21 \pm 1.6\frac{0.26}{\sqrt{133}}$$

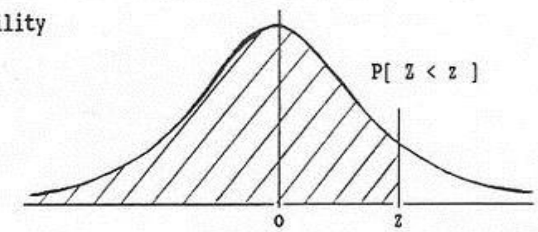
$$= 157.21 \pm 0.036$$

STANDARD STATISTICAL TABLES

1. Areas under the Normal Distribution

The table gives the cumulative probability up to the standardised normal value z i.e.

$$P[\ Z < z\ ] = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp(-\tfrac{1}{2}Z^2)\ dZ$$



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5159	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7854
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8804	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9773	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9865	0.9868	0.9871	0.9874	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9924	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9980	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986

z	3.00	3.10	3.20	3.30	3.40	3.50	3.60	3.70	3.80	3.90
P	0.9986	0.9990	0.9993	0.9995	0.9997	0.9998	0.9998	0.9999	0.9999	1.0000

Appendix 6: FEA Results

6.1. FEA: A Data

SG 1_A 214.55N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	163.31
Average	148.87
Min	106.04
Nodes ID	Max Principal
34073	149.406
34089	155.099
34097	153.496
68971	144.324
68972	140.146
68973	135.450
68974	130.088
68975	124.385
68976	118.291
68977	112.003
68978	106.036
68979	157.399
68980	159.888
68981	161.110
68982	162.547

SG 2_A 214.55N	FEA Strain Value
Number Nodes	181
Units	Micro m/m
Max	99.89
Average	88.17
Min	77.24
Nodes ID	Max Principal
32105	84.509
32114	99.887
32130	99.843
66828	77.285
66829	77.281
66830	77.294
66831	77.278
66832	77.236
66833	77.362
66834	77.502
66835	77.707
66836	78.033
66837	78.459
66838	79.062
66839	79.753

SG 3_A 214.55N	FEA Strain Value
Number Nodes	169
Units	Micro m/m
Max	45.90
Average	39.70
Min	35.72
Nodes ID	Max Principal
31688	40.425
31689	37.380
31697	45.899
66394	36.982
66395	36.650
66396	36.307
66397	36.024
66398	35.798
66399	35.715
66400	35.740
66401	35.743
66402	35.972
66403	36.427
66404	36.743
66405	37.130

SG 4_A 214.55N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-16.62
Average	-28.94
Min	-40.86
Nodes ID	Min Principal
31476	-22.913
31485	-40.858
31501	-16.622
66165	-38.739
66166	-37.924
66167	-36.766
66168	-35.733
66169	-34.724
66170	-33.763
66171	-32.626
66172	-31.601
66173	-30.549
66174	-29.453
66175	-28.353
66176	-27.315

68983	162.832	66840	80.683	66406	37.811	66177	-26.316
68984	163.307	66841	81.753	66407	38.546	66178	-25.211
68985	163.313	66842	83.066	66408	39.537	66179	-23.992
68986	162.778	66843	77.257	66409	44.562	66180	-39.903
68987	161.648	66844	96.752	66410	43.291	66181	-40.821
68988	161.272	66845	93.839	66411	42.200	66182	-40.709
68989	159.714	66846	90.818	66412	41.078	66183	-40.634
68990	158.175	66847	87.847	66413	40.063	66184	-40.270
68991	156.252	66848	85.034	66414	39.157	66185	-40.237
68992	154.250	66849	82.263	66415	38.289	66186	-40.353
68993	151.653	66850	79.678	66416	42.304	66187	-40.032
68994	154.411	66851	98.713	66417	42.203	66188	-17.796
68995	155.136	66852	97.867	66418	42.057	66189	-19.108
68996	155.920	66853	97.324	66419	41.914	66190	-20.441
68997	155.917	66854	97.003	66420	42.070	66191	-21.778
68998	155.752	66855	96.685	66421	42.266	66192	-23.266
68999	156.024	66856	96.556	66422	42.542	66193	-24.730
69000	155.676	66857	96.642	66423	42.749	66194	-26.194
69001	110.129	66858	96.919	66424	42.980	66195	-27.744
69002	115.061	66859	97.112	66425	43.303	66196	-29.226
69003	118.976	66860	97.478	66426	43.690	66197	-30.802
69004	122.928	66861	97.792	66427	44.083	66198	-32.359
69005	126.477	66862	98.195	66428	44.524	66199	-34.217
69006	130.164	66863	98.626	66429	44.841	66200	-35.676
69007	133.523	66864	99.121	66430	45.316	66201	-37.425
69008	136.796	66865	99.529	66431	42.567	66202	-38.956
69009	139.944	66866	86.147	66432	40.376	66203	-22.103
69010	142.986	66867	88.089	66433	40.240	66204	-21.145
69011	145.194	66868	89.926	66434	40.137	66205	-20.460
69012	147.532	66869	91.851	66435	40.283	66206	-19.774

69013	149.127	66870	93.677	66436	40.625	66207	-18.919
69014	150.861	66871	95.668	66437	41.054	66208	-18.148
69015	151.877	66872	97.798	66438	41.828	66209	-17.353
77846	140.352	69016	81.179	77038	37.528	66439	-29.659
77847	133.299	69017	83.969	77039	37.702	66440	-31.830
77848	142.732	69018	82.161	77040	37.044	66441	-29.705
77849	139.342	69019	84.345	77041	37.796	66442	-30.733
77850	130.900	69020	83.846	77042	39.367	66443	-29.414
77851	137.894	69021	87.052	77043	36.514	66444	-30.275
77852	128.109	69022	88.871	77044	36.849	66445	-30.957
77853	131.973	69023	85.502	77045	37.471	66446	-29.914
77854	158.556	69024	87.893	77046	37.879	66447	-36.389
77855	157.784	69025	87.991	77047	38.471	66448	-34.950
77856	156.885	69026	85.899	77048	38.816	66449	-34.232
77857	156.648	69027	85.517	77049	40.291	66450	-35.876
77858	143.488	69028	89.389	77050	40.411	66451	-29.995
77859	141.124	69029	86.893	77051	38.197	66452	-30.735
77860	135.120	69030	89.829	77052	39.793	66453	-32.259
77861	138.943	69031	86.802	77053	41.143	66454	-32.730
77862	154.349	69032	83.660	77054	43.083	66455	-27.658
77863	151.897	69033	83.837	77055	39.545	66456	-28.894
77864	149.982	69034	80.228	77056	39.052	66457	-29.654
77865	152.575	69035	80.895	77057	42.230	66458	-28.680
77866	158.550	69036	81.160	77058	41.524	66459	-23.172
77867	160.422	69037	80.960	77059	41.328	66460	-22.266
77868	161.568	69038	80.538	77060	40.262	66461	-21.536
77869	160.456	69039	81.765	77061	39.782	66462	-24.476
77870	160.448	69040	80.799	77062	40.309	66463	-26.180
77871	158.262	69041	84.624	77063	38.661	66464	-23.784
77872	159.282	69042	88.814	77064	37.830	66465	-28.433

77873	157.176	69043	91.828	77065	37.430	66466	-26.538
77874	155.316	69044	95.707	77066	37.794	66467	-20.102
77875	154.138	69045	86.432	77067	37.055	66468	-18.891
77876	158.501	69046	85.489	77068	36.726	66469	-21.936
77877	156.689	69047	93.899	77069	37.612	66470	-20.781
77878	152.574	69048	91.983	77070	36.841	66471	-23.432
77879	152.223	69049	85.738	77071	37.317	66472	-25.408
77880	147.756	69050	85.151	77072	36.482	66473	-27.022
77881	146.219	69051	90.749	77073	36.294	66474	-32.332
77882	151.160	69052	89.952	77074	36.746	66475	-34.580
77883	145.892	69053	89.611	77075	36.151	66476	-30.372
77884	146.622	69054	93.338	77076	36.035	66477	-28.885
77885	142.155	69055	93.666	77077	36.592	66478	-34.447
77886	140.189	69056	92.766	77078	36.239	66479	-33.175
77887	127.866	69057	94.228	77079	36.583	66480	-36.337
77888	151.010	69058	94.486	77080	37.064	66481	-38.325
77889	150.329	69059	79.690	77081	36.948	66482	-37.391
77890	147.024	69060	81.659	77082	37.295	66483	-36.312
77891	147.871	69061	79.224	77083	37.619	66484	-28.860
77892	142.828	69062	81.087	77084	37.483	66485	-38.828
77893	143.472	69063	79.070	77085	38.080	66486	-39.089
77894	139.984	69064	79.036	77086	38.548	66487	-38.129
77895	135.201	69065	80.634	77087	38.984	66488	-37.342
77896	134.249	69066	78.942	77088	39.870	66489	-37.095
77897	128.968	69067	78.885	77089	40.022	66490	-35.998
77898	123.420	69068	81.157	77090	39.734	66491	-35.456
77899	121.480	69069	79.508	77091	38.972	66492	-35.199
77900	116.568	69070	81.231	77092	39.500	66493	-34.112
77901	125.330	69071	78.985	77093	39.566	66494	-33.378
77902	133.665	69072	79.186	77094	40.336	66495	-33.017

77903	135.787	69073	79.505	77095	40.784	66496	-31.865
77904	136.834	69074	83.156	77096	41.507	66497	-31.247
77905	139.975	69075	81.429	77097	41.170	66498	-31.241
77906	149.338	69076	82.304	77098	40.343	66499	-30.381
77907	142.289	69077	84.191	77099	41.245	66500	-29.298
77908	144.739	69078	82.431	77100	41.008	66501	-28.962
77909	147.055	69079	82.754	77101	40.209	66502	-27.699
77910	150.423	69080	86.217	77102	41.170	66503	-27.255
77911	150.736	69081	84.674	77103	41.226	66504	-26.734
77912	152.734	69082	87.321	77104	40.015	66505	-25.329
77913	154.725	69083	87.707	77105	41.049	66506	-25.960
77914	153.088	69084	90.510	77106	40.004	66507	-24.824
77915	154.294	69085	92.034	77107	41.350	66508	-23.848
77916	154.877	69086	92.949	77108	41.426	66509	-24.186
77917	155.324	69087	95.070	77109	40.733	66510	-23.032
77918	156.024	69088	97.218	77110	41.951	66511	-22.287
77919	157.878	69089	96.099	77111	42.291	66512	-22.803
77920	158.829	69090	94.271	77112	41.458	66513	-21.752
77921	157.180	69091	96.047	77113	42.429	66514	-20.968
77922	156.888	69092	95.507	77114	42.837	66515	-21.880
77923	158.227	69093	93.435	77115	41.850	66516	-20.585
77924	157.273	69094	94.842	77116	43.129	66517	-20.744
77925	156.690	69095	93.191	77117	43.614	66518	-19.793
77926	159.275	69096	95.201	77118	42.639	66519	-19.103
77927	159.410	69097	95.125	77119	43.985	66520	-19.507
77928	159.968	69098	93.431	77120	44.384	66521	-18.509
77929	161.598	69099	94.889	77121	43.116	66522	-17.744
77930	160.894	69100	94.994	77122	41.995	66523	-18.964
77931	161.792	69101	92.079	77123	42.154	66524	-19.826
77932	162.406	69102	93.673	77124	41.051	66525	-19.964

77933	161.144
77934	162.223
77935	160.705
77936	162.419
77937	161.859
77938	159.261
77939	160.392
77940	159.909
77941	157.485
77942	158.943
77943	157.299
77944	154.949
77945	155.373
77946	152.338
77947	154.950
77948	153.253
77949	149.849
77950	149.284
77951	147.101
77952	143.031
77953	144.050
77954	143.986
77955	138.020
77956	148.603
77957	146.719
77958	145.713
77959	152.697
77960	154.378
77961	155.626
77962	158.309

69103	91.168
69104	94.216
69105	94.777
69106	95.073
69107	92.952
69108	96.030
69109	96.436
69110	94.731
69111	97.377
69112	97.761
69113	94.780
69114	93.733
69115	92.820
69116	90.328
69117	91.312
69118	88.364
69119	86.623
69120	86.200
69121	83.468
69122	82.885
69123	82.773
69124	85.549
69125	83.799
69126	83.329
69127	84.015
69128	85.900
69129	83.564
69130	83.021
69131	85.519
69132	88.577

77125	40.499
77126	40.351
77127	39.424
77128	39.035
77129	39.641
77130	38.820
77131	38.490
77132	38.663
77133	39.291
77134	38.379
77135	38.089
77136	38.488
77137	37.412
77138	37.231
77139	37.311
77140	38.206
77141	37.601
77142	37.911
77143	38.525
77144	38.105
77145	38.292
77146	39.286
77147	39.587
77148	39.349
77149	39.028
77150	38.892
77151	39.136
77152	39.700
77153	40.267
77154	40.251

66526	-21.245
66527	-22.157
66528	-22.613
66529	-24.050
66530	-24.386
66531	-25.060
66532	-26.257
66533	-25.898
66534	-27.287
66535	-27.946
66536	-28.366
66537	-29.751
66538	-28.920
66539	-30.519
66540	-30.984
66541	-32.007
66542	-33.658
66543	-34.659
66544	-35.193
66545	-36.786
66546	-38.906
66547	-38.346
66548	-37.019
66549	-38.765
66550	-38.795
66551	-37.869
66552	-39.239
66553	-36.803
66554	-35.823
66555	-35.438

77963	156.880
77964	158.781
77965	159.834
77966	160.705
77967	159.829
77968	159.323
77969	158.700
77970	157.930
77971	154.906
77972	153.973
77973	151.471
77974	149.158

69133	88.099
69134	88.165
69135	90.198
69136	87.858
69137	86.246
69138	89.627
69139	91.320
69140	91.045
69141	91.800
69142	91.743
69143	91.557
69144	89.137
69145	90.014
69146	89.024
69147	92.905
69148	87.576

77155	40.492
77156	40.788
77157	40.253
77158	41.660

66556	-34.386
66557	-33.283
66558	-31.770
66559	-33.675
66560	-31.248
66561	-30.103
66562	-29.090
66563	-27.602
66564	-27.416
66565	-26.189
66566	-25.019
66567	-24.873
66568	-23.985
66569	-23.145
66570	-23.511
66571	-22.701
66572	-22.928
66573	-21.765
66574	-20.957
66575	-21.326
66576	-20.490
66577	-22.699
66578	-23.528
66579	-24.949
66580	-25.957
66581	-26.587
66582	-27.885
66583	-35.518

SG 5_A 214.55N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-80.76
Average	-102.92
Min	-132.86
Nodes ID	Min Principal
28114	-132.856
28115	-107.127
28139	-92.787
62753	-109.118
62754	-111.327
62755	-114.876
62756	-117.741
62757	-121.324
62758	-124.922
62759	-128.818
62760	-81.954
62761	-83.419
62762	-85.145
62763	-87.135
62764	-88.907
62765	-90.952
62766	-92.831
62767	-94.633

SG 6_A 214.55N	FEA Strain Value
Number Nodes	173
Units	Micro m/m
Max	-81.58
Average	-97.21
Min	-111.01
Nodes ID	Min Principal
27920	-93.749
27929	-97.024
27945	-111.005
62531	-82.463
62532	-83.332
62533	-84.358
62534	-85.117
62535	-86.256
62536	-87.054
62537	-87.951
62538	-88.588
62539	-89.480
62540	-90.153
62541	-90.918
62542	-91.500
62543	-92.197
62544	-92.742
62545	-93.341

SG 7_A 214.55N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	-21.54
Average	-41.03
Min	-58.39
Nodes ID	Min Principal
26645	-52.639
26654	-29.649
26670	-58.386
61257	-23.293
61258	-25.306
61259	-27.176
61260	-29.250
61261	-31.136
61262	-33.085
61263	-35.143
61264	-37.077
61265	-39.095
61266	-41.123
61267	-43.048
61268	-45.034
61269	-46.979
61270	-48.839
61271	-50.690

SG 8_A 214.55N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	21.62
Average	17.97
Min	15.15
Nodes ID	Max Principal
26272	16.475
26281	21.623
26297	15.153
119873	19.924
119874	19.719
119875	19.595
119876	19.408
119877	19.284
119878	19.154
119879	19.025
119880	18.861
119881	18.728
119882	18.580
119883	18.480
119884	18.370
119885	18.266
119886	18.139
119887	18.023

62768	-96.752	62546	-81.577	61272	-21.538	119888	17.922
62769	-98.585	62547	-95.400	61273	-28.725	119889	17.822
62770	-100.543	62548	-93.630	61274	-27.862	119890	17.697
62771	-102.190	62549	-91.653	61275	-27.004	119891	17.618
62772	-103.448	62550	-89.808	61276	-26.071	119892	17.530
62773	-104.452	62551	-88.027	61277	-24.884	119893	17.404
62774	-105.497	62552	-86.042	61278	-23.884	119894	17.291
62775	-80.756	62553	-83.840	61279	-22.763	119895	17.219
62776	-91.695	62554	-110.676	61280	-56.698	119896	17.129
62777	-90.487	62555	-109.982	61281	-55.100	119897	17.027
62778	-88.875	62556	-109.321	61282	-53.607	119898	16.947
62779	-87.353	62557	-108.767	61283	-51.787	119899	16.871
62780	-85.663	62558	-107.955	61284	-50.045	119900	16.781
62781	-84.152	62559	-107.095	61285	-48.426	119901	16.648
62782	-82.395	62560	-106.386	61286	-46.392	119902	16.584
62783	-131.348	62561	-105.441	61287	-44.453	119903	16.564
62784	-129.766	62562	-104.514	61288	-42.844	119904	19.976
62785	-127.552	62563	-103.340	61289	-40.786	119905	21.450
62786	-125.342	62564	-102.347	61290	-39.106	119906	21.246
62787	-123.018	62565	-101.276	61291	-37.136	119907	21.051
62788	-120.077	62566	-100.391	61292	-35.320	119908	20.872
62789	-117.181	62567	-99.283	61293	-33.312	119909	20.753
62790	-114.467	62568	-98.219	61294	-31.637	119910	20.604
62791	-111.361	62569	-96.350	61295	-53.494	119911	20.488
62792	-108.244	62570	-98.734	61296	-54.378	119912	20.353
62793	-105.215	62571	-101.229	61297	-55.232	119913	20.220
62794	-102.409	62572	-103.333	61298	-56.033	119914	20.139
62795	-99.614	62573	-105.474	61299	-56.702	119915	20.126
62796	-96.956	62574	-107.525	61300	-57.432	119916	20.085
62797	-94.807	62575	-109.220	61301	-57.971	119917	20.042

77701	-100.120	76574	-97.227	61302	-34.217	119918	19.996
77702	-103.074	76575	-94.990	61303	-34.186	119919	19.976
77703	-102.365	76576	-93.899	61304	-31.404	119920	15.260
77704	-106.066	76577	-96.436	61305	-32.908	119921	15.460
77705	-97.897	76578	-96.068	61306	-38.202	119922	15.617
77706	-99.999	76579	-93.777	61307	-40.194	119923	15.786
77707	-92.895	76580	-92.103	61308	-37.424	119924	15.946
77708	-96.998	76581	-89.804	61309	-40.784	119925	16.107
77709	-99.487	76582	-86.189	61310	-32.827	119926	16.327
77710	-105.349	76583	-96.406	61311	-29.568	119927	16.500
77711	-98.937	76584	-98.100	61312	-30.247	119928	16.681
77712	-100.493	76585	-98.806	61313	-28.183	119929	16.850
77713	-108.509	76586	-99.499	61314	-26.409	119930	17.050
77714	-106.059	76587	-94.409	61315	-27.136	119931	17.241
77715	-111.618	76588	-90.120	61316	-28.494	119932	17.463
77716	-111.856	76589	-97.210	61317	-30.765	119933	17.639
77717	-114.249	76590	-92.125	61318	-30.392	119934	17.862
77718	-117.074	76591	-101.586	61319	-34.517	119935	18.074
77719	-111.478	76592	-103.590	61320	-35.579	119936	18.289
77720	-115.840	76593	-103.684	61321	-35.619	119937	18.495
77721	-85.048	76594	-105.451	61322	-39.129	119938	18.725
77722	-87.308	76595	-99.775	61323	-40.702	119939	18.928
77723	-91.760	76596	-94.109	61324	-42.447	119940	19.177
77724	-94.044	76597	-101.598	61325	-43.602	119941	19.404
77725	-85.294	76598	-95.901	61326	-46.664	119942	19.633
77726	-87.757	76599	-105.993	61327	-41.912	119943	19.812
77727	-92.312	76600	-106.835	61328	-46.122	119944	20.063
77728	-94.062	76601	-102.345	61329	-45.986	119945	20.294
77729	-89.282	76602	-96.805	61330	-48.268	119946	20.584
77730	-97.285	76603	-86.066	61331	-49.808	119947	20.756

77731	-99.492	76604	-83.818	61332	-51.247	119948	20.988
77732	-103.443	76605	-84.825	61333	-49.416	119949	21.238
77733	-96.333	76606	-85.822	61334	-52.069	119950	21.431
77734	-99.359	76607	-88.240	61335	-53.080	119951	16.337
77735	-104.352	76608	-87.756	61336	-53.911	119952	16.217
77736	-105.445	76609	-88.672	61337	-55.992	119953	16.185
77737	-108.909	76610	-91.186	61338	-25.075	119954	16.088
77738	-111.968	76611	-89.592	61339	-23.925	119955	15.979
77739	-109.122	76612	-90.517	61340	-25.906	119956	15.909
77740	-112.035	76613	-93.233	61341	-27.629	119957	15.828
77741	-117.357	76614	-91.362	61342	-28.353	119958	15.745
77742	-120.925	76615	-92.159	61343	-30.065	119959	15.661
77743	-117.381	76616	-95.135	61344	-33.077	119960	15.596
77744	-123.249	76617	-93.116	61345	-31.052	119961	15.510
77745	-124.315	76618	-93.676	61346	-32.808	119962	15.404
77746	-95.059	76619	-96.381	61347	-35.617	119963	15.338
77747	-107.922	76620	-94.168	61348	-34.493	119964	15.294
77748	-108.433	76621	-94.743	61349	-36.309	119965	15.178
77749	-111.603	76622	-95.460	61350	-37.352	119966	16.318
77750	-114.929	76623	-97.907	61351	-38.069	119967	16.533
77751	-114.699	76624	-99.793	61352	-39.931	119968	16.229
77752	-117.796	76625	-100.555	61353	-38.976	119969	16.274
77753	-120.844	76626	-102.881	61354	-40.988	119970	16.597
77754	-120.894	76627	-104.585	61355	-42.217	119971	16.272
77755	-124.700	76628	-105.128	61356	-42.347	119972	16.559
77756	-128.544	76629	-107.248	61357	-44.414	119973	16.344
77757	-127.120	76630	-109.064	61358	-45.310	119974	15.457
77758	-123.804	76631	-108.427	61359	-45.814	119975	15.564
77759	-126.400	76632	-106.411	61360	-47.805	119976	15.687
77760	-122.206	76633	-108.011	61361	-47.956	119977	15.544

77761	-125.389	76634	-107.397	61362	-49.248	119978	15.736
77762	-123.224	76635	-105.773	61363	-50.835	119979	15.878
77763	-119.194	76636	-107.217	61364	-50.401	119980	16.272
77764	-121.397	76637	-106.159	61365	-52.353	119981	16.462
77765	-118.661	76638	-104.587	61366	-53.272	119982	16.701
77766	-113.161	76639	-105.431	61367	-53.104	119983	17.537
77767	-114.030	76640	-103.662	61368	-54.164	119984	17.005
77768	-109.047	76641	-105.486	61369	-54.961	119985	17.389
77769	-106.039	76642	-104.372	61370	-53.539	119986	16.093
77770	-108.829	76643	-102.620	61371	-54.540	119987	16.703
77771	-105.822	76644	-103.471	61372	-54.648	119988	16.205
77772	-101.455	76645	-102.560	61373	-55.938	119989	16.637
77773	-103.766	76646	-100.576	61374	-56.752	119990	17.203
77774	-100.883	76647	-101.363	61375	-57.257	119991	19.117
77775	-96.780	76648	-99.174	61376	-55.522	119992	19.351
77776	-98.179	76649	-101.192	61377	-54.047	119993	19.639
77777	-94.511	76650	-99.974	61378	-52.069	119994	20.937
77778	-98.597	76651	-98.468	61379	-53.152	119995	20.080
77779	-96.003	76652	-99.798	61380	-51.517	119996	20.595
77780	-93.945	76653	-98.695	61381	-49.734	119997	21.191
77781	-92.748	76654	-97.271	61382	-49.709	119998	20.897
77782	-92.271	76655	-97.853	61383	-48.339	119999	20.611
77783	-90.689	76656	-96.243	61384	-47.126	120000	17.763
77784	-93.123	76657	-97.662	61385	-47.078	120001	18.090
77785	-89.758	76658	-96.545	61386	-45.315	120002	18.472
77786	-89.936	76659	-94.927	61387	-44.073	120003	17.715
77787	-87.575	76660	-94.907	61388	-43.209	120004	18.207
77788	-85.799	76661	-93.756	61389	-42.050	120005	18.828
77789	-86.435	76662	-91.839	61390	-38.811	120006	19.246
77790	-84.696	76663	-92.928	61391	-39.365	120007	18.416

77791	-82.883
77792	-85.185
77793	-82.755
77794	-84.231
77795	-86.179
77796	-85.350
77797	-87.093
77798	-89.525
77799	-89.494
77800	-91.176
77801	-92.862
77802	-92.465
77803	-95.187
77804	-93.622
77805	-95.445
77806	-97.845
77807	-97.080
77808	-98.963
77809	-101.870
77810	-101.431
77811	-104.933
77812	-102.057
77813	-103.699
77814	-107.064
77815	-105.461
77816	-106.818
77817	-110.615
77818	-113.074
77819	-110.461
77820	-114.843

76664	-90.945
76665	-91.003
76666	-89.724
76667	-87.835
76668	-87.999
76669	-89.975
76670	-92.161
76671	-92.308
76672	-92.851
76673	-95.587
76674	-94.803
76675	-95.732
76676	-98.728
76677	-97.199
76678	-97.821
76679	-100.713
76680	-98.777
76681	-99.278
76682	-102.150
76683	-103.884
76684	-104.255
76685	-103.614
76686	-102.709
76687	-101.698
76688	-101.702
76689	-100.688
76690	-99.480
76691	-98.384
76692	-97.548
76693	-96.603

61392	-36.767
61393	-35.030
61394	-35.959
61395	-33.997
61396	-32.730
61397	-32.018
61398	-30.358
61399	-29.371
61400	-29.640
61401	-28.232
61402	-27.256
61403	-27.807
61404	-26.592
61405	-25.515
61406	-26.734
61407	-28.700
61408	-29.428
61409	-30.661
61410	-32.503
61411	-40.529
61412	-37.314
61413	-42.272
61414	-40.699
61415	-41.581
61416	-43.001
61417	-44.247
61418	-44.983
61419	-46.506
61420	-47.822
61421	-48.000

120008	18.959
120009	17.853
120010	18.468
120011	19.616
120012	20.191
120013	19.414
120014	19.863
120015	20.409
120016	20.234
120017	20.125
120018	19.956
120019	19.093
120020	19.557
120021	18.950
120022	19.460
120023	19.896
120024	19.761
120025	19.722
120026	19.743
120027	15.804
120028	15.894
120029	16.012
120030	15.978
120031	16.094
120032	16.260
120033	16.155
120034	16.277
120035	16.375
120036	16.406
120037	16.519

77821	-116.666
77822	-119.084
77823	-120.273
77824	-114.626
77825	-110.476
77826	-108.164
77827	-106.891
77828	-103.091
77829	-101.540
77830	-96.831
77831	-102.983
77832	-99.677
77833	-94.156
77834	-96.588
77835	-94.458
77836	-90.740
77837	-95.888
77838	-88.510
77839	-87.234
77840	-87.173
77841	-88.305
77842	-90.593
77843	-94.410
77844	-95.661
77845	-108.618

76694	-96.241
76695	-95.443
76696	-94.043
76697	-95.082
76698	-93.224

61422	-49.652
61423	-51.371
61424	-51.253
61425	-52.496
61426	-50.589
61427	-48.992
61428	-47.257
61429	-45.973
61430	-44.073

120038	16.660
120039	16.737
120040	17.059
120041	17.478
120042	17.100
120043	17.421
120044	16.746
120045	17.116
120046	17.343

6.2. FEA: B Data

SG 1_B 415.16N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	316.02
Average	288.07
Min	205.18
Nodes ID	Max Principal
34073	289.107
34089	300.122
34097	297.020
68971	279.273
68972	271.187
68973	262.100
68974	251.725
68975	240.690
68976	228.898
68977	216.729
68978	205.183
68979	304.572
68980	309.389
68981	311.754
68982	314.535
68983	315.085
68984	316.005

SG 2_B 415.16N	FEA Strain Value
Number Nodes	181
Units	Micro m/m
Max	193.28
Average	170.62
Min	149.45
Nodes ID	Max Principal
32105	163.528
32114	193.285
32130	193.201
66828	149.550
66829	149.541
66830	149.567
66831	149.536
66832	149.455
66833	149.698
66834	149.968
66835	150.365
66836	150.997
66837	151.820
66838	152.987
66839	154.325
66840	156.124
66841	158.196

SG 3_B 415.16N	FEA Strain Value
Number Nodes	169
Units	Micro m/m
Max	88.82
Average	76.82
Min	69.11
Nodes ID	Max Principal
31688	78.223
31689	72.332
31697	88.816
66394	71.561
66395	70.919
66396	70.255
66397	69.709
66398	69.271
66399	69.110
66400	69.159
66401	69.164
66402	69.607
66403	70.488
66404	71.099
66405	71.849
66406	73.165
66407	74.588

SG 4_B 415.16N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-32.16
Average	-55.99
Min	-79.06
Nodes ID	Min Principal
31476	-44.338
31485	-79.061
31501	-32.164
66165	-74.961
66166	-73.384
66167	-71.143
66168	-69.144
66169	-67.192
66170	-65.333
66171	-63.132
66172	-61.149
66173	-59.113
66174	-56.993
66175	-54.864
66176	-52.856
66177	-50.923
66178	-48.784

68985	316.017	66842	160.735	66408	76.506	66179	-46.425
68986	314.982	66843	149.496	66409	86.229	66180	-77.214
68987	312.795	66844	187.219	66410	83.771	66181	-78.989
68988	312.067	66845	181.581	66411	81.658	66182	-78.773
68989	309.052	66846	175.736	66412	79.487	66183	-78.629
68990	306.074	66847	169.987	66413	77.523	66184	-77.924
68991	302.353	66848	164.544	66414	75.769	66185	-77.859
68992	298.479	66849	159.182	66415	74.090	66186	-78.085
68993	293.454	66850	154.180	66416	81.860	66187	-77.463
68994	298.790	66851	191.014	66417	81.664	66188	-34.436
68995	300.194	66852	189.376	66418	81.383	66189	-36.974
68996	301.711	66853	188.326	66419	81.106	66190	-39.554
68997	301.705	66854	187.705	66420	81.407	66191	-42.141
68998	301.387	66855	187.089	66421	81.787	66192	-45.020
68999	301.912	66856	186.839	66422	82.321	66193	-47.853
69000	301.238	66857	187.005	66423	82.721	66194	-50.687
69001	213.103	66858	187.543	66424	83.169	66195	-53.685
69002	222.647	66859	187.915	66425	83.793	66196	-56.553
69003	230.222	66860	188.623	66426	84.543	66197	-59.604
69004	237.870	66861	189.232	66427	85.302	66198	-62.617
69005	244.737	66862	190.012	66428	86.155	66199	-66.211
69006	251.873	66863	190.846	66429	86.768	66200	-69.034
69007	258.372	66864	191.802	66430	87.688	66201	-72.419
69008	264.706	66865	192.592	66431	82.368	66202	-75.382
69009	270.797	66866	166.698	66432	78.129	66203	-42.771
69010	276.683	66867	170.455	66433	77.866	66204	-40.916
69011	280.955	66868	174.010	66434	77.666	66205	-39.591
69012	285.479	66869	177.735	66435	77.949	66206	-38.263
69013	288.567	66870	181.268	66436	78.611	66207	-36.608
69014	291.921	66871	185.122	66437	79.441	66208	-35.116

69015	293.887	66872	189.243	66438	80.938	66209	-33.579
77846	271.586	69016	157.085	77038	72.619	66439	-57.392
77847	257.938	69017	162.483	77039	72.956	66440	-61.593
77848	276.192	69018	158.985	77040	71.681	66441	-57.480
77849	269.631	69019	163.210	77041	73.137	66442	-59.470
77850	253.296	69020	162.246	77042	76.176	66443	-56.916
77851	266.829	69021	168.449	77043	70.655	66444	-58.584
77852	247.896	69022	171.969	77044	71.304	66445	-59.903
77853	255.373	69023	165.449	77045	72.508	66446	-57.885
77854	306.812	69024	170.077	77046	73.297	66447	-70.414
77855	305.318	69025	170.267	77047	74.443	66448	-67.630
77856	303.578	69026	166.218	77048	75.110	66449	-66.240
77857	303.119	69027	165.478	77049	77.964	66450	-69.421
77858	277.655	69028	172.971	77050	78.197	66451	-58.040
77859	273.081	69029	168.142	77051	73.913	66452	-59.474
77860	261.462	69030	173.822	77052	77.001	66453	-62.423
77861	268.859	69031	167.965	77053	79.612	66454	-63.334
77862	298.672	69032	161.886	77054	83.368	66455	-53.518
77863	293.926	69033	162.227	77055	76.521	66456	-55.911
77864	290.222	69034	155.245	77056	75.568	66457	-57.382
77865	295.237	69035	156.535	77057	81.717	66458	-55.498
77866	306.800	69036	157.049	77058	80.351	66459	-44.840
77867	310.423	69037	156.660	77059	79.972	66460	-43.086
77868	312.640	69038	155.845	77060	77.908	66461	-41.674
77869	310.487	69039	158.219	77061	76.979	66462	-47.362
77870	310.472	69040	156.348	77062	77.999	66463	-50.658
77871	306.243	69041	163.750	77063	74.811	66464	-46.023
77872	308.217	69042	171.859	77064	73.203	66465	-55.020
77873	304.142	69043	177.690	77065	72.429	66466	-51.353
77874	300.543	69044	185.196	77066	73.132	66467	-38.898

77875	298.262
77876	306.704
77877	303.198
77878	295.237
77879	294.556
77880	285.914
77881	282.940
77882	292.500
77883	282.307
77884	283.718
77885	275.076
77886	271.272
77887	247.425
77888	292.211
77889	290.892
77890	284.498
77891	286.135
77892	276.378
77893	277.623
77894	270.874
77895	261.619
77896	259.777
77897	249.559
77898	238.823
77899	235.069
77900	225.564
77901	242.519
77902	258.648
77903	262.754
77904	264.780

69045	167.249
69046	165.425
69047	181.699
69048	177.991
69049	165.906
69050	164.770
69051	175.602
69052	174.060
69053	173.400
69054	180.613
69055	181.247
69056	179.506
69057	182.334
69058	182.834
69059	154.203
69060	158.013
69061	153.302
69062	156.907
69063	153.003
69064	152.938
69065	156.030
69066	152.756
69067	152.646
69068	157.041
69069	153.850
69070	157.186
69071	152.839
69072	153.227
69073	153.845
69074	160.910

77067	71.703
77068	71.067
77069	72.781
77070	71.289
77071	72.209
77072	70.595
77073	70.230
77074	71.106
77075	69.953
77076	69.728
77077	70.806
77078	70.124
77079	70.789
77080	71.721
77081	71.495
77082	72.167
77083	72.793
77084	72.532
77085	73.686
77086	74.592
77087	75.435
77088	77.149
77089	77.445
77090	76.886
77091	75.412
77092	76.434
77093	76.561
77094	78.052
77095	78.918
77096	80.318

66468	-36.556
66469	-42.448
66470	-40.212
66471	-45.341
66472	-49.165
66473	-52.288
66474	-62.564
66475	-66.913
66476	-58.771
66477	-55.894
66478	-66.656
66479	-64.195
66480	-70.313
66481	-74.161
66482	-72.353
66483	-70.266
66484	-55.845
66485	-75.133
66486	-75.639
66487	-73.781
66488	-72.258
66489	-71.781
66490	-69.658
66491	-68.609
66492	-68.111
66493	-66.009
66494	-64.587
66495	-63.888
66496	-61.660
66497	-60.464

77905	270.858	69075	157.569	77097	79.666	66498	-60.452
77906	288.974	69076	159.261	77098	78.066	66499	-58.789
77907	275.334	69077	162.914	77099	79.811	66500	-56.694
77908	280.076	69078	159.507	77100	79.351	66501	-56.042
77909	284.557	69079	160.133	77101	77.806	66502	-53.599
77910	291.075	69080	166.833	77102	79.665	66503	-52.739
77911	291.680	69081	163.848	77103	79.774	66504	-51.730
77912	295.547	69082	168.970	77104	77.430	66505	-49.012
77913	299.398	69083	169.716	77105	79.432	66506	-50.234
77914	296.232	69084	175.141	77106	77.409	66507	-48.036
77915	298.565	69085	178.089	77107	80.013	66508	-46.146
77916	299.693	69086	179.860	77108	80.161	66509	-46.800
77917	300.557	69087	183.964	77109	78.820	66510	-44.568
77918	301.912	69088	188.121	77110	81.177	66511	-43.126
77919	305.499	69089	185.956	77111	81.835	66512	-44.125
77920	307.339	69090	182.417	77112	80.222	66513	-42.090
77921	304.150	69091	185.855	77113	82.101	66514	-40.574
77922	303.584	69092	184.809	77114	82.890	66515	-42.338
77923	306.175	69093	180.800	77115	80.980	66516	-39.833
77924	304.329	69094	183.523	77116	83.457	66517	-40.141
77925	303.201	69095	180.327	77117	84.394	66518	-38.299
77926	308.203	69096	184.218	77118	82.508	66519	-36.965
77927	308.463	69097	184.070	77119	85.112	66520	-37.746
77928	309.543	69098	180.792	77120	85.884	66521	-35.815
77929	312.698	69099	183.615	77121	83.431	66522	-34.334
77930	311.336	69100	183.816	77122	81.262	66523	-36.695
77931	313.074	69101	178.177	77123	81.569	66524	-38.363
77932	314.262	69102	181.260	77124	79.435	66525	-38.631
77933	311.820	69103	176.413	77125	78.367	66526	-41.110
77934	313.908	69104	182.311	77126	78.080	66527	-42.874

77935	310.970	69105	183.396	77127	76.286	66528	-43.757
77936	314.286	69106	183.970	77128	75.534	66529	-46.537
77937	313.203	69107	179.866	77129	76.706	66530	-47.189
77938	308.177	69108	185.822	77130	75.119	66531	-48.492
77939	310.365	69109	186.608	77131	74.480	66532	-50.808
77940	309.429	69110	183.308	77132	74.815	66533	-50.113
77941	304.739	69111	188.427	77133	76.029	66534	-52.802
77942	307.561	69112	189.170	77134	74.265	66535	-54.077
77943	304.379	69113	183.404	77135	73.703	66536	-54.890
77944	299.833	69114	181.377	77136	74.476	66537	-57.569
77945	300.653	69115	179.610	77137	72.394	66538	-55.962
77946	294.780	69116	174.788	77138	72.043	66539	-59.055
77947	299.833	69117	176.693	77139	72.198	66540	-59.955
77948	296.550	69118	170.987	77140	73.930	66541	-61.936
77949	289.964	69119	167.620	77141	72.759	66542	-65.129
77950	288.871	69120	166.800	77142	73.358	66543	-67.067
77951	284.646	69121	161.514	77143	74.547	66544	-68.100
77952	276.771	69122	160.386	77144	73.734	66545	-71.182
77953	278.742	69123	160.169	77145	74.096	66546	-75.285
77954	278.619	69124	165.540	77146	76.020	66547	-74.201
77955	267.075	69125	162.154	77147	76.603	66548	-71.632
77956	287.552	69126	161.245	77148	76.142	66549	-75.011
77957	283.906	69127	162.572	77149	75.521	66550	-75.070
77958	281.960	69128	166.220	77150	75.258	66551	-73.278
77959	295.475	69129	161.699	77151	75.729	66552	-75.930
77960	298.726	69130	160.649	77152	76.822	66553	-71.215
77961	301.143	69131	165.482	77153	77.918	66554	-69.318
77962	306.334	69132	171.400	77154	77.888	66555	-68.574
77963	303.568	69133	170.475	77155	78.353	66556	-66.538
77964	307.246	69134	170.603	77156	78.927	66557	-64.404

77965	309.284
77966	310.970
77967	309.275
77968	308.296
77969	307.090
77970	305.601
77971	299.750
77972	297.943
77973	293.102
77974	288.627

69135	174.536
69136	170.009
69137	166.890
69138	173.432
69139	176.707
69140	176.175
69141	177.637
69142	177.525
69143	177.167
69144	172.483
69145	174.180
69146	172.264
69147	179.775
69148	169.462

77157	77.890
77158	80.614

66558	-61.476
66559	-65.163
66560	-60.465
66561	-58.249
66562	-56.290
66563	-53.411
66564	-53.051
66565	-50.676
66566	-48.412
66567	-48.131
66568	-46.413
66569	-44.787
66570	-45.496
66571	-43.928
66572	-44.366
66573	-42.117
66574	-40.553
66575	-41.266
66576	-39.650
66577	-43.924
66578	-45.527
66579	-48.278
66580	-50.228
66581	-51.446
66582	-53.959
66583	-68.729

SG 5_B 415.16N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-156.27
Average	-199.15
Min	-257.08
Nodes ID	Min Principal
28114	-257.081
28115	-207.294
28139	-179.546
62753	-211.147
62754	-215.422
62755	-222.290
62756	-227.833
62757	-234.766
62758	-241.728
62759	-249.268
62760	-158.585
62761	-161.418
62762	-164.759
62763	-168.610
62764	-172.039
62765	-175.996
62766	-179.632

SG 6_B 415.16N	FEA Strain Value
Number Nodes	173
Units	Micro m/m
Max	-157.85
Average	-188.10
Min	-214.80
Nodes ID	Min Principal
27920	-181.407
27929	-187.745
27945	-214.800
62531	-159.569
62532	-161.250
62533	-163.235
62534	-164.704
62535	-166.909
62536	-168.454
62537	-170.189
62538	-171.421
62539	-173.147
62540	-174.450
62541	-175.930
62542	-177.056
62543	-178.404
62544	-179.459

SG 7_B 415.16N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	-41.68
Average	-79.40
Min	-112.98
Nodes ID	Min Principal
26645	-101.859
26654	-57.371
26670	-112.979
61257	-45.072
61258	-48.968
61259	-52.586
61260	-56.601
61261	-60.250
61262	-64.022
61263	-68.004
61264	-71.746
61265	-75.651
61266	-79.575
61267	-83.299
61268	-87.142
61269	-90.906
61270	-94.505

SG 8_B 415.16N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	41.19
Average	33.99
Min	28.81
Nodes ID	Max Principal
26272	31.721
26281	41.195
26297	28.807
60892	38.013
60893	37.473
60894	36.901
60895	36.318
60896	35.815
60897	35.291
60898	34.924
60899	34.529
60900	34.095
60901	33.612
60902	33.303
60903	32.898
60904	32.644
60905	32.296

62767	-183.118
62768	-187.219
62769	-190.766
62770	-194.554
62771	-197.741
62772	-200.176
62773	-202.119
62774	-204.142
62775	-156.267
62776	-177.434
62777	-175.096
62778	-171.977
62779	-169.032
62780	-165.762
62781	-162.837
62782	-159.438
62783	-254.163
62784	-251.101
62785	-246.818
62786	-242.541
62787	-238.045
62788	-232.354
62789	-226.750
62790	-221.499
62791	-215.488
62792	-209.455
62793	-203.596
62794	-198.165
62795	-192.756
62796	-187.614

62545	-180.617
62546	-157.855
62547	-184.603
62548	-181.177
62549	-177.352
62550	-173.782
62551	-170.336
62552	-166.495
62553	-162.234
62554	-214.162
62555	-212.819
62556	-211.541
62557	-210.468
62558	-208.896
62559	-207.233
62560	-205.860
62561	-204.033
62562	-202.238
62563	-199.967
62564	-198.045
62565	-195.972
62566	-194.260
62567	-192.117
62568	-190.058
62569	-186.440
62570	-191.054
62571	-195.883
62572	-199.953
62573	-204.095
62574	-208.065

61271	-98.087
61272	-41.677
61273	-55.585
61274	-53.914
61275	-52.254
61276	-50.448
61277	-48.152
61278	-46.217
61279	-44.047
61280	-109.712
61281	-106.620
61282	-103.731
61283	-100.210
61284	-96.839
61285	-93.706
61286	-89.771
61287	-86.018
61288	-82.905
61289	-78.922
61290	-75.672
61291	-71.859
61292	-68.346
61293	-64.459
61294	-61.218
61295	-103.512
61296	-105.224
61297	-106.875
61298	-108.425
61299	-109.721
61300	-111.133

60906	31.972
60907	38.535
60908	40.334
60909	39.696
60910	39.445
60911	38.842
60912	38.470
60913	38.375
60914	38.458
60915	29.466
60916	30.016
60917	30.720
60918	31.335
60919	32.177
60920	32.759
60921	33.608
60922	34.320
60923	35.087
60924	35.874
60925	36.760
60926	37.591
60927	38.602
60928	39.286
60929	40.419
60930	31.247
60931	30.820
60932	30.464
60933	30.128
60934	29.853
60935	29.508

62797	-183.455
77701	-193.736
77702	-199.452
77703	-198.079
77704	-205.241
77705	-189.434
77706	-193.502
77707	-179.756
77708	-187.695
77709	-192.512
77710	-203.855
77711	-191.447
77712	-194.457
77713	-209.969
77714	-205.228
77715	-215.986
77716	-216.446
77717	-221.076
77718	-226.543
77719	-215.715
77720	-224.155
77721	-164.571
77722	-168.945
77723	-177.559
77724	-181.980
77725	-165.048
77726	-169.813
77727	-178.627
77728	-182.013
77729	-172.764

62575	-211.344
76574	-188.138
76575	-183.810
76576	-181.698
76577	-186.607
76578	-185.895
76579	-181.462
76580	-178.223
76581	-173.773
76582	-166.779
76583	-186.549
76584	-189.828
76585	-191.193
76586	-192.534
76587	-182.685
76588	-174.386
76589	-188.105
76590	-178.266
76591	-196.573
76592	-200.450
76593	-200.633
76594	-204.052
76595	-193.068
76596	-182.104
76597	-196.595
76598	-185.573
76599	-205.100
76600	-206.731
76601	-198.042
76602	-187.320

61301	-112.176
61302	-66.212
61303	-66.151
61304	-60.768
61305	-63.678
61306	-73.923
61307	-77.777
61308	-72.416
61309	-78.918
61310	-63.522
61311	-57.215
61312	-58.529
61313	-54.535
61314	-51.103
61315	-52.509
61316	-55.136
61317	-59.531
61318	-58.810
61319	-66.791
61320	-68.847
61321	-68.923
61322	-75.716
61323	-78.760
61324	-82.137
61325	-84.372
61326	-90.297
61327	-81.101
61328	-89.248
61329	-88.986
61330	-93.400

60936	29.184
60937	31.085
60938	31.651
60939	31.639
60940	31.877
60941	32.822
60942	33.174
60943	32.246
60944	32.799
60945	31.946
60946	32.311
60947	31.327
60948	32.428
60949	29.872
60950	30.273
60951	32.203
60952	33.100
60953	30.990
60954	32.895
60955	37.704
60956	38.894
60957	36.008
60958	34.339
60959	35.657
60960	37.333
60961	37.087
60962	30.769
60963	31.243
60964	31.711
60965	31.824

77730	-188.250	76603	-166.541	61331	-96.380	60966	32.850
77731	-192.520	76604	-162.191	61332	-99.165	60967	32.105
77732	-200.165	76605	-164.139	61333	-95.622	60968	33.551
77733	-186.408	76606	-166.070	61334	-100.755	60969	34.629
77734	-192.264	76607	-170.748	61335	-102.711	60970	33.993
77735	-201.924	76608	-169.812	61336	-104.320	60971	35.450
77736	-204.040	76609	-171.584	61337	-108.347	60972	36.368
77737	-210.743	76610	-176.448	61338	-48.521	60973	37.790
77738	-216.662	76611	-173.364	61339	-46.297	60974	37.784
77739	-211.155	76612	-175.153	61340	-50.129	60975	37.219
77740	-216.792	76613	-180.408	61341	-53.463	60976	36.738
77741	-227.091	76614	-176.790	61342	-54.863	60977	36.902
77742	-233.995	76615	-178.331	61343	-58.177	60978	36.356
77743	-227.136	76616	-184.090	61344	-64.005	60979	35.932
77744	-238.491	76617	-180.182	61345	-60.087	60980	35.840
77745	-240.554	76618	-181.267	61346	-63.485	60981	35.382
77746	-183.942	76619	-186.501	61347	-68.920	60982	35.063
77747	-208.834	76620	-182.219	61348	-66.745	60983	34.844
77748	-209.822	76621	-183.332	61349	-70.259	60984	34.320
77749	-215.956	76622	-184.718	61350	-72.278	60985	34.614
77750	-222.391	76623	-189.453	61351	-73.664	60986	34.235
77751	-221.947	76624	-193.103	61352	-77.267	60987	33.800
77752	-227.939	76625	-194.577	61353	-75.420	60988	33.380
77753	-233.838	76626	-199.078	61354	-79.313	60989	33.264
77754	-233.935	76627	-202.375	61355	-81.691	60990	32.415
77755	-241.299	76628	-203.426	61356	-81.943	60991	32.740
77756	-248.737	76629	-207.530	61357	-85.942	60992	32.362
77757	-245.983	76630	-211.043	61358	-87.677	60993	31.935
77758	-239.566	76631	-209.811	61359	-88.652	60994	32.457
77759	-244.589	76632	-205.909	61360	-92.504	60995	32.184

77760	-236.472	76633	-209.005	61361	-92.797	60996	31.842
77761	-242.632	76634	-207.817	61362	-95.297	60997	31.955
77762	-238.443	76635	-204.675	61363	-98.367	60998	31.258
77763	-230.644	76636	-207.469	61364	-97.529	60999	31.528
77764	-234.908	76637	-205.422	61365	-101.304	61000	31.355
77765	-229.614	76638	-202.380	61366	-103.084	61001	31.062
77766	-218.971	76639	-204.013	61367	-102.759	61002	30.671
77767	-220.652	76640	-200.591	61368	-104.810	61003	31.006
77768	-211.011	76641	-204.120	61369	-106.352	61004	30.474
77769	-205.189	76642	-201.964	61370	-103.600	61005	30.173
77770	-210.589	76643	-198.573	61371	-105.537	61006	30.484
77771	-204.770	76644	-200.221	61372	-105.746	61007	29.926
77772	-196.318	76645	-198.457	61373	-108.242	61008	30.080
77773	-200.790	76646	-194.617	61374	-109.817	61009	29.736
77774	-195.213	76647	-196.141	61375	-110.795	61010	29.357
77775	-187.273	76648	-191.906	61376	-107.437	61011	29.893
77776	-189.981	76649	-195.811	61377	-104.582	61012	30.367
77777	-182.883	76650	-193.454	61378	-100.756	61013	30.465
77778	-190.788	76651	-190.540	61379	-102.851	61014	31.149
77779	-185.768	76652	-193.112	61380	-99.687	61015	31.582
77780	-181.787	76653	-190.979	61381	-96.237	61016	31.720
77781	-179.470	76654	-188.224	61382	-96.188	61017	32.474
77782	-178.547	76655	-189.350	61383	-93.539	61018	32.672
77783	-175.486	76656	-186.233	61384	-91.191	61019	32.904
77784	-180.197	76657	-188.979	61385	-91.098	61020	33.778
77785	-173.684	76658	-186.818	61386	-87.687	61021	33.722
77786	-174.030	76659	-183.687	61387	-85.282	61022	34.260
77787	-169.462	76660	-183.648	61388	-83.610	61023	35.092
77788	-166.025	76661	-181.421	61389	-81.367	61024	35.185
77789	-167.256	76662	-177.712	61390	-75.101	61025	35.936

77790	-163.890	76663	-179.820	61391	-76.173	61026	36.910
77791	-160.382	76664	-175.981	61392	-71.146	61027	36.881
77792	-164.835	76665	-176.093	61393	-67.785	61028	37.530
77793	-160.134	76666	-173.618	61394	-69.582	61029	38.483
77794	-162.989	76667	-169.963	61395	-65.785	61030	38.316
77795	-166.760	76668	-170.281	61396	-63.335	61031	39.069
77796	-165.156	76669	-174.105	61397	-61.956	61032	39.977
77797	-168.528	76670	-178.334	61398	-58.743	61033	39.175
77798	-173.235	76671	-178.620	61399	-56.835	61034	38.882
77799	-173.175	76672	-179.670	61400	-57.355	61035	38.085
77800	-176.428	76673	-184.964	61401	-54.631	61036	38.124
77801	-179.691	76674	-183.448	61402	-52.741	61037	37.874
77802	-178.922	76675	-185.245	61403	-53.808	61038	37.102
77803	-184.191	76676	-191.041	61404	-51.457	61039	36.536
77804	-181.162	76677	-188.084	61405	-49.373	61040	36.419
77805	-184.689	76678	-189.287	61406	-51.731	61041	36.043
77806	-189.334	76679	-194.883	61407	-55.535	61042	35.465
77807	-187.854	76680	-191.138	61408	-56.944	61043	35.086
77808	-191.498	76681	-192.107	61409	-59.330	61044	34.998
77809	-197.122	76682	-197.665	61410	-62.895	61045	34.410
77810	-196.273	76683	-201.019	61411	-78.426	61046	33.888
77811	-203.048	76684	-201.736	61412	-72.204	61047	34.099
77812	-197.484	76685	-200.497	61413	-81.798	61048	33.806
77813	-200.662	76686	-198.746	61414	-78.754	61049	33.225
77814	-207.173	76687	-196.790	61415	-80.462	61050	33.209
77815	-204.072	76688	-196.796	61416	-83.209	61051	32.886
77816	-206.697	76689	-194.836	61417	-85.620	61052	32.038
77817	-214.043	76690	-192.498	61418	-87.044	61053	31.874
77818	-218.803	76691	-190.377	61419	-89.990	61054	31.349
77819	-213.746	76692	-188.759	61420	-92.537	61055	31.058

77820	-222.226
77821	-225.754
77822	-230.432
77823	-232.733
77824	-221.807
77825	-213.775
77826	-209.301
77827	-206.838
77828	-199.485
77829	-196.484
77830	-187.371
77831	-199.275
77832	-192.880
77833	-182.194
77834	-186.902
77835	-182.780
77836	-175.586
77837	-185.546
77838	-171.270
77839	-168.801
77840	-168.684
77841	-170.874
77842	-175.301
77843	-182.687
77844	-185.108
77845	-210.180

76693	-186.930
76694	-186.230
76695	-184.687
76696	-181.976
76697	-183.987
76698	-180.392

61421	-92.881
61422	-96.079
61423	-99.405
61424	-99.176
61425	-101.582
61426	-97.891
61427	-94.800
61428	-91.444
61429	-88.960
61430	-85.282

61056	31.329
61057	31.536
61058	31.614
61059	30.601
61060	32.514
61061	32.975
61062	33.650
61063	35.679
61064	36.652
61065	37.536

6.3. FEA: C Data

SG 1_C 620.48N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	472.30
Average	430.53
Min	306.66
Nodes ID	Max Principal
34073	432.085
34089	448.549
34097	443.912
68971	417.389
68972	405.303
68973	391.723
68974	376.217
68975	359.725
68976	342.100
68977	323.914
68978	306.657
68979	455.199
68980	462.399
68981	465.934
68982	470.089
68983	470.912
68984	472.287

SG 2_C 620.48N	FEA Strain Value
Number Nodes	181
Units	Micro m/m
Max	288.87
Average	255.00
Min	223.37
Nodes ID	Max Principal
32105	244.401
32114	288.874
32130	288.749
66828	223.510
66829	223.497
66830	223.536
66831	223.490
66832	223.368
66833	223.732
66834	224.136
66835	224.729
66836	225.674
66837	226.904
66838	228.648
66839	230.647
66840	233.336
66841	236.432

SG 3_C 620.48N	FEA Strain Value
Number Nodes	169
Units	Micro m/m
Max	132.74
Average	114.80
Min	103.29
Nodes ID	Max Principal
31688	116.909
31689	108.104
31697	132.740
66394	106.952
66395	105.992
66396	105.001
66397	104.183
66398	103.529
66399	103.288
66400	103.362
66401	103.369
66402	104.032
66403	105.348
66404	106.262
66405	107.382
66406	109.349
66407	111.476

SG 4 620.48N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-48.07
Average	-83.69
Min	-118.16
Nodes ID	Min Principal
31476	-66.265
31485	-118.161
31501	-48.071
66165	-112.034
66166	-109.676
66167	-106.328
66168	-103.339
66169	-100.422
66170	-97.644
66171	-94.354
66172	-91.391
66173	-88.347
66174	-85.179
66175	-81.997
66176	-78.996
66177	-76.107
66178	-72.911

68985	472.305	66842	240.228	66408	114.343	66179	-69.384
68986	470.757	66843	223.429	66409	128.874	66180	-115.401
68987	467.489	66844	279.808	66410	125.200	66181	-118.054
68988	466.402	66845	271.383	66411	122.043	66182	-117.730
68989	461.895	66846	262.647	66412	118.798	66183	-117.516
68990	457.444	66847	254.055	66413	115.862	66184	-116.461
68991	451.883	66848	245.920	66414	113.242	66185	-116.365
68992	446.093	66849	237.907	66415	110.731	66186	-116.702
68993	438.583	66850	230.430	66416	122.345	66187	-115.772
68994	446.558	66851	285.480	66417	122.051	66188	-51.467
68995	448.657	66852	283.033	66418	121.631	66189	-55.259
68996	450.923	66853	281.463	66419	121.217	66190	-59.115
68997	450.915	66854	280.536	66420	121.668	66191	-62.982
68998	450.439	66855	279.615	66421	122.235	66192	-67.285
68999	451.224	66856	279.240	66422	123.033	66193	-71.519
69000	450.217	66857	279.489	66423	123.631	66194	-75.754
69001	318.494	66858	280.293	66424	124.300	66195	-80.235
69002	332.759	66859	280.850	66425	125.233	66196	-84.522
69003	344.079	66860	281.907	66426	126.354	66197	-89.081
69004	355.510	66861	282.817	66427	127.489	66198	-93.584
69005	365.773	66862	283.983	66428	128.763	66199	-98.957
69006	376.437	66863	285.229	66429	129.680	66200	-103.175
69007	386.151	66864	286.659	66430	131.055	66201	-108.234
69008	395.617	66865	287.839	66431	123.104	66202	-112.662
69009	404.720	66866	249.139	66432	116.769	66203	-63.924
69010	413.517	66867	254.754	66433	116.376	66204	-61.150
69011	419.902	66868	260.068	66434	116.077	66205	-59.171
69012	426.664	66869	265.635	66435	116.499	66206	-57.186
69013	431.279	66870	270.915	66436	117.489	66207	-54.713
69014	436.292	66871	276.675	66437	118.728	66208	-52.483

69015	439.230	66872	282.834	66438	120.967	66209	-50.186
77846	405.900	69016	234.772	77038	108.532	66439	-85.775
77847	385.502	69017	242.840	77039	109.036	66440	-92.054
77848	412.784	69018	237.611	77040	107.131	66441	-85.908
77849	402.978	69019	243.927	77041	109.307	66442	-88.881
77850	378.564	69020	242.485	77042	113.849	66443	-85.064
77851	398.791	69021	251.756	77043	105.598	66444	-87.557
77852	370.494	69022	257.017	77044	106.567	66445	-89.528
77853	381.669	69023	247.272	77045	108.367	66446	-86.512
77854	458.547	69024	254.189	77046	109.546	66447	-105.238
77855	456.314	69025	254.473	77047	111.260	66448	-101.077
77856	453.714	69026	248.422	77048	112.257	66449	-98.999
77857	453.027	69027	247.316	77049	116.521	66450	-103.753
77858	414.971	69028	258.514	77050	116.870	66451	-86.745
77859	408.134	69029	251.297	77051	110.468	66452	-88.887
77860	390.769	69030	259.787	77052	115.082	66453	-93.294
77861	401.824	69031	251.032	77053	118.985	66454	-94.657
77862	446.381	69032	241.947	77054	124.598	66455	-79.986
77863	439.289	69033	242.457	77055	114.365	66456	-83.562
77864	433.752	69034	232.022	77056	112.940	66457	-85.760
77865	441.248	69035	233.950	77057	122.130	66458	-82.944
77866	458.529	69036	234.718	77058	120.089	66459	-67.015
77867	463.945	69037	234.137	77059	119.522	66460	-64.395
77868	467.257	69038	232.919	77060	116.437	66461	-62.284
77869	464.040	69039	236.466	77061	115.050	66462	-70.785
77870	464.018	69040	233.671	77062	116.574	66463	-75.712
77871	457.697	69041	244.734	77063	111.810	66464	-68.784
77872	460.647	69042	256.853	77064	109.406	66465	-82.230
77873	454.556	69043	265.567	77065	108.249	66466	-76.749
77874	449.177	69044	276.785	77066	109.299	66467	-58.135

77875	445.769
77876	458.386
77877	453.146
77878	441.247
77879	440.230
77880	427.314
77881	422.869
77882	437.157
77883	421.923
77884	424.032
77885	411.116
77886	405.430
77887	369.791
77888	436.725
77889	434.753
77890	425.197
77891	427.645
77892	413.062
77893	414.923
77894	404.836
77895	391.004
77896	388.250
77897	372.979
77898	356.934
77899	351.323
77900	337.117
77901	362.457
77902	386.563
77903	392.700
77904	395.727

69045	249.962
69046	247.237
69047	271.559
69048	266.017
69049	247.955
69050	246.258
69051	262.447
69052	260.143
69053	259.156
69054	269.935
69055	270.883
69056	268.281
69057	272.509
69058	273.255
69059	230.465
69060	236.159
69061	229.118
69062	234.506
69063	228.671
69064	228.575
69065	233.195
69066	228.302
69067	228.137
69068	234.706
69069	229.938
69070	234.923
69071	228.426
69072	229.006
69073	229.930
69074	240.489

77067	107.164
77068	106.213
77069	108.776
77070	106.545
77071	107.920
77072	105.508
77073	104.963
77074	106.271
77075	104.548
77076	104.213
77077	105.823
77078	104.804
77079	105.798
77080	107.191
77081	106.853
77082	107.858
77083	108.794
77084	108.403
77085	110.128
77086	111.482
77087	112.741
77088	115.304
77089	115.746
77090	114.911
77091	112.707
77092	114.235
77093	114.425
77094	116.653
77095	117.948
77096	120.040

66468	-54.635
66469	-63.440
66470	-60.099
66471	-67.765
66472	-73.480
66473	-78.147
66474	-93.505
66475	-100.005
66476	-87.837
66477	-83.536
66478	-99.622
66479	-95.943
66480	-105.086
66481	-110.838
66482	-108.136
66483	-105.016
66484	-83.463
66485	-112.290
66486	-113.047
66487	-110.270
66488	-107.993
66489	-107.280
66490	-104.107
66491	-102.541
66492	-101.796
66493	-98.654
66494	-96.529
66495	-95.485
66496	-92.154
66497	-90.367

77905	404.811	69075	235.495	77097	119.065	66498	-90.348
77906	431.887	69076	238.025	77098	116.673	66499	-87.863
77907	411.502	69077	243.483	77099	119.283	66500	-84.732
77908	418.589	69078	238.392	77100	118.594	66501	-83.759
77909	425.286	69079	239.327	77101	116.285	66502	-80.107
77910	435.027	69080	249.341	77102	119.064	66503	-78.822
77911	435.931	69081	244.880	77103	119.227	66504	-77.314
77912	441.711	69082	252.535	77104	115.723	66505	-73.252
77913	447.467	69083	253.649	77105	118.715	66506	-75.078
77914	442.734	69084	261.757	77106	115.691	66507	-71.792
77915	446.222	69085	266.164	77107	119.584	66508	-68.968
77916	447.908	69086	268.811	77108	119.806	66509	-69.946
77917	449.199	69087	274.944	77109	117.801	66510	-66.609
77918	451.224	69088	281.156	77110	121.323	66511	-64.454
77919	456.585	69089	277.921	77111	122.307	66512	-65.947
77920	459.335	69090	272.632	77112	119.896	66513	-62.906
77921	454.568	69091	277.771	77113	122.705	66514	-60.641
77922	453.723	69092	276.207	77114	123.884	66515	-63.277
77923	457.595	69093	270.215	77115	121.030	66516	-59.532
77924	454.836	69094	274.285	77116	124.731	66517	-59.993
77925	453.151	69095	269.509	77117	126.131	66518	-57.241
77926	460.626	69096	275.323	77118	123.312	66519	-55.246
77927	461.015	69097	275.102	77119	127.205	66520	-56.414
77928	462.629	69098	270.203	77120	128.358	66521	-53.527
77929	467.343	69099	274.422	77121	124.692	66522	-51.315
77930	465.308	69100	274.724	77122	121.450	66523	-54.843
77931	467.907	69101	266.295	77123	121.910	66524	-57.336
77932	469.682	69102	270.903	77124	118.720	66525	-57.737
77933	466.032	69103	263.659	77125	117.124	66526	-61.441
77934	469.153	69104	272.474	77126	116.695	66527	-64.077

77935	464.762	69105	274.096	77127	114.014	66528	-65.397
77936	469.718	69106	274.953	77128	112.890	66529	-69.552
77937	468.098	69107	268.820	77129	114.642	66530	-70.526
77938	460.586	69108	277.721	77130	112.269	66531	-72.475
77939	463.857	69109	278.896	77131	111.314	66532	-75.936
77940	462.459	69110	273.963	77132	111.815	66533	-74.897
77941	455.448	69111	281.615	77133	113.629	66534	-78.915
77942	459.666	69112	282.725	77134	110.993	66535	-80.821
77943	454.911	69113	274.107	77135	110.153	66536	-82.035
77944	448.116	69114	271.078	77136	111.308	66537	-86.040
77945	449.342	69115	268.437	77137	108.197	66538	-83.638
77946	440.565	69116	261.230	77138	107.673	66539	-88.261
77947	448.117	69117	264.077	77139	107.904	66540	-89.606
77948	443.210	69118	255.549	77140	110.492	66541	-92.566
77949	433.367	69119	250.517	77141	108.742	66542	-97.339
77950	431.733	69120	249.292	77142	109.638	66543	-100.236
77951	425.419	69121	241.392	77143	111.414	66544	-101.780
77952	413.649	69122	239.705	77144	110.200	66545	-106.385
77953	416.595	69123	239.381	77145	110.740	66546	-112.517
77954	416.411	69124	247.408	77146	113.616	66547	-110.898
77955	399.157	69125	242.347	77147	114.487	66548	-107.058
77956	429.763	69126	240.990	77148	113.798	66549	-112.108
77957	424.313	69127	242.972	77149	112.870	66550	-112.197
77958	421.404	69128	248.425	77150	112.477	66551	-109.518
77959	441.603	69129	241.668	77151	113.182	66552	-113.481
77960	446.462	69130	240.098	77152	114.814	66553	-106.435
77961	450.074	69131	247.321	77153	116.453	66554	-103.600
77962	457.833	69132	256.167	77154	116.408	66555	-102.487
77963	453.699	69133	254.784	77155	117.103	66556	-99.445
77964	459.196	69134	254.975	77156	117.960	66557	-96.256

77965	462.242
77966	464.761
77967	462.229
77968	460.766
77969	458.962
77970	456.737
77971	447.992
77972	445.292
77973	438.057
77974	431.369

69135	260.854
69136	254.087
69137	249.426
69138	259.204
69139	264.098
69140	263.303
69141	265.488
69142	265.321
69143	264.785
69144	257.785
69145	260.322
69146	257.458
69147	268.684
69148	253.271

77157	116.412
77158	120.482

66558	-91.879
66559	-97.389
66560	-90.369
66561	-87.057
66562	-84.128
66563	-79.826
66564	-79.287
66565	-75.739
66566	-72.354
66567	-71.934
66568	-69.366
66569	-66.937
66570	-67.995
66571	-65.652
66572	-66.307
66573	-62.946
66574	-60.609
66575	-61.674
66576	-59.258
66577	-65.646
66578	-68.043
66579	-72.154
66580	-75.069
66581	-76.889
66582	-80.645
66583	-102.720

SG 5_C	FEA

SG 6_C	FEA

SG 7_C	FEA

SG 8_C	FEA

620.48N	Strain Value
Number Nodes	193
Units	Micro m/m
Max	-233.55
Average	-297.65
Min	-384.22
Nodes ID	Min Principal
28114	-384.222
28115	-309.812
28139	-268.341
62753	-315.570
62754	-321.960
62755	-332.224
62756	-340.509
62757	-350.870
62758	-361.276
62759	-372.544
62760	-237.013
62761	-241.248
62762	-246.241
62763	-251.996
62764	-257.121
62765	-263.036
62766	-268.470
62767	-273.680
62768	-279.809

620.48N	Strain Value
Number Nodes	173
Units	Micro m/m
Max	-235.92
Average	-281.13
Min	-321.03
Nodes ID	Min Principal
27920	-271.122
27929	-280.596
27945	-321.030
62531	-238.484
62532	-240.997
62533	-243.964
62534	-246.158
62535	-249.454
62536	-251.763
62537	-254.356
62538	-256.197
62539	-258.778
62540	-260.725
62541	-262.937
62542	-264.619
62543	-266.634
62544	-268.212
62545	-269.943
62546	-235.922

620.48N	Strain Value
Number Nodes	177
Units	Micro m/m
Max	-62.29
Average	-118.66
Min	-168.85
Nodes ID	Min Principal
26645	-152.233
26654	-85.744
26670	-168.854
61257	-67.363
61258	-73.185
61259	-78.593
61260	-84.593
61261	-90.046
61262	-95.684
61263	-101.635
61264	-107.229
61265	-113.064
61266	-118.929
61267	-124.494
61268	-130.238
61269	-135.864
61270	-141.243
61271	-146.597
61272	-62.289

620.48N	Strain Value
Number Nodes	177
Units	Micro m/m
Max	61.57
Average	50.80
Min	43.05
Nodes ID	Max Principal
26272	47.409
26281	61.568
26297	43.054
60892	56.813
60893	56.006
60894	55.150
60895	54.279
60896	53.527
60897	52.744
60898	52.196
60899	51.606
60900	50.957
60901	50.235
60902	49.773
60903	49.167
60904	48.788
60905	48.269
60906	47.784
60907	57.593

62769	-285.111	62547	-275.900	61273	-83.075	60908	60.282
62770	-290.771	62548	-270.779	61274	-80.577	60909	59.328
62771	-295.535	62549	-265.062	61275	-78.097	60910	58.953
62772	-299.174	62550	-259.726	61276	-75.397	60911	58.052
62773	-302.077	62551	-254.576	61277	-71.966	60912	57.496
62774	-305.101	62552	-248.835	61278	-69.074	60913	57.354
62775	-233.549	62553	-242.467	61279	-65.830	60914	57.477
62776	-265.184	62554	-320.077	61280	-163.970	60915	44.038
62777	-261.691	62555	-318.070	61281	-159.349	60916	44.860
62778	-257.029	62556	-316.159	61282	-155.032	60917	45.913
62779	-252.627	62557	-314.556	61283	-149.769	60918	46.832
62780	-247.740	62558	-312.206	61284	-144.732	60919	48.090
62781	-243.369	62559	-309.720	61285	-140.048	60920	48.960
62782	-238.289	62560	-307.669	61286	-134.167	60921	50.230
62783	-379.861	62561	-304.938	61287	-128.559	60922	51.293
62784	-375.284	62562	-302.256	61288	-123.906	60923	52.440
62785	-368.883	62563	-298.862	61289	-117.953	60924	53.616
62786	-362.490	62564	-295.989	61290	-113.095	60925	54.940
62787	-355.771	62565	-292.891	61291	-107.397	60926	56.182
62788	-347.265	62566	-290.331	61292	-102.147	60927	57.693
62789	-338.890	62567	-287.129	61293	-96.338	60928	58.715
62790	-331.042	62568	-284.052	61294	-91.494	60929	60.409
62791	-322.058	62569	-278.645	61295	-154.705	60930	46.701
62792	-313.042	62570	-285.540	61296	-157.264	60931	46.062
62793	-304.285	62571	-292.757	61297	-159.731	60932	45.530
62794	-296.168	62572	-298.841	61298	-162.048	60933	45.027
62795	-288.084	62573	-305.031	61299	-163.984	60934	44.617
62796	-280.398	62574	-310.964	61300	-166.094	60935	44.101
62797	-274.184	62575	-315.865	61301	-167.653	60936	43.618
77701	-289.549	76574	-281.182	61302	-98.957	60937	46.457

77702	-298.092
77703	-296.040
77704	-306.744
77705	-283.119
77706	-289.199
77707	-268.654
77708	-280.520
77709	-287.720
77710	-304.672
77711	-286.128
77712	-290.627
77713	-313.809
77714	-306.724
77715	-322.802
77716	-323.490
77717	-330.410
77718	-338.580
77719	-322.397
77720	-335.012
77721	-245.961
77722	-252.497
77723	-265.372
77724	-271.978
77725	-246.673
77726	-253.795
77727	-266.967
77728	-272.028
77729	-258.206
77730	-281.349
77731	-287.732

76575	-274.713
76576	-271.558
76577	-278.894
76578	-277.830
76579	-271.205
76580	-266.364
76581	-259.714
76582	-249.260
76583	-278.807
76584	-283.708
76585	-285.748
76586	-287.752
76587	-273.033
76588	-260.629
76589	-281.133
76590	-266.428
76591	-293.789
76592	-299.584
76593	-299.856
76594	-304.967
76595	-288.550
76596	-272.164
76597	-293.822
76598	-277.348
76599	-306.533
76600	-308.970
76601	-295.984
76602	-279.961
76603	-248.905
76604	-242.403

61303	-98.867
61304	-90.821
61305	-95.171
61306	-110.482
61307	-116.241
61308	-108.230
61309	-117.947
61310	-94.937
61311	-85.511
61312	-87.474
61313	-81.506
61314	-76.376
61315	-78.478
61316	-82.404
61317	-88.973
61318	-87.895
61319	-99.823
61320	-102.895
61321	-103.010
61322	-113.161
61323	-117.711
61324	-122.758
61325	-126.098
61326	-134.954
61327	-121.210
61328	-133.387
61329	-132.994
61330	-139.592
61331	-144.045
61332	-148.207

60938	47.304
60939	47.286
60940	47.643
60941	49.054
60942	49.581
60943	48.194
60944	49.020
60945	47.745
60946	48.291
60947	46.820
60948	48.465
60949	44.645
60950	45.244
60951	48.130
60952	49.470
60953	46.316
60954	49.163
60955	56.350
60956	58.129
60957	53.816
60958	51.322
60959	53.291
60960	55.795
60961	55.428
60962	45.985
60963	46.695
60964	47.394
60965	47.563
60966	49.096
60967	47.983

77732	-299.158	76605	-245.314	61333	-142.913	60968	50.144
77733	-278.597	76606	-248.200	61334	-150.584	60969	51.755
77734	-287.349	76607	-255.192	61335	-153.507	60970	50.805
77735	-301.787	76608	-253.793	61336	-155.912	60971	52.982
77736	-304.949	76609	-256.441	61337	-161.931	60972	54.354
77737	-314.967	76610	-263.711	61338	-72.517	60973	56.480
77738	-323.813	76611	-259.101	61339	-69.193	60974	56.471
77739	-315.582	76612	-261.776	61340	-74.920	60975	55.626
77740	-324.007	76613	-269.630	61341	-79.903	60976	54.907
77741	-339.399	76614	-264.221	61342	-81.996	60977	55.151
77742	-349.718	76615	-266.525	61343	-86.949	60978	54.336
77743	-339.467	76616	-275.132	61344	-95.659	60979	53.702
77744	-356.438	76617	-269.292	61345	-89.803	60980	53.566
77745	-359.520	76618	-270.913	61346	-94.882	60981	52.880
77746	-274.911	76619	-278.736	61347	-103.005	60982	52.403
77747	-312.113	76620	-272.336	61348	-99.755	60983	52.076
77748	-313.590	76621	-273.999	61349	-105.007	60984	51.293
77749	-322.758	76622	-276.071	61350	-108.023	60985	51.732
77750	-332.376	76623	-283.148	61351	-110.095	60986	51.167
77751	-331.712	76624	-288.603	61352	-115.480	60987	50.516
77752	-340.667	76625	-290.806	61353	-112.720	60988	49.889
77753	-349.484	76626	-297.533	61354	-118.537	60989	49.715
77754	-349.628	76627	-302.460	61355	-122.091	60990	48.446
77755	-360.635	76628	-304.031	61356	-122.468	60991	48.932
77756	-371.751	76629	-310.164	61357	-128.445	60992	48.367
77757	-367.634	76630	-315.415	61358	-131.038	60993	47.729
77758	-358.045	76631	-313.574	61359	-132.496	60994	48.509
77759	-365.551	76632	-307.742	61360	-138.253	60995	48.101
77760	-353.421	76633	-312.369	61361	-138.690	60996	47.589
77761	-362.627	76634	-310.593	61362	-142.427	60997	47.759

77762	-356.366	76635	-305.898	61363	-147.015	60998	46.716
77763	-344.711	76636	-310.073	61364	-145.762	60999	47.121
77764	-351.083	76637	-307.015	61365	-151.405	61000	46.862
77765	-343.170	76638	-302.468	61366	-154.065	61001	46.423
77766	-327.264	76639	-304.908	61367	-153.578	61002	45.839
77767	-329.776	76640	-299.793	61368	-156.645	61003	46.340
77768	-315.367	76641	-305.068	61369	-158.949	61004	45.546
77769	-306.666	76642	-301.845	61370	-154.836	61005	45.096
77770	-314.736	76643	-296.778	61371	-157.731	61006	45.560
77771	-306.040	76644	-299.241	61372	-158.043	61007	44.726
77772	-293.408	76645	-296.605	61373	-161.774	61008	44.956
77773	-300.092	76646	-290.866	61374	-164.127	61009	44.442
77774	-291.757	76647	-293.143	61375	-165.589	61010	43.875
77775	-279.889	76648	-286.814	61376	-160.571	61011	44.676
77776	-283.936	76649	-292.650	61377	-156.304	61012	45.385
77777	-273.328	76650	-289.127	61378	-150.585	61013	45.532
77778	-285.143	76651	-284.772	61379	-153.717	61014	46.553
77779	-277.641	76652	-288.617	61380	-148.987	61015	47.201
77780	-271.690	76653	-285.428	61381	-143.831	61016	47.407
77781	-268.228	76654	-281.311	61382	-143.758	61017	48.534
77782	-266.848	76655	-282.993	61383	-139.799	61018	48.831
77783	-262.273	76656	-278.335	61384	-136.291	61019	49.177
77784	-269.314	76657	-282.440	61385	-136.152	61020	50.482
77785	-259.580	76658	-279.210	61386	-131.053	61021	50.399
77786	-260.097	76659	-274.530	61387	-127.459	61022	51.203
77787	-253.269	76660	-274.472	61388	-124.960	61023	52.446
77788	-248.133	76661	-271.143	61389	-121.608	61024	52.586
77789	-249.972	76662	-265.600	61390	-112.242	61025	53.708
77790	-244.942	76663	-268.751	61391	-113.845	61026	55.164
77791	-239.699	76664	-263.013	61392	-106.332	61027	55.120

77792	-246.355	76665	-263.181	61393	-101.308	61028	56.091
77793	-239.329	76666	-259.482	61394	-103.994	61029	57.515
77794	-243.596	76667	-254.019	61395	-98.319	61030	57.265
77795	-249.231	76668	-254.493	61396	-94.657	61031	58.391
77796	-246.834	76669	-260.209	61397	-92.597	61032	59.747
77797	-251.873	76670	-266.530	61398	-87.795	61033	58.549
77798	-258.909	76671	-266.957	61399	-84.943	61034	58.112
77799	-258.819	76672	-268.526	61400	-85.721	61035	56.920
77800	-263.682	76673	-276.439	61401	-81.649	61036	56.979
77801	-268.559	76674	-274.173	61402	-78.824	61037	56.605
77802	-267.409	76675	-276.859	61403	-80.419	61038	55.451
77803	-275.284	76676	-285.522	61404	-76.906	61039	54.604
77804	-270.757	76677	-281.102	61405	-73.791	61040	54.431
77805	-276.028	76678	-282.900	61406	-77.315	61041	53.868
77806	-282.970	76679	-291.264	61407	-83.000	61042	53.005
77807	-280.757	76680	-285.665	61408	-85.106	61043	52.437
77808	-286.204	76681	-287.115	61409	-88.671	61044	52.307
77809	-294.609	76682	-295.420	61410	-94.001	61045	51.428
77810	-293.341	76683	-300.433	61411	-117.212	61046	50.648
77811	-303.467	76684	-301.506	61412	-107.912	61047	50.963
77812	-295.150	76685	-299.654	61413	-122.251	61048	50.525
77813	-299.901	76686	-297.037	61414	-117.703	61049	49.656
77814	-309.631	76687	-294.113	61415	-120.254	61050	49.632
77815	-304.996	76688	-294.123	61416	-124.360	61051	49.149
77816	-308.920	76689	-291.193	61417	-127.964	61052	47.883
77817	-319.899	76690	-287.698	61418	-130.092	61053	47.638
77818	-327.013	76691	-284.528	61419	-134.496	61054	46.852
77819	-319.455	76692	-282.111	61420	-138.301	61055	46.418
77820	-332.129	76693	-279.377	61421	-138.816	61056	46.822
77821	-337.401	76694	-278.330	61422	-143.595	61057	47.132

77822	-344.393
77823	-347.833
77824	-331.502
77825	-319.498
77826	-312.812
77827	-309.131
77828	-298.141
77829	-293.657
77830	-280.036
77831	-297.827
77832	-288.269
77833	-272.299
77834	-279.335
77835	-273.174
77836	-262.423
77837	-277.309
77838	-255.972
77839	-252.282
77840	-252.107
77841	-255.381
77842	-261.996
77843	-273.035
77844	-276.654
77845	-314.126

76695	-276.024
76696	-271.974
76697	-274.978
76698	-269.606

61423	-148.566
61424	-148.223
61425	-151.820
61426	-146.303
61427	-141.684
61428	-136.668
61429	-132.955
61430	-127.459

61058	47.248
61059	45.735
61060	48.594
61061	49.283
61062	50.292
61063	53.324
61064	54.778
61065	56.100

6.4. FEA: D Data

SG 1_D 821.20N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	625.09
Average	569.81
Min	405.86
Nodes ID	Max Principal
34073	571.862
34089	593.651
34097	587.514
68971	552.411
68972	536.416
68973	518.442
68974	497.920
68975	476.093
68976	452.767
68977	428.697
68978	405.858
68979	602.453
68980	611.981
68981	616.660
68982	622.159
68983	623.248
68984	625.068

SG 2_D 821.20N	FEA Strain Value
Number Nodes	181
Units	Micro m/m
Max	382.32
Average	337.49
Min	295.63
Nodes ID	Max Principal
32105	323.463
32114	382.323
32130	382.157
66828	295.814
66829	295.796
66830	295.848
66831	295.787
66832	295.626
66833	296.108
66834	296.642
66835	297.427
66836	298.678
66837	300.305
66838	302.613
66839	305.259
66840	308.819
66841	312.916

SG 3_D 821.20N	FEA Strain Value
Number Nodes	169
Units	Micro m/m
Max	175.68
Average	151.94
Min	136.70
Nodes ID	Max Principal
31688	154.728
31689	143.075
31697	175.680
66394	141.550
66395	140.280
66396	138.967
66397	137.886
66398	137.020
66399	136.701
66400	136.799
66401	136.808
66402	137.685
66403	139.427
66404	140.637
66405	142.119
66406	144.722
66407	147.538

SG 4_D 821.20N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-63.62
Average	-110.76
Min	-156.38
Nodes ID	Min Principal
31476	-87.702
31485	-156.385
31501	-63.622
66165	-148.276
66166	-145.155
66167	-140.724
66168	-136.769
66169	-132.908
66170	-129.231
66171	-124.877
66172	-120.956
66173	-116.926
66174	-112.734
66175	-108.523
66176	-104.550
66177	-100.728
66178	-96.497

68985	625.092
68986	623.043
68987	618.717
68988	617.279
68989	611.314
68990	605.423
68991	598.063
68992	590.400
68993	580.462
68994	591.017
68995	593.794
68996	596.793
68997	596.782
68998	596.152
68999	597.191
69000	595.859
69001	421.524
69002	440.404
69003	455.387
69004	470.515
69005	484.098
69006	498.212
69007	511.068
69008	523.596
69009	535.644
69010	547.287
69011	555.737
69012	564.686
69013	570.794
69014	577.430

66842	317.940
66843	295.707
66844	370.324
66845	359.173
66846	347.611
66847	336.240
66848	325.473
66849	314.868
66850	304.972
66851	377.831
66852	374.592
66853	372.514
66854	371.287
66855	370.068
66856	369.573
66857	369.902
66858	370.965
66859	371.702
66860	373.101
66861	374.306
66862	375.849
66863	377.499
66864	379.391
66865	380.953
66866	329.733
66867	337.165
66868	344.197
66869	351.565
66870	358.554
66871	366.177

66408	151.332
66409	170.564
66410	165.701
66411	161.523
66412	157.228
66413	153.343
66414	149.874
66415	146.552
66416	161.922
66417	161.533
66418	160.977
66419	160.430
66420	161.027
66421	161.777
66422	162.833
66423	163.625
66424	164.510
66425	165.744
66426	167.228
66427	168.731
66428	170.417
66429	171.630
66430	173.450
66431	162.927
66432	154.542
66433	154.022
66434	153.626
66435	154.185
66436	155.496
66437	157.136

66179	-91.829
66180	-152.732
66181	-156.243
66182	-155.815
66183	-155.531
66184	-154.136
66185	-154.008
66186	-154.454
66187	-153.224
66188	-68.116
66189	-73.135
66190	-78.238
66191	-83.356
66192	-89.051
66193	-94.654
66194	-100.260
66195	-106.190
66196	-111.864
66197	-117.898
66198	-123.858
66199	-130.968
66200	-136.551
66201	-143.247
66202	-149.107
66203	-84.602
66204	-80.932
66205	-78.313
66206	-75.685
66207	-72.412
66208	-69.461

69015	581.317	66872	374.329	66438	160.098	66209	-66.421
77846	537.206	69016	310.718	77038	143.642	66439	-113.522
77847	510.209	69017	321.396	77039	144.308	66440	-121.833
77848	546.317	69018	314.476	77040	141.788	66441	-113.698
77849	533.339	69019	322.835	77041	144.667	66442	-117.634
77850	501.027	69020	320.927	77042	150.679	66443	-112.582
77851	527.796	69021	333.197	77043	139.759	66444	-115.880
77852	490.347	69022	340.160	77044	141.041	66445	-118.489
77853	505.136	69023	327.262	77045	143.423	66446	-114.498
77854	606.883	69024	336.418	77046	144.984	66447	-139.282
77855	603.928	69025	336.793	77047	147.251	66448	-133.775
77856	600.487	69026	328.785	77048	148.571	66449	-131.025
77857	599.578	69027	327.321	77049	154.215	66450	-137.316
77858	549.211	69028	342.141	77050	154.676	66451	-114.806
77859	540.162	69029	332.590	77051	146.203	66452	-117.641
77860	517.180	69030	343.826	77052	152.310	66453	-123.474
77861	531.811	69031	332.239	77053	157.476	66454	-125.277
77862	590.782	69032	320.215	77054	164.904	66455	-105.861
77863	581.395	69033	320.891	77055	151.361	66456	-110.594
77864	574.067	69034	307.079	77056	149.476	66457	-113.503
77865	583.989	69035	309.631	77057	161.638	66458	-109.776
77866	606.860	69036	310.647	77058	158.936	66459	-88.694
77867	614.027	69037	309.878	77059	158.186	66460	-85.226
77868	618.411	69038	308.266	77060	154.104	66461	-82.432
77869	614.154	69039	312.961	77061	152.267	66462	-93.684
77870	614.124	69040	309.262	77062	154.285	66463	-100.204
77871	605.758	69041	323.903	77063	147.979	66464	-91.034
77872	609.663	69042	339.942	77064	144.798	66465	-108.831
77873	601.602	69043	351.476	77065	143.266	66466	-101.577
77874	594.483	69044	366.323	77066	144.657	66467	-76.941

77875	589.972
77876	606.671
77877	599.735
77878	583.987
77879	582.642
77880	565.547
77881	559.664
77882	578.574
77883	558.411
77884	561.203
77885	544.108
77886	536.583
77887	489.415
77888	578.002
77889	575.393
77890	562.745
77891	565.985
77892	546.684
77893	549.147
77894	535.798
77895	517.491
77896	513.846
77897	493.635
77898	472.399
77899	464.973
77900	446.172
77901	479.710
77902	511.613
77903	519.735
77904	523.742

69045	330.823
69046	327.216
69047	359.406
69048	352.072
69049	328.167
69050	325.921
69051	347.346
69052	344.297
69053	342.990
69054	357.257
69055	358.512
69056	355.068
69057	360.663
69058	361.651
69059	305.019
69060	312.554
69061	303.236
69062	310.366
69063	302.645
69064	302.517
69065	308.631
69066	302.156
69067	301.938
69068	310.632
69069	304.321
69070	310.918
69071	302.321
69072	303.088
69073	304.311
69074	318.285

77067	141.831
77068	140.573
77069	143.964
77070	141.011
77071	142.831
77072	139.639
77073	138.917
77074	140.649
77075	138.369
77076	137.925
77077	140.056
77078	138.708
77079	140.022
77080	141.867
77081	141.419
77082	142.749
77083	143.987
77084	143.470
77085	145.753
77086	147.545
77087	149.212
77088	152.604
77089	153.188
77090	152.083
77091	149.167
77092	151.189
77093	151.440
77094	154.390
77095	156.103
77096	158.871

66468	-72.308
66469	-83.963
66470	-79.540
66471	-89.686
66472	-97.251
66473	-103.428
66474	-123.753
66475	-132.356
66476	-116.251
66477	-110.559
66478	-131.849
66479	-126.980
66480	-139.081
66481	-146.693
66482	-143.117
66483	-138.988
66484	-110.463
66485	-148.615
66486	-149.617
66487	-145.941
66488	-142.928
66489	-141.985
66490	-137.785
66491	-135.712
66492	-134.726
66493	-130.568
66494	-127.756
66495	-126.373
66496	-121.965
66497	-119.600

77905	535.765	69075	311.676	77097	157.582	66498	-119.575
77906	571.599	69076	315.024	77098	154.416	66499	-116.287
77907	544.619	69077	322.248	77099	157.870	66500	-112.142
77908	553.999	69078	315.510	77100	156.959	66501	-110.854
77909	562.862	69079	316.747	77101	153.902	66502	-106.021
77910	575.755	69080	330.001	77102	157.580	66503	-104.320
77911	576.951	69081	324.097	77103	157.796	66504	-102.324
77912	584.601	69082	334.228	77104	153.158	66505	-96.948
77913	592.219	69083	335.703	77105	157.118	66506	-99.365
77914	585.955	69084	346.434	77106	153.117	66507	-95.016
77915	590.571	69085	352.266	77107	158.268	66508	-91.279
77916	592.803	69086	355.770	77108	158.562	66509	-92.573
77917	594.511	69087	363.887	77109	155.908	66510	-88.157
77918	597.192	69088	372.108	77110	160.570	66511	-85.304
77919	604.287	69089	367.827	77111	161.872	66512	-87.280
77920	607.927	69090	360.827	77112	158.682	66513	-83.255
77921	601.617	69091	367.627	77113	162.399	66514	-80.257
77922	600.499	69092	365.559	77114	163.960	66515	-83.747
77923	605.624	69093	357.628	77115	160.182	66516	-78.790
77924	601.972	69094	363.014	77116	165.081	66517	-79.400
77925	599.741	69095	356.693	77117	166.934	66518	-75.758
77926	609.635	69096	364.389	77118	163.203	66519	-73.117
77927	610.150	69097	364.095	77119	168.355	66520	-74.663
77928	612.286	69098	357.612	77120	169.881	66521	-70.843
77929	618.526	69099	363.195	77121	165.028	66522	-67.914
77930	615.832	69100	363.595	77122	160.738	66523	-72.584
77931	619.271	69101	352.440	77123	161.347	66524	-75.883
77932	621.620	69102	358.538	77124	157.125	66525	-76.414
77933	616.789	69103	348.951	77125	155.012	66526	-81.317
77934	620.920	69104	360.617	77126	154.445	66527	-84.806

77935	615.108
77936	621.668
77937	619.525
77938	609.583
77939	613.911
77940	612.061
77941	602.782
77942	608.365
77943	602.071
77944	593.078
77945	594.700
77946	583.085
77947	593.079
77948	586.586
77949	573.558
77950	571.396
77951	563.039
77952	547.462
77953	551.360
77954	551.116
77955	528.282
77956	568.788
77957	561.576
77958	557.725
77959	584.459
77960	590.890
77961	595.669
77962	605.939
77963	600.467
77964	607.743

69105	362.763
69106	363.899
69107	355.781
69108	367.562
69109	369.117
69110	362.589
69111	372.715
69112	374.185
69113	362.778
69114	358.770
69115	355.274
69116	345.735
69117	349.504
69118	338.217
69119	331.557
69120	329.936
69121	319.480
69122	317.248
69123	316.819
69124	327.442
69125	320.745
69126	318.948
69127	321.572
69128	328.789
69129	319.846
69130	317.768
69131	327.328
69132	339.035
69133	337.205
69134	337.458

77127	150.896
77128	149.409
77129	151.728
77130	148.588
77131	147.323
77132	147.987
77133	150.388
77134	146.899
77135	145.787
77136	147.316
77137	143.198
77138	142.504
77139	142.810
77140	146.235
77141	143.919
77142	145.105
77143	147.456
77144	145.849
77145	146.564
77146	150.370
77147	151.523
77148	150.611
77149	149.383
77150	148.863
77151	149.795
77152	151.956
77153	154.124
77154	154.065
77155	154.985
77156	156.120

66528	-86.552
66529	-92.051
66530	-93.341
66531	-95.920
66532	-100.501
66533	-99.125
66534	-104.444
66535	-106.966
66536	-108.573
66537	-113.873
66538	-110.694
66539	-116.813
66540	-118.593
66541	-122.511
66542	-128.827
66543	-132.661
66544	-134.705
66545	-140.799
66546	-148.915
66547	-146.772
66548	-141.691
66549	-148.374
66550	-148.492
66551	-144.946
66552	-150.191
66553	-140.866
66554	-137.114
66555	-135.641
66556	-131.614
66557	-127.394

77965	611.774
77966	615.107
77967	611.756
77968	609.820
77969	607.433
77970	604.488
77971	592.914
77972	589.341
77973	579.765
77974	570.914

69135	345.238
69136	336.282
69137	330.114
69138	343.054
69139	349.531
69140	348.480
69141	351.371
69142	351.151
69143	350.441
69144	341.177
69145	344.534
69146	340.744
69147	355.601
69148	335.202

77157	154.070
77158	159.458

66558	-121.601
66559	-128.894
66560	-119.602
66561	-115.219
66562	-111.343
66563	-105.649
66564	-104.936
66565	-100.239
66566	-95.760
66567	-95.204
66568	-91.806
66569	-88.591
66570	-89.992
66571	-86.890
66572	-87.757
66573	-83.308
66574	-80.215
66575	-81.626
66576	-78.428
66577	-86.883
66578	-90.054
66579	-95.495
66580	-99.353
66581	-101.762
66582	-106.733
66583	-135.949

SG 5_D 821.20N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-309.10
Average	-393.93
Min	-508.51
Nodes ID	Min Principal
28114	-508.514
28115	-410.034
28139	-355.147
62753	-417.655
62754	-426.111
62755	-439.696
62756	-450.662
62757	-464.374
62758	-478.146
62759	-493.059
62760	-313.685
62761	-319.290
62762	-325.899
62763	-333.515
62764	-340.298
62765	-348.126
62766	-355.318
62767	-362.213

SG 6_D 821.20N	FEA Strain Value
Number Nodes	173
Units	Micro m/m
Max	-312.24
Average	-372.07
Min	-424.88
Nodes ID	Min Principal
27920	-358.828
27929	-371.366
27945	-424.880
62531	-315.632
62532	-318.957
62533	-322.884
62534	-325.789
62535	-330.151
62536	-333.206
62537	-336.639
62538	-339.075
62539	-342.490
62540	-345.068
62541	-347.994
62542	-350.221
62543	-352.888
62544	-354.976
62545	-357.267

SG 7 821.20N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	-82.44
Average	-157.05
Min	-223.48
Nodes ID	Min Principal
26645	-201.480
26654	-113.482
26670	-223.477
61257	-89.154
61258	-96.860
61259	-104.017
61260	-111.958
61261	-119.176
61262	-126.637
61263	-134.513
61264	-141.916
61265	-149.640
61266	-157.401
61267	-164.767
61268	-172.369
61269	-179.815
61270	-186.934
61271	-194.020

SG 8_D 821.20N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	81.48
Average	67.23
Min	56.98
Nodes ID	Max Principal
26272	62.745
26281	81.485
26297	56.981
60892	75.192
60893	74.123
60894	72.991
60895	71.837
60896	70.843
60897	69.806
60898	69.081
60899	68.300
60900	67.442
60901	66.485
60902	65.874
60903	65.073
60904	64.570
60905	63.883
60906	63.241

62768	-370.326	62546	-312.241	61272	-82.439	60907	76.224
62769	-377.342	62547	-365.151	61273	-109.949	60908	79.782
62770	-384.833	62548	-358.374	61274	-106.643	60909	78.520
62771	-391.138	62549	-350.807	61275	-103.360	60910	78.024
62772	-395.954	62550	-343.746	61276	-99.788	60911	76.831
62773	-399.797	62551	-336.929	61277	-95.246	60912	76.096
62774	-403.798	62552	-329.332	61278	-91.419	60913	75.908
62775	-309.100	62553	-320.903	61279	-87.126	60914	76.071
62776	-350.969	62554	-423.619	61280	-217.014	60915	58.284
62777	-346.346	62555	-420.963	61281	-210.897	60916	59.372
62778	-340.176	62556	-418.434	61282	-205.184	60917	60.766
62779	-334.350	62557	-416.313	61283	-198.218	60918	61.982
62780	-327.881	62558	-413.203	61284	-191.551	60919	63.647
62781	-322.097	62559	-409.912	61285	-185.353	60920	64.798
62782	-315.374	62560	-407.197	61286	-177.570	60921	66.478
62783	-502.743	62561	-403.583	61287	-170.147	60922	67.886
62784	-496.686	62562	-400.033	61288	-163.989	60923	69.404
62785	-488.213	62563	-395.542	61289	-156.110	60924	70.960
62786	-479.753	62564	-391.739	61290	-149.681	60925	72.712
62787	-470.860	62565	-387.639	61291	-142.140	60926	74.356
62788	-459.602	62566	-384.251	61292	-135.191	60927	76.356
62789	-448.518	62567	-380.013	61293	-127.502	60928	77.709
62790	-438.131	62568	-375.941	61294	-121.092	60929	79.951
62791	-426.242	62569	-368.784	61295	-204.751	60930	61.808
62792	-414.309	62570	-377.910	61296	-208.137	60931	60.963
62793	-402.719	62571	-387.462	61297	-211.403	60932	60.258
62794	-391.976	62572	-395.513	61298	-214.469	60933	59.593
62795	-381.278	62573	-403.707	61299	-217.031	60934	59.050
62796	-371.105	62574	-411.559	61300	-219.824	60935	58.368
62797	-362.880	62575	-418.045	61301	-221.887	60936	57.728

77701	-383.216	76574	-372.143	61302	-130.969	60937	61.486
77702	-394.522	76575	-363.581	61303	-130.849	60938	62.607
77703	-391.807	76576	-359.405	61304	-120.201	60939	62.582
77704	-405.974	76577	-369.114	61305	-125.958	60940	63.055
77705	-374.706	76578	-367.706	61306	-146.222	60941	64.922
77706	-382.753	76579	-358.938	61307	-153.845	60942	65.620
77707	-355.562	76580	-352.531	61308	-143.242	60943	63.784
77708	-371.266	76581	-343.729	61309	-156.102	60944	64.877
77709	-380.795	76582	-329.893	61310	-125.649	60945	63.190
77710	-403.231	76583	-369.000	61311	-113.173	60946	63.913
77711	-378.688	76584	-375.485	61312	-115.771	60947	61.965
77712	-384.643	76585	-378.186	61313	-107.872	60948	64.143
77713	-415.324	76586	-380.838	61314	-101.083	60949	59.088
77714	-405.947	76587	-361.358	61315	-103.865	60950	59.880
77715	-427.227	76588	-344.941	61316	-109.061	60951	63.699
77716	-428.137	76589	-372.077	61317	-117.755	60952	65.473
77717	-437.295	76590	-352.616	61318	-116.328	60953	61.298
77718	-448.109	76591	-388.828	61319	-132.114	60954	65.067
77719	-426.690	76592	-396.497	61320	-136.181	60955	74.579
77720	-443.385	76593	-396.857	61321	-136.333	60956	76.933
77721	-325.527	76594	-403.622	61322	-149.768	60957	71.225
77722	-334.178	76595	-381.894	61323	-155.790	60958	67.924
77723	-351.218	76596	-360.207	61324	-162.470	60959	70.530
77724	-359.961	76597	-388.871	61325	-166.890	60960	73.845
77725	-326.470	76598	-367.068	61326	-178.610	60961	73.359
77726	-335.896	76599	-405.694	61327	-160.421	60962	60.861
77727	-353.329	76600	-408.919	61328	-176.536	60963	61.800
77728	-360.027	76601	-391.733	61329	-176.016	60964	62.725
77729	-341.733	76602	-370.526	61330	-184.748	60965	62.949
77730	-372.364	76603	-329.424	61331	-190.642	60966	64.979

77731	-380.811	76604	-320.819	61332	-196.151	60967	63.505
77732	-395.933	76605	-324.671	61333	-189.144	60968	66.365
77733	-368.720	76606	-328.491	61334	-199.297	60969	68.498
77734	-380.304	76607	-337.745	61335	-203.166	60970	67.240
77735	-399.413	76608	-335.893	61336	-206.348	60971	70.121
77736	-403.598	76609	-339.398	61337	-214.315	60972	71.937
77737	-416.857	76610	-349.019	61338	-95.976	60973	74.751
77738	-428.564	76611	-342.919	61339	-91.576	60974	74.739
77739	-417.671	76612	-346.458	61340	-99.156	60975	73.620
77740	-428.821	76613	-356.853	61341	-105.751	60976	72.669
77741	-449.192	76614	-349.695	61342	-108.521	60977	72.992
77742	-462.849	76615	-352.743	61343	-115.076	60978	71.914
77743	-449.282	76616	-364.135	61344	-126.604	60979	71.074
77744	-471.743	76617	-356.406	61345	-118.853	60980	70.894
77745	-475.823	76618	-358.551	61346	-125.576	60981	69.986
77746	-363.843	76619	-368.905	61347	-136.327	60982	69.355
77747	-413.079	76620	-360.434	61348	-132.024	60983	68.922
77748	-415.035	76621	-362.636	61349	-138.975	60984	67.887
77749	-427.167	76622	-365.378	61350	-142.968	60985	68.467
77750	-439.897	76623	-374.744	61351	-145.710	60986	67.719
77751	-439.018	76624	-381.963	61352	-152.837	60987	66.857
77752	-450.870	76625	-384.880	61353	-149.183	60988	66.028
77753	-462.540	76626	-393.782	61354	-156.883	60989	65.798
77754	-462.730	76627	-400.304	61355	-161.587	60990	64.117
77755	-477.297	76628	-402.382	61356	-162.085	60991	64.761
77756	-492.010	76629	-410.500	61357	-169.996	60992	64.014
77757	-486.561	76630	-417.449	61358	-173.428	60993	63.169
77758	-473.869	76631	-415.012	61359	-175.357	60994	64.201
77759	-483.804	76632	-407.294	61360	-182.976	60995	63.662
77760	-467.750	76633	-413.418	61361	-183.556	60996	62.983

77761	-479.934	76634	-411.067	61362	-188.501	60997	63.208
77762	-471.647	76635	-404.853	61363	-194.573	60998	61.829
77763	-456.222	76636	-410.379	61364	-192.915	60999	62.364
77764	-464.655	76637	-406.331	61365	-200.383	61000	62.021
77765	-454.183	76638	-400.314	61366	-203.903	61001	61.441
77766	-433.132	76639	-403.544	61367	-203.260	61002	60.667
77767	-436.456	76640	-396.774	61368	-207.318	61003	61.331
77768	-417.386	76641	-403.756	61369	-210.368	61004	60.279
77769	-405.870	76642	-399.490	61370	-204.924	61005	59.684
77770	-416.551	76643	-392.783	61371	-208.755	61006	60.298
77771	-405.041	76644	-396.043	61372	-209.169	61007	59.194
77772	-388.324	76645	-392.555	61373	-214.107	61008	59.499
77773	-397.169	76646	-384.959	61374	-217.221	61009	58.819
77774	-386.138	76647	-387.973	61375	-219.156	61010	58.069
77775	-370.431	76648	-379.596	61376	-212.514	61011	59.129
77776	-375.788	76649	-387.320	61377	-206.867	61012	60.067
77777	-361.748	76650	-382.657	61378	-199.298	61013	60.262
77778	-377.384	76651	-376.894	61379	-203.443	61014	61.613
77779	-367.456	76652	-381.982	61380	-197.184	61015	62.470
77780	-359.580	76653	-377.762	61381	-190.359	61016	62.743
77781	-354.998	76654	-372.313	61382	-190.263	61017	64.235
77782	-353.172	76655	-374.539	61383	-185.022	61018	64.627
77783	-347.117	76656	-368.374	61384	-180.380	61019	65.086
77784	-356.435	76657	-373.807	61385	-180.195	61020	66.813
77785	-343.553	76658	-369.532	61386	-173.448	61021	66.703
77786	-344.236	76659	-363.339	61387	-168.691	61022	67.767
77787	-335.200	76660	-363.262	61388	-165.384	61023	69.412
77788	-328.402	76661	-358.856	61389	-160.947	61024	69.597
77789	-330.837	76662	-351.519	61390	-148.552	61025	71.082
77790	-324.179	76663	-355.689	61391	-150.673	61026	73.009

77791	-317.240	76664	-348.096	61392	-140.730	61027	72.951
77792	-326.049	76665	-348.318	61393	-134.081	61028	74.236
77793	-316.751	76666	-343.423	61394	-137.636	61029	76.121
77794	-322.398	76667	-336.193	61395	-130.125	61030	75.790
77795	-329.856	76668	-336.820	61396	-125.278	61031	77.280
77796	-326.683	76669	-344.385	61397	-122.552	61032	79.075
77797	-333.353	76670	-352.750	61398	-116.196	61033	77.489
77798	-342.664	76671	-353.316	61399	-112.421	61034	76.910
77799	-342.545	76672	-355.392	61400	-113.451	61035	75.334
77800	-348.981	76673	-365.864	61401	-108.062	61036	75.411
77801	-355.435	76674	-362.866	61402	-104.322	61037	74.916
77802	-353.914	76675	-366.420	61403	-106.434	61038	73.389
77803	-364.336	76676	-377.886	61404	-101.784	61039	72.269
77804	-358.345	76677	-372.036	61405	-97.662	61040	72.038
77805	-365.321	76678	-374.416	61406	-102.326	61041	71.294
77806	-374.509	76679	-385.485	61407	-109.850	61042	70.151
77807	-371.580	76680	-378.076	61408	-112.637	61043	69.400
77808	-378.789	76681	-379.994	61409	-117.356	61044	69.228
77809	-389.913	76682	-390.987	61410	-124.409	61045	68.064
77810	-388.234	76683	-397.621	61411	-155.129	61046	67.032
77811	-401.636	76684	-399.041	61412	-142.821	61047	67.449
77812	-390.629	76685	-396.590	61413	-161.799	61048	66.869
77813	-396.916	76686	-393.126	61414	-155.779	61049	65.720
77814	-409.794	76687	-389.256	61415	-159.156	61050	65.688
77815	-403.660	76688	-389.269	61416	-164.590	61051	65.049
77816	-408.853	76689	-385.391	61417	-169.359	61052	63.372
77817	-423.384	76690	-380.766	61418	-172.176	61053	63.048
77818	-432.799	76691	-376.571	61419	-178.004	61054	62.009
77819	-422.797	76692	-373.372	61420	-183.040	61055	61.433
77820	-439.570	76693	-369.754	61421	-183.722	61056	61.969

77821	-446.548
77822	-455.801
77823	-460.354
77824	-438.740
77825	-422.853
77826	-414.004
77827	-409.132
77828	-394.588
77829	-388.652
77830	-370.626
77831	-394.172
77832	-381.522
77833	-360.386
77834	-369.698
77835	-361.544
77836	-347.314
77837	-367.016
77838	-338.777
77839	-333.894
77840	-333.661
77841	-337.995
77842	-346.750
77843	-361.360
77844	-366.150
77845	-415.743

76694	-368.368
76695	-365.316
76696	-359.955
76697	-363.931
76698	-356.822

61422	-190.046
61423	-196.626
61424	-196.172
61425	-200.932
61426	-193.631
61427	-187.518
61428	-180.879
61429	-175.965
61430	-168.691

61057	62.379
61058	62.533
61059	60.530
61060	64.313
61061	65.226
61062	66.561
61063	70.573
61064	72.498
61065	74.248

6.5. FEA: E Data

SG 1_E 1025.54N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	780.63
Average	711.60
Min	506.85
Nodes ID	Max Principal
34073	714.158
34089	741.370
34097	733.705
68971	689.868
68972	669.892
68973	647.446
68974	621.817
68975	594.559
68976	565.429
68977	535.370
68978	506.847
68979	752.362
68980	764.260
68981	770.103
68982	776.971
68983	778.331
68984	780.604

SG 2_E 1025.54N	FEA Strain Value
Number Nodes	181
Units	Micro m/m
Max	477.46
Average	421.47
Min	369.19
Nodes ID	Max Principal
32105	403.950
32114	477.456
32130	477.249
66828	369.421
66829	369.399
66830	369.463
66831	369.388
66832	369.187
66833	369.788
66834	370.456
66835	371.436
66836	372.998
66837	375.030
66838	377.913
66839	381.217
66840	385.663
66841	390.779

SG 3_E 1025.54N	FEA Strain Value
Number Nodes	169
Units	Micro m/m
Max	219.39
Average	189.75
Min	170.72
Nodes ID	Max Principal
31688	193.229
31689	178.676
31697	219.395
66394	176.771
66395	175.186
66396	173.547
66397	172.196
66398	171.115
66399	170.717
66400	170.838
66401	170.850
66402	171.945
66403	174.121
66404	175.632
66405	177.483
66406	180.733
66407	184.250

SG 4_E 1025.54N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-79.45
Average	-138.32
Min	-195.30
Nodes ID	Min Principal
31476	-109.524
31485	-195.298
31501	-79.453
66165	-185.171
66166	-181.274
66167	-175.740
66168	-170.801
66169	-165.980
66170	-161.387
66171	-155.950
66172	-151.053
66173	-146.021
66174	-140.785
66175	-135.527
66176	-130.566
66177	-125.792
66178	-120.508

68985	780.634	66842	397.052	66408	188.988	66179	-114.679
68986	778.075	66843	369.287	66409	213.005	66180	-190.736
68987	772.673	66844	462.472	66410	206.932	66181	-195.121
68988	770.876	66845	448.546	66411	201.715	66182	-194.587
68989	763.428	66846	434.107	66412	196.351	66183	-194.232
68990	756.071	66847	419.907	66413	191.499	66184	-192.490
68991	746.879	66848	406.460	66414	187.168	66185	-192.330
68992	737.310	66849	393.216	66415	183.018	66186	-192.886
68993	724.898	66850	380.858	66416	202.213	66187	-191.350
68994	738.079	66851	471.846	66417	201.727	66188	-85.065
68995	741.547	66852	467.802	66418	201.033	66189	-91.333
68996	745.293	66853	465.207	66419	200.350	66190	-97.707
68997	745.279	66854	463.674	66420	201.095	66191	-104.097
68998	744.493	66855	462.152	66421	202.032	66192	-111.209
68999	745.791	66856	461.533	66422	203.351	66193	-118.207
69000	744.126	66857	461.944	66423	204.340	66194	-125.208
69001	526.412	66858	463.273	66424	205.446	66195	-132.613
69002	549.989	66859	464.193	66425	206.986	66196	-139.700
69003	568.701	66860	465.940	66426	208.840	66197	-147.235
69004	587.593	66861	467.445	66427	210.716	66198	-154.677
69005	604.556	66862	469.372	66428	212.822	66199	-163.557
69006	622.182	66863	471.432	66429	214.337	66200	-170.530
69007	638.237	66864	473.794	66430	216.610	66201	-178.891
69008	653.883	66865	475.746	66431	203.468	66202	-186.210
69009	668.929	66866	411.781	66432	192.997	66203	-105.654
69010	683.468	66867	421.062	66433	192.347	66204	-101.071
69011	694.022	66868	429.844	66434	191.853	66205	-97.800
69012	705.197	66869	439.045	66435	192.551	66206	-94.518
69013	712.824	66870	447.773	66436	194.188	66207	-90.431
69014	721.112	66871	457.293	66437	196.236	66208	-86.745

69015	725.966	66872	467.473	66438	199.936	66209	-82.948
77846	670.879	69016	388.034	77038	179.384	66439	-141.770
77847	637.165	69017	401.369	77039	180.216	66440	-152.149
77848	682.257	69018	392.727	77040	177.069	66441	-141.990
77849	666.049	69019	403.166	77041	180.665	66442	-146.905
77850	625.697	69020	400.783	77042	188.172	66443	-140.596
77851	659.128	69021	416.107	77043	174.535	66444	-144.715
77852	612.360	69022	424.802	77044	176.136	66445	-147.973
77853	630.829	69023	408.695	77045	179.110	66446	-142.988
77854	757.894	69024	420.129	77046	181.060	66447	-173.939
77855	754.203	69025	420.597	77047	183.892	66448	-167.062
77856	749.906	69026	410.597	77048	185.540	66449	-163.628
77857	748.771	69027	408.769	77049	192.588	66450	-171.485
77858	685.871	69028	427.276	77050	193.164	66451	-143.373
77859	674.570	69029	415.348	77051	182.583	66452	-146.914
77860	645.870	69030	429.380	77052	190.210	66453	-154.198
77861	664.142	69031	414.910	77053	196.660	66454	-156.450
77862	737.787	69032	399.894	77054	205.938	66455	-132.203
77863	726.064	69033	400.738	77055	189.024	66456	-138.113
77864	716.913	69034	383.489	77056	186.670	66457	-141.746
77865	729.302	69035	386.676	77057	201.858	66458	-137.092
77866	757.865	69036	387.945	77058	198.484	66459	-110.764
77867	766.815	69037	386.985	77059	197.548	66460	-106.432
77868	772.291	69038	384.972	77060	192.450	66461	-102.943
77869	766.974	69039	390.836	77061	190.156	66462	-116.995
77870	766.936	69040	386.216	77062	192.675	66463	-125.137
77871	756.489	69041	404.500	77063	184.801	66464	-113.687
77872	761.366	69042	424.530	77064	180.829	66465	-135.911
77873	751.298	69043	438.934	77065	178.915	66466	-126.852
77874	742.408	69044	457.475	77066	180.652	66467	-96.086

77875	736.774	69045	413.142	77067	177.123	66468	-90.301
77876	757.629	69046	408.637	77068	175.551	66469	-104.855
77877	748.968	69047	448.837	77069	179.787	66470	-99.332
77878	729.301	69048	439.678	77070	176.099	66471	-112.002
77879	727.620	69049	409.825	77071	178.372	66472	-121.449
77880	706.272	69050	407.020	77072	174.385	66473	-129.163
77881	698.925	69051	433.776	77073	173.484	66474	-154.546
77882	722.541	69052	429.968	77074	175.647	66475	-165.291
77883	697.361	69053	428.337	77075	172.799	66476	-145.178
77884	700.847	69054	446.154	77076	172.245	66477	-138.070
77885	679.499	69055	447.720	77077	174.907	66478	-164.656
77886	670.102	69056	443.419	77078	173.222	66479	-158.576
77887	611.196	69057	450.407	77079	174.864	66480	-173.689
77888	721.826	69058	451.641	77080	177.167	66481	-183.194
77889	718.568	69059	380.917	77081	176.608	66482	-178.729
77890	702.773	69060	390.327	77082	178.270	66483	-173.573
77891	706.819	69061	378.690	77083	179.816	66484	-137.949
77892	682.715	69062	387.595	77084	179.170	66485	-185.595
77893	685.791	69063	377.952	77085	182.021	66486	-186.846
77894	669.121	69064	377.792	77086	184.259	66487	-182.256
77895	646.258	69065	385.428	77087	186.341	66488	-178.492
77896	641.707	69066	377.341	77088	190.576	66489	-177.315
77897	616.466	69067	377.069	77089	191.306	66490	-172.070
77898	589.946	69068	387.926	77090	189.926	66491	-169.481
77899	580.673	69069	380.045	77091	186.284	66492	-168.250
77900	557.193	69070	388.284	77092	188.810	66493	-163.057
77901	599.076	69071	377.547	77093	189.123	66494	-159.545
77902	638.918	69072	378.505	77094	192.807	66495	-157.819
77903	649.061	69073	380.033	77095	194.946	66496	-152.313
77904	654.065	69074	397.484	77096	198.403	66497	-149.360

77905	669.079	69075	389.231	77097	196.793	66498	-149.329
77906	713.830	69076	393.411	77098	192.840	66499	-145.222
77907	680.137	69077	402.433	77099	197.152	66500	-140.046
77908	691.851	69078	394.019	77100	196.015	66501	-138.438
77909	702.919	69079	395.564	77101	192.198	66502	-132.402
77910	719.020	69080	412.116	77102	196.791	66503	-130.278
77911	720.514	69081	404.742	77103	197.061	66504	-127.786
77912	730.067	69082	417.394	77104	191.268	66505	-121.071
77913	739.581	69083	419.236	77105	196.214	66506	-124.090
77914	731.759	69084	432.637	77106	191.217	66507	-118.659
77915	737.523	69085	439.921	77107	197.650	66508	-113.992
77916	740.310	69086	444.296	77108	198.017	66509	-115.608
77917	742.443	69087	454.433	77109	194.703	66510	-110.093
77918	745.791	69088	464.700	77110	200.525	66511	-106.531
77919	754.652	69089	459.353	77111	202.151	66512	-108.997
77920	759.197	69090	450.611	77112	198.167	66513	-103.972
77921	751.318	69091	459.104	77113	202.808	66514	-100.228
77922	749.921	69092	456.520	77114	204.758	66515	-104.586
77923	756.321	69093	446.616	77115	200.040	66516	-98.395
77924	751.761	69094	453.343	77116	206.158	66517	-99.158
77925	748.975	69095	445.449	77117	208.472	66518	-94.608
77926	761.330	69096	455.059	77118	203.812	66519	-91.311
77927	761.974	69097	454.693	77119	210.246	66520	-93.241
77928	764.642	69098	446.596	77120	212.152	66521	-88.471
77929	772.433	69099	453.569	77121	206.092	66522	-84.814
77930	769.070	69100	454.068	77122	200.735	66523	-90.645
77931	773.364	69101	440.138	77123	201.495	66524	-94.766
77932	776.298	69102	447.753	77124	196.223	66525	-95.428
77933	770.265	69103	435.781	77125	193.584	66526	-101.551
77934	775.424	69104	450.350	77126	192.876	66527	-105.908

77935	768.166	69105	453.030	77127	188.444	66528	-108.089
77936	776.358	69106	454.448	77128	186.586	66529	-114.957
77937	773.681	69107	444.310	77129	189.482	66530	-116.567
77938	761.265	69108	459.022	77130	185.561	66531	-119.787
77939	766.671	69109	460.964	77131	183.982	66532	-125.508
77940	764.360	69110	452.811	77132	184.810	66533	-123.791
77941	752.773	69111	465.457	77133	187.809	66534	-130.433
77942	759.744	69112	467.293	77134	183.452	66535	-133.582
77943	751.884	69113	453.048	77135	182.063	66536	-135.590
77944	740.654	69114	448.043	77136	183.972	66537	-142.208
77945	742.680	69115	443.677	77137	178.830	66538	-138.238
77946	728.174	69116	431.765	77138	177.963	66539	-145.880
77947	740.655	69117	436.471	77139	178.346	66540	-148.102
77948	732.546	69118	422.376	77140	182.623	66541	-152.995
77949	716.277	69119	414.058	77141	179.730	66542	-160.883
77950	713.576	69120	412.033	77142	181.212	66543	-165.671
77951	703.140	69121	398.977	77143	184.147	66544	-168.223
77952	683.687	69122	396.188	77144	182.141	66545	-175.834
77953	688.555	69123	395.654	77145	183.034	66546	-185.970
77954	688.251	69124	408.920	77146	187.787	66547	-183.294
77955	659.734	69125	400.556	77147	189.226	66548	-176.948
77956	710.319	69126	398.312	77148	188.087	66549	-185.294
77957	701.312	69127	401.589	77149	186.554	66550	-185.441
77958	696.504	69128	410.602	77150	185.904	66551	-181.013
77959	729.889	69129	399.433	77151	187.069	66552	-187.563
77960	737.921	69130	396.838	77152	189.767	66553	-175.917
77961	743.890	69131	408.777	77153	192.475	66554	-171.232
77962	756.715	69132	423.397	77154	192.401	66555	-169.392
77963	749.881	69133	421.111	77155	193.550	66556	-164.364
77964	758.968	69134	421.427	77156	194.967	66557	-159.093

77965	764.002
77966	768.164
77967	763.979
77968	761.561
77969	758.581
77970	754.903
77971	740.449
77972	735.987
77973	724.028
77974	712.974

69135	431.143
69136	419.960
69137	412.256
69138	428.416
69139	436.505
69140	435.192
69141	438.803
69142	438.528
69143	437.641
69144	426.072
69145	430.264
69146	425.531
69147	444.085
69148	418.610

77157	192.407
77158	199.135

66558	-151.860
66559	-160.966
66560	-149.363
66561	-143.889
66562	-139.048
66563	-131.937
66564	-131.047
66565	-125.182
66566	-119.588
66567	-118.893
66568	-114.650
66569	-110.634
66570	-112.384
66571	-108.511
66572	-109.594
66573	-104.038
66574	-100.175
66575	-101.936
66576	-97.943
66577	-108.502
66578	-112.462
66579	-119.258
66580	-124.076
66581	-127.083
66582	-133.291
66583	-169.777

SG 5_E 1025.54N	FEA Strain Value
Number Nodes	193
Units	Micro m/m
Max	-386.01
Average	-491.95
Min	-635.05
Nodes ID	Min Principal
28114	-635.048
28115	-512.063
28139	-443.518
62753	-521.580
62754	-532.140
62755	-549.106
62756	-562.800
62757	-579.925
62758	-597.123
62759	-615.747
62760	-391.739
62761	-398.739
62762	-406.992
62763	-416.503
62764	-424.975
62765	-434.751
62766	-443.732
62767	-452.342

SG 6_A 1025.54N	FEA Strain Value
Number Nodes	173
Units	Micro m/m
Max	-389.94
Average	-464.65
Min	-530.60
Nodes ID	Min Principal
27920	-448.116
27929	-463.773
27945	-530.603
62531	-394.171
62532	-398.324
62533	-403.227
62534	-406.855
62535	-412.302
62536	-416.118
62537	-420.404
62538	-423.447
62539	-427.712
62540	-430.931
62541	-434.586
62542	-437.367
62543	-440.698
62544	-443.305
62545	-446.166

SG 7_A 1025.54N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	-102.95
Average	-196.13
Min	-279.08
Nodes ID	Min Principal
26645	-251.614
26654	-141.720
26670	-279.084
61257	-111.338
61258	-120.962
61259	-129.899
61260	-139.816
61261	-148.830
61262	-158.148
61263	-167.984
61264	-177.230
61265	-186.874
61266	-196.567
61267	-205.766
61268	-215.259
61269	-224.559
61270	-233.448
61271	-242.298

SG 8_A 1025.54N	FEA Strain Value
Number Nodes	177
Units	Micro m/m
Max	101.76
Average	83.96
Min	71.16
Nodes ID	Max Principal
26272	78.358
26281	101.760
26297	71.160
60892	93.902
60893	92.568
60894	91.153
60895	89.713
60896	88.471
60897	87.176
60898	86.271
60899	85.295
60900	84.223
60901	83.029
60902	82.265
60903	81.265
60904	80.637
60905	79.779
60906	78.978

62768	-462.474	62546	-389.936	61272	-102.952	60907	95.191
62769	-471.236	62547	-456.011	61273	-137.307	60908	99.635
62770	-480.591	62548	-447.548	61274	-133.179	60909	98.058
62771	-488.465	62549	-438.099	61275	-129.079	60910	97.439
62772	-494.479	62550	-429.280	61276	-124.618	60911	95.949
62773	-499.279	62551	-420.767	61277	-118.946	60912	95.031
62774	-504.275	62552	-411.280	61278	-114.166	60913	94.796
62775	-386.014	62553	-400.753	61279	-108.805	60914	95.000
62776	-438.301	62554	-529.029	61280	-271.013	60915	72.787
62777	-432.527	62555	-525.711	61281	-263.375	60916	74.146
62778	-424.822	62556	-522.553	61282	-256.240	60917	75.886
62779	-417.547	62557	-519.904	61283	-247.541	60918	77.405
62780	-409.468	62558	-516.020	61284	-239.215	60919	79.484
62781	-402.245	62559	-511.911	61285	-231.474	60920	80.921
62782	-393.848	62560	-508.520	61286	-221.754	60921	83.020
62783	-627.841	62561	-504.007	61287	-212.484	60922	84.778
62784	-620.277	62562	-499.573	61288	-204.794	60923	86.673
62785	-609.696	62563	-493.964	61289	-194.955	60924	88.617
62786	-599.130	62564	-489.216	61290	-186.926	60925	90.805
62787	-588.024	62565	-484.095	61291	-177.508	60926	92.859
62788	-573.965	62566	-479.865	61292	-168.830	60927	95.356
62789	-560.122	62567	-474.572	61293	-159.229	60928	97.046
62790	-547.151	62568	-469.487	61294	-151.223	60929	99.845
62791	-532.304	62569	-460.548	61295	-255.699	60930	77.188
62792	-517.402	62570	-471.946	61296	-259.928	60931	76.132
62793	-502.927	62571	-483.874	61297	-264.006	60932	75.252
62794	-489.511	62572	-493.929	61298	-267.835	60933	74.422
62795	-476.151	62573	-504.161	61299	-271.035	60934	73.744
62796	-463.447	62574	-513.967	61300	-274.522	60935	72.892
62797	-453.176	62575	-522.067	61301	-277.099	60936	72.092

77701	-478.572
77702	-492.691
77703	-489.301
77704	-506.992
77705	-467.944
77706	-477.994
77707	-444.037
77708	-463.648
77709	-475.548
77710	-503.567
77711	-472.917
77712	-480.353
77713	-518.669
77714	-506.959
77715	-533.533
77716	-534.670
77717	-546.107
77718	-559.611
77719	-532.863
77720	-553.713
77721	-406.528
77722	-417.331
77723	-438.611
77724	-449.530
77725	-407.705
77726	-419.477
77727	-441.248
77728	-449.613
77729	-426.767
77730	-465.019

76574	-464.743
76575	-454.051
76576	-448.836
76577	-460.961
76578	-459.202
76579	-448.252
76580	-440.252
76581	-429.259
76582	-411.981
76583	-460.818
76584	-468.917
76585	-472.289
76586	-475.602
76587	-451.274
76588	-430.772
76589	-464.661
76590	-440.357
76591	-485.580
76592	-495.157
76593	-495.607
76594	-504.055
76595	-476.921
76596	-449.838
76597	-485.634
76598	-458.406
76599	-506.643
76600	-510.671
76601	-489.208
76602	-462.723
76603	-411.395

61302	-163.558
61303	-163.409
61304	-150.111
61305	-157.300
61306	-182.606
61307	-192.126
61308	-178.885
61309	-194.945
61310	-156.914
61311	-141.334
61312	-144.579
61313	-134.714
61314	-126.235
61315	-129.710
61316	-136.199
61317	-147.056
61318	-145.274
61319	-164.988
61320	-170.067
61321	-170.256
61322	-187.035
61323	-194.555
61324	-202.897
61325	-208.417
61326	-223.054
61327	-200.339
61328	-220.464
61329	-219.814
61330	-230.719
61331	-238.080

60937	76.786
60938	78.186
60939	78.155
60940	78.744
60941	81.077
60942	81.948
60943	79.655
60944	81.021
60945	78.913
60946	79.816
60947	77.384
60948	80.104
60949	73.790
60950	74.780
60951	79.550
60952	81.765
60953	76.551
60954	81.258
60955	93.136
60956	96.076
60957	88.947
60958	84.826
60959	88.080
60960	92.220
60961	91.612
60962	76.005
60963	77.178
60964	78.333
60965	78.613
60966	81.147

77731	-475.568	76604	-400.648	61332	-244.959	60967	79.307
77732	-494.453	76605	-405.460	61333	-236.208	60968	82.879
77733	-460.469	76606	-410.229	61334	-248.889	60969	85.542
77734	-474.935	76607	-421.786	61335	-253.720	60970	83.971
77735	-498.799	76608	-419.473	61336	-257.693	60971	87.570
77736	-504.025	76609	-423.850	61337	-267.643	60972	89.837
77737	-520.583	76610	-435.866	61338	-119.858	60973	93.351
77738	-535.204	76611	-428.247	61339	-114.363	60974	93.336
77739	-521.600	76612	-432.667	61340	-123.830	60975	91.939
77740	-535.524	76613	-445.649	61341	-132.065	60976	90.751
77741	-560.965	76614	-436.710	61342	-135.524	60977	91.155
77742	-578.019	76615	-440.516	61343	-143.711	60978	89.808
77743	-561.077	76616	-454.743	61344	-158.107	60979	88.760
77744	-589.127	76617	-445.091	61345	-148.428	60980	88.534
77745	-594.221	76618	-447.769	61346	-156.823	60981	87.400
77746	-454.378	76619	-460.700	61347	-170.249	60982	86.613
77747	-515.866	76620	-450.121	61348	-164.876	60983	86.072
77748	-518.308	76621	-452.871	61349	-173.557	60984	84.779
77749	-533.459	76622	-456.295	61350	-178.543	60985	85.504
77750	-549.356	76623	-467.992	61351	-181.967	60986	84.569
77751	-548.259	76624	-477.007	61352	-190.867	60987	83.493
77752	-563.060	76625	-480.649	61353	-186.305	60988	82.457
77753	-577.633	76626	-491.767	61354	-195.920	60989	82.170
77754	-577.871	76627	-499.912	61355	-201.795	60990	80.072
77755	-596.063	76628	-502.507	61356	-202.417	60991	80.875
77756	-614.437	76629	-512.645	61357	-212.296	60992	79.943
77757	-607.632	76630	-521.323	61358	-216.582	60993	78.887
77758	-591.782	76631	-518.280	61359	-218.992	60994	80.176
77759	-604.189	76632	-508.641	61360	-228.506	60995	79.503
77760	-584.140	76633	-516.288	61361	-229.230	60996	78.656

77761	-599.357	76634	-513.353	61362	-235.405	60997	78.936
77762	-589.008	76635	-505.593	61363	-242.989	60998	77.213
77763	-569.744	76636	-512.494	61364	-240.917	60999	77.882
77764	-580.275	76637	-507.439	61365	-250.244	61000	77.454
77765	-567.197	76638	-499.924	61366	-254.640	61001	76.729
77766	-540.908	76639	-503.957	61367	-253.837	61002	75.763
77767	-545.059	76640	-495.504	61368	-258.905	61003	76.592
77768	-521.244	76641	-504.222	61369	-262.714	61004	75.278
77769	-506.862	76642	-498.895	61370	-255.915	61005	74.535
77770	-520.201	76643	-490.519	61371	-260.700	61006	75.302
77771	-505.828	76644	-494.591	61372	-261.217	61007	73.923
77772	-484.950	76645	-490.234	61373	-267.383	61008	74.304
77773	-495.997	76646	-480.748	61374	-271.272	61009	73.455
77774	-482.220	76647	-484.512	61375	-273.689	61010	72.518
77775	-462.605	76648	-474.051	61376	-265.394	61011	73.842
77776	-469.295	76649	-483.696	61377	-258.342	61012	75.013
77777	-451.762	76650	-477.874	61378	-248.889	61013	75.257
77778	-471.289	76651	-470.676	61379	-254.066	61014	76.944
77779	-458.890	76652	-477.030	61380	-246.249	61015	78.014
77780	-449.054	76653	-471.760	61381	-237.726	61016	78.356
77781	-443.332	76654	-464.955	61382	-237.606	61017	80.218
77782	-441.051	76655	-467.736	61383	-231.061	61018	80.708
77783	-433.490	76656	-460.037	61384	-225.263	61019	81.281
77784	-445.127	76657	-466.822	61385	-225.034	61020	83.438
77785	-429.039	76658	-461.483	61386	-216.607	61021	83.301
77786	-429.892	76659	-453.749	61387	-210.666	61022	84.630
77787	-418.608	76660	-453.653	61388	-206.536	61023	86.684
77788	-410.119	76661	-448.150	61389	-200.996	61024	86.915
77789	-413.159	76662	-438.988	61390	-185.516	61025	88.769
77790	-404.845	76663	-444.195	61391	-188.165	61026	91.176

77791	-396.179	76664	-434.713	61392	-175.747	61027	91.103
77792	-407.180	76665	-434.990	61393	-167.444	61028	92.708
77793	-395.568	76666	-428.876	61394	-171.884	61029	95.062
77794	-402.620	76667	-419.848	61395	-162.503	61030	94.649
77795	-411.934	76668	-420.631	61396	-156.450	61031	96.509
77796	-407.972	76669	-430.079	61397	-153.046	61032	98.751
77797	-416.301	76670	-440.525	61398	-145.109	61033	96.771
77798	-427.929	76671	-441.232	61399	-140.395	61034	96.048
77799	-427.780	76672	-443.824	61400	-141.681	61035	94.079
77800	-435.818	76673	-456.902	61401	-134.951	61036	94.176
77801	-443.878	76674	-453.158	61402	-130.281	61037	93.557
77802	-441.978	76675	-457.597	61403	-132.918	61038	91.651
77803	-454.993	76676	-471.915	61404	-127.111	61039	90.251
77804	-447.511	76677	-464.609	61405	-121.963	61040	89.964
77805	-456.224	76678	-467.582	61406	-127.787	61041	89.034
77806	-467.698	76679	-481.405	61407	-137.184	61042	87.607
77807	-464.040	76680	-472.153	61408	-140.665	61043	86.669
77808	-473.043	76681	-474.548	61409	-146.558	61044	86.454
77809	-486.935	76682	-488.276	61410	-155.366	61045	85.001
77810	-484.839	76683	-496.561	61411	-193.730	61046	83.712
77811	-501.575	76684	-498.334	61412	-178.360	61047	84.232
77812	-487.829	76685	-495.274	61413	-202.059	61048	83.508
77813	-495.681	76686	-490.948	61414	-194.541	61049	82.073
77814	-511.763	76687	-486.114	61415	-198.758	61050	82.033
77815	-504.102	76688	-486.131	61416	-205.545	61051	81.235
77816	-510.588	76689	-481.288	61417	-211.501	61052	79.141
77817	-528.735	76690	-475.512	61418	-215.019	61053	78.736
77818	-540.492	76691	-470.273	61419	-222.297	61054	77.439
77819	-528.001	76692	-466.278	61420	-228.586	61055	76.720
77820	-548.949	76693	-461.759	61421	-229.438	61056	77.389

77821	-557.662
77822	-569.218
77823	-574.904
77824	-547.912
77825	-528.072
77826	-517.021
77827	-510.936
77828	-492.773
77829	-485.361
77830	-462.849
77831	-492.254
77832	-476.456
77833	-450.061
77834	-461.689
77835	-451.506
77836	-433.737
77837	-458.341
77838	-423.076
77839	-416.976
77840	-416.686
77841	-422.098
77842	-433.032
77843	-451.277
77844	-457.259
77845	-519.193

76694	-460.029
76695	-456.217
76696	-449.522
76697	-454.488
76698	-445.610

61422	-237.336
61423	-245.552
61424	-244.986
61425	-250.930
61426	-241.812
61427	-234.178
61428	-225.887
61429	-219.750
61430	-210.666

61057	77.900
61058	78.093
61059	75.592
61060	80.316
61061	81.456
61062	83.124
61063	88.134
61064	90.538
61065	92.723

Appendix 7: Strain Gauge Results

7.1. Strain gauge one (SG 1) data

The highlighted data in the table were used for the validation purpose.

Strain gauge 1: Average Strain Values					
	Experiment A	**Experiment B**	**Experiment C**	**Experiment D**	**Experiment E**
Samples	**133**	**133**	**133**	**133**	**133**
Units	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**
Min	**156.83**	**286.38**	**461.77**	**625.29**	**787.03**
Max	**157.84**	**287.73**	**463.76**	**625.94**	**789.36**
Mean	**157.21**	**286.88**	**462.62**	**625.66**	**787.97**
STD	**0.26**	**0.29**	**0.45**	**0.12**	**0.56**
1	-0.034	-0.004	-0.070	-0.021	-0.016
2	-0.074	-0.003	-0.131	-0.020	-0.089
3	0.144	3.012	-0.553	0.899	-0.116
4	6.142	5.217	1.144	3.498	1.218
5	5.968	5.513	-0.698	7.195	3.391
6	7.965	7.178	5.411	7.054	6.649
7	9.604	8.991	100.010	6.629	11.934
8	10.059	157.611	145.833	76.742	141.076
9	53.173	192.553	162.837	309.807	258.000
10	79.531	245.367	165.470	493.830	492.373
11	99.115	276.347	235.438	623.573	636.473
12	119.047	285.667	303.652	638.447	740.357
13	136.040	289.073	317.446	628.480	780.900
14	153.197	283.917	356.630	625.117	790.927
15	148.183	285.533	411.030	627.713	794.300
16	157.350	286.963	441.403	634.810	798.427
17	155.863	287.980	462.817	630.833	797.627
18	156.920	287.990	460.390	630.323	792.893
19	157.207	287.593	461.313	631.043	794.340
20	156.850	287.713	462.180	628.523	793.737
21	157.843	287.953	464.010	628.720	794.157
22	158.107	287.793	464.267	628.883	794.447
23	157.673	287.430	464.957	625.270	792.153

24	157.017	287.453	464.493	626.050	791.883
25	157.243	287.833	464.637	625.537	792.110
26	157.877	287.730	463.440	625.743	791.230
27	157.720	287.320	465.003	626.130	792.170
28	157.090	287.263	464.113	626.063	791.307
29	157.067	287.613	463.667	626.233	790.847
30	157.710	287.727	463.810	626.117	790.090
31	157.800	287.323	463.737	626.047	790.293
32	157.187	287.130	463.263	626.020	789.877
33	156.993	287.430	463.410	625.863	788.640
34	157.537	287.667	463.407	625.930	788.610
35	157.843	287.313	463.763	625.920	788.930
36	157.353	287.080	463.713	625.943	787.813
37	156.937	287.323	463.097	625.837	788.087
38	157.340	287.727	463.077	625.850	789.017
39	157.833	287.303	463.440	625.860	788.647
40	157.500	286.997	463.237	625.840	788.003
41	156.913	287.197	462.800	625.783	789.150
42	157.163	287.500	462.990	625.733	789.357
43	157.733	287.283	463.477	625.813	788.117
44	157.613	286.973	463.267	625.877	788.153
45	157.030	287.117	462.970	625.820	789.283
46	157.037	287.420	463.130	625.783	788.603
47	157.577	287.283	463.417	625.790	787.467
48	157.693	286.917	463.183	625.723	788.300
49	157.147	287.027	462.730	625.720	788.907
50	156.920	287.360	462.917	625.753	787.693
51	157.403	287.247	463.303	625.820	787.857
52	157.777	286.890	463.200	625.677	788.897
53	157.260	286.977	462.760	625.700	788.377
54	156.867	287.317	462.930	625.727	787.817
55	157.237	287.250	463.240	625.787	788.267
56	157.673	286.867	463.017	625.723	788.960
57	157.403	286.877	462.597	625.567	787.723
58	156.907	287.213	462.930	625.560	787.590
59	157.097	287.240	463.197	625.440	788.660
60	157.587	286.890	462.987	625.537	788.463
61	157.480	286.813	462.677	625.620	787.287

62	156.983	287.130	462.873	625.770	788.157
63	156.973	287.360	463.107	625.653	788.857
64	157.493	286.890	462.920	625.477	787.757
65	157.593	286.797	462.477	625.643	787.513
66	157.083	287.057	462.920	625.747	788.540
67	156.883	287.190	463.093	625.687	788.347
68	157.367	286.920	462.897	625.660	787.337
69	157.623	286.760	462.580	625.767	788.037
70	157.187	286.980	462.747	625.627	788.700
71	156.837	287.140	463.007	625.643	787.750
72	157.220	286.903	462.763	625.587	787.323
73	157.587	286.740	462.447	625.537	788.463
74	157.323	286.887	462.733	625.470	788.337
75	156.927	287.097	462.920	625.470	787.333
76	157.093	286.967	462.687	625.567	787.877
77	157.470	286.720	462.430	625.747	788.593
78	157.427	286.820	462.677	625.667	787.697
79	156.973	286.990	462.923	625.540	787.273
80	156.977	286.963	462.603	625.520	788.303
81	157.443	286.737	462.353	625.693	788.333
82	157.477	286.753	462.593	625.620	787.327
83	157.040	286.943	462.920	625.693	787.817
84	156.903	286.940	462.587	625.663	788.457
85	157.300	286.747	462.343	625.633	787.720
86	157.510	286.677	462.517	625.417	787.197
87	157.137	286.887	462.760	625.527	788.103
88	156.880	286.933	462.490	625.577	788.297
89	157.210	286.700	462.307	625.637	787.337
90	157.497	286.633	462.513	625.573	787.567
91	157.260	286.830	462.747	625.553	788.320
92	156.880	286.930	462.430	625.657	787.607
93	157.053	286.750	462.263	625.627	787.207
94	157.403	286.570	462.427	625.630	788.067
95	157.390	286.753	462.653	625.630	788.210
96	156.923	286.927	462.420	625.717	787.263
97	156.947	286.730	462.200	625.517	787.420
98	157.323	286.543	462.430	625.487	788.390
99	157.423	286.687	462.687	625.747	787.747

100	156.987	286.880	462.323	625.653	787.150
101	156.860	286.743	462.077	625.613	788.040
102	157.233	286.517	462.407	625.567	788.167
103	157.417	286.650	462.587	625.673	787.280
104	157.103	286.853	462.240	625.657	787.330
105	156.827	286.723	462.067	625.667	788.330
106	157.143	286.497	462.383	625.570	787.677
107	157.423	286.607	462.500	625.647	787.117
108	157.227	286.823	462.250	625.723	787.897
109	156.860	286.727	462.077	625.600	788.267
110	157.067	286.520	462.270	625.457	787.100
111	157.367	286.547	462.497	625.293	787.280
112	157.307	286.787	462.267	625.457	788.330
113	156.900	286.723	461.993	625.487	787.953
114	156.957	286.493	462.307	625.617	787.030
115	157.290	286.507	462.417	625.710	788.197
116	157.313	286.850	462.113	625.640	788.113
117	156.953	286.723	461.927	625.680	787.430
118	156.877	286.517	462.153	625.720	787.350
119	157.163	286.483	462.340	625.693	788.203
120	157.347	286.667	461.937	625.587	787.580
121	157.043	286.700	461.970	625.563	787.100
122	156.847	286.557	462.243	625.723	787.863
123	157.067	286.463	462.347	625.667	788.313
124	157.360	286.600	462.033	625.600	787.313
125	157.157	286.697	461.870	625.717	787.417
126	156.870	286.553	462.177	625.730	788.223
127	156.993	286.457	462.227	625.580	787.930
128	157.310	286.527	461.903	625.677	787.113
129	157.203	286.697	461.883	625.687	787.910
130	156.897	286.563	462.153	625.703	788.103
131	156.923	286.380	462.177	625.657	787.437
132	157.253	286.497	461.880	625.583	787.267
133	157.250	286.623	461.770	625.680	788.327
Average	**157.210**	**286.880**	**462.620**	**625.660**	**787.970**

7.2. Strain gauge two (SG 2) data

Strain gauge 2: Average Strain Values					
	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Samples	133	133	133	133	133
Units	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)
Min	83.97	157.68	259.41	398.86	546.24
Max	84.27	158.67	261.94	402.33	551.29
Mean	84.13	158.22	260.98	401.06	549.47
STD	0.08	0.25	0.65	0.94	1.31
1	0.006	-0.026	-0.006	0.002	-0.041
2	0.026	-0.042	0.001	-0.020	-0.047
3	1.409	-0.042	0.083	-0.009	0.356
4	1.825	1.427	2.719	1.614	0.460
5	2.306	1.885	2.776	2.522	1.495
6	2.408	2.467	2.912	2.679	2.111
7	4.753	28.805	2.746	2.582	2.211
8	34.480	43.785	4.027	2.403	2.252
9	70.020	63.837	36.012	52.657	2.074
10	83.440	103.843	65.331	155.802	3.024
11	83.613	106.368	110.990	253.860	154.053
12	83.343	130.017	216.660	378.163	259.273
13	83.567	154.967	255.733	394.263	412.257
14	83.743	157.953	256.647	392.360	511.247
15	83.800	158.150	255.370	396.517	534.190
16	83.813	156.550	255.637	395.117	540.500
17	83.760	157.080	256.147	394.343	543.897
18	83.760	157.473	257.247	396.277	542.763
19	83.840	157.310	257.247	396.500	543.320
20	83.840	157.247	257.380	396.850	544.010
21	83.820	157.377	257.697	397.097	544.380
22	83.813	157.400	258.120	397.367	544.877
23	83.907	157.330	258.063	397.437	544.943
24	83.920	157.433	258.360	397.680	544.817
25	83.890	157.600	258.833	397.940	545.230
26	83.867	157.637	258.853	398.103	545.447

27	83.910	157.477	258.727	398.243	545.620
28	83.953	157.507	258.893	398.227	545.463
29	83.920	157.670	259.270	398.640	545.780
30	83.917	157.713	259.250	398.673	545.947
31	83.957	157.637	259.120	398.623	546.220
32	84.003	157.590	259.263	398.757	546.100
33	83.990	157.687	259.547	398.863	546.733
34	83.990	157.787	259.553	398.943	546.243
35	83.967	157.777	259.410	398.943	547.087
36	84.027	157.683	259.527	399.210	546.560
37	84.027	157.717	259.840	399.170	547.240
38	84.010	157.860	259.813	399.250	546.947
39	83.977	157.837	259.680	399.393	547.343
40	84.010	157.713	259.797	399.433	547.450
41	84.050	157.750	260.207	399.513	547.220
42	84.023	157.953	260.017	399.640	547.413
43	84.013	157.943	259.840	399.610	547.403
44	84.023	157.773	259.990	399.853	547.613
45	84.077	157.800	260.233	399.787	547.660
46	84.020	157.993	260.180	399.787	547.717
47	84.037	158.040	260.007	399.830	547.950
48	84.003	157.877	260.137	400.003	547.787
49	84.093	157.857	260.377	399.990	547.900
50	84.073	158.033	260.330	400.137	548.200
51	84.033	158.077	260.150	400.197	548.103
52	84.033	157.917	260.250	400.313	548.090
53	84.083	157.890	260.510	400.120	548.333
54	84.110	158.080	260.487	400.150	548.170
55	84.043	158.123	260.247	400.270	548.460
56	84.043	158.000	260.427	400.330	548.303
57	84.080	157.927	260.673	400.353	548.573
58	84.133	158.087	260.567	400.333	548.570
59	84.090	158.187	260.420	400.460	548.613
60	84.043	158.030	260.580	400.453	548.653
61	84.117	157.960	260.787	400.520	548.617
62	84.133	158.067	260.697	400.560	548.730
63	84.090	158.213	260.543	400.573	548.687
64	84.030	158.137	260.700	400.670	548.783

65	84.077	158.017	260.837	400.637	548.853
66	84.147	158.113	260.773	400.703	549.003
67	84.117	158.213	260.643	400.787	548.847
68	84.083	158.163	260.773	400.737	549.113
69	84.097	158.063	260.970	400.787	549.157
70	84.133	158.087	260.877	400.817	549.060
71	84.160	158.227	260.707	400.977	549.257
72	84.053	158.227	260.873	400.907	549.110
73	84.067	158.077	261.050	400.950	549.283
74	84.147	158.087	260.933	400.933	549.383
75	84.147	158.243	260.800	401.110	549.390
76	84.113	158.283	260.967	400.980	549.437
77	84.107	158.157	261.100	401.037	549.327
78	84.143	158.113	260.997	401.137	549.523
79	84.137	158.317	260.907	401.123	549.557
80	84.110	158.337	261.037	401.200	549.603
81	84.080	158.183	261.193	401.143	549.450
82	84.143	158.140	261.093	401.273	549.767
83	84.170	158.307	260.993	401.233	549.743
84	84.137	158.400	261.130	401.320	549.677
85	84.117	158.253	261.247	401.253	549.847
86	84.143	158.170	261.150	401.320	549.803
87	84.167	158.330	261.050	401.360	549.937
88	84.173	158.420	261.203	401.397	549.793
89	84.123	158.283	261.320	401.547	549.907
90	84.147	158.187	261.203	401.413	550.003
91	84.173	158.337	261.107	401.423	549.977
92	84.163	158.437	261.280	401.520	549.817
93	84.120	158.343	261.397	401.497	550.063
94	84.133	158.197	261.273	401.553	550.150
95	84.203	158.297	261.163	401.477	550.267
96	84.203	158.467	261.357	401.583	550.147
97	84.153	158.403	261.460	401.610	549.990
98	84.167	158.273	261.313	401.667	550.427
99	84.173	158.347	261.253	401.597	550.260
100	84.197	158.487	261.420	401.660	550.437
101	84.187	158.430	261.507	401.763	550.173
102	84.167	158.310	261.410	401.707	550.397

103	84.180	158.343	261.303	401.643	550.543
104	84.243	158.467	261.483	402.140	550.400
105	84.157	158.493	261.553	401.833	550.510
106	84.217	158.320	261.440	401.920	550.530
107	84.197	158.310	261.410	401.897	550.473
108	84.207	158.467	261.560	401.880	550.513
109	84.190	158.543	261.633	401.890	550.747
110	84.183	158.403	261.497	401.900	550.433
111	84.197	158.350	261.453	401.850	550.780
112	84.207	158.520	261.600	402.020	550.750
113	84.220	158.597	261.693	401.907	550.623
114	84.200	158.463	261.557	401.847	550.767
115	84.193	158.367	261.537	402.053	550.707
116	84.213	158.510	261.667	402.053	550.977
117	84.223	158.580	261.727	401.890	550.877
118	84.213	158.480	261.590	402.033	550.837
119	84.190	158.393	261.573	402.067	550.823
120	84.213	158.493	261.737	402.117	551.120
121	84.240	158.653	261.800	401.997	550.913
122	84.217	158.487	261.650	402.220	551.040
123	84.213	158.380	261.633	402.177	551.080
124	84.197	158.487	261.807	402.080	551.090
125	84.233	158.627	261.860	402.110	551.117
126	84.270	158.540	261.717	402.200	551.143
127	84.223	158.403	261.697	402.233	551.187
128	84.197	158.510	261.873	402.077	551.043
129	84.233	158.643	261.880	402.257	551.123
130	84.270	158.587	261.713	402.187	551.227
131	84.217	158.450	261.733	402.327	551.177
132	84.213	158.533	261.920	402.180	551.287
133	84.260	158.670	261.940	402.227	551.263
Average	**84.130**	**158.220**	**260.980**	**401.060**	**549.470**

7.3. Strain gauge three (SG 3) data

Strain gauge 3: Average Strain Values					
	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Samples	**133**	**133**	**133**	**133**	**133**
Units	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**
Min	**43.11**	**77.73**	**108.66**	**140.31**	**185.25**
Max	**43.15**	**77.95**	**108.86**	**140.77**	**185.86**
Mean	**43.13**	**77.86**	**108.79**	**140.58**	**185.66**
STD	**0.01**	**0.06**	**0.05**	**0.11**	**0.14**
1	0.001	-0.008	-0.004	-0.005	-0.006
2	0.013	-0.006	-0.005	-0.006	-0.014
3	0.774	0.601	-0.003	-0.003	0.200
4	0.941	0.872	1.181	0.753	0.285
5	1.248	0.906	1.199	1.151	0.711
6	1.365	3.536	1.289	1.194	1.029
7	3.329	28.547	1.383	1.205	1.080
8	17.732	73.217	2.805	1.284	1.130
9	35.370	76.923	19.119	28.517	1.133
10	42.673	77.687	30.016	68.671	2.189
11	43.047	77.800	50.513	102.457	64.968
12	43.040	77.843	96.753	135.183	106.317
13	42.990	77.593	107.187	138.153	149.057
14	43.057	77.690	107.833	138.507	174.983
15	43.100	77.947	108.120	140.043	181.560
16	43.080	77.870	108.407	139.980	184.027
17	43.077	77.640	108.463	139.943	184.960
18	43.093	77.710	108.480	140.153	184.833
19	43.097	77.930	108.443	140.150	184.853
20	43.083	77.887	108.417	140.157	184.933
21	43.090	77.683	108.470	140.170	185.013
22	43.093	77.710	108.513	140.177	185.123
23	43.103	77.903	108.523	140.180	185.100
24	43.097	77.907	108.553	140.203	185.100
25	43.087	77.733	108.610	140.230	185.173
26	43.097	77.717	108.597	140.243	185.183
27	43.110	77.873	108.570	140.267	185.253

28	43.103	77.910	108.600	140.257	185.217
29	43.100	77.797	108.643	140.287	185.237
30	43.107	77.727	108.637	140.317	185.243
31	43.107	77.827	108.617	140.300	185.343
32	43.107	77.923	108.633	140.310	185.257
33	43.107	77.850	108.673	140.313	185.390
34	43.110	77.740	108.673	140.340	185.250
35	43.117	77.790	108.657	140.337	185.507
36	43.113	77.917	108.663	140.367	185.280
37	43.113	77.890	108.700	140.357	185.463
38	43.117	77.750	108.693	140.377	185.400
39	43.107	77.770	108.693	140.400	185.473
40	43.117	77.910	108.693	140.357	185.467
41	43.113	77.920	108.723	140.407	185.413
42	43.120	77.770	108.727	140.440	185.470
43	43.117	77.743	108.697	140.417	185.430
44	43.117	77.893	108.713	140.460	185.473
45	43.120	77.943	108.743	140.440	185.500
46	43.123	77.793	108.733	140.450	185.490
47	43.120	77.730	108.710	140.447	185.510
48	43.110	77.880	108.727	140.470	185.473
49	43.127	77.953	108.757	140.463	185.500
50	43.123	77.817	108.747	140.500	185.553
51	43.117	77.737	108.723	140.503	185.507
52	43.110	77.853	108.730	140.520	185.507
53	43.113	77.947	108.767	140.473	185.560
54	43.133	77.843	108.763	140.483	185.487
55	43.127	77.747	108.727	140.497	185.563
56	43.110	77.827	108.753	140.497	185.537
57	43.123	77.943	108.780	140.503	185.587
58	43.133	77.873	108.770	140.497	185.570
59	43.127	77.760	108.743	140.510	185.597
60	43.117	77.810	108.763	140.507	185.607
61	43.123	77.930	108.793	140.523	185.570
62	43.137	77.897	108.770	140.523	185.597
63	43.133	77.783	108.760	140.520	185.583
64	43.120	77.797	108.783	140.533	185.590
65	43.120	77.907	108.797	140.527	185.597

66	43.133	77.920	108.783	140.537	185.650
67	43.127	77.807	108.763	140.543	185.580
68	43.117	77.780	108.780	140.540	185.633
69	43.123	77.887	108.803	140.550	185.643
70	43.137	77.930	108.793	140.537	185.617
71	43.127	77.837	108.763	140.570	185.653
72	43.120	77.773	108.777	140.543	185.590
73	43.117	77.880	108.807	140.557	185.643
74	43.137	77.947	108.787	140.550	185.667
75	43.133	77.853	108.770	140.583	185.653
76	43.120	77.770	108.787	140.557	185.653
77	43.120	77.857	108.803	140.570	185.617
78	43.137	77.943	108.800	140.583	185.667
79	43.140	77.877	108.780	140.570	185.663
80	43.123	77.783	108.793	140.587	185.677
81	43.120	77.843	108.813	140.567	185.627
82	43.130	77.943	108.797	140.587	185.697
83	43.130	77.890	108.780	140.577	185.683
84	43.127	77.790	108.797	140.600	185.667
85	43.123	77.820	108.813	140.580	185.690
86	43.137	77.930	108.793	140.587	185.677
87	43.137	77.917	108.787	140.597	185.707
88	43.127	77.810	108.810	140.603	185.653
89	43.127	77.813	108.820	140.630	185.687
90	43.130	77.910	108.807	140.597	185.727
91	43.137	77.930	108.790	140.607	185.717
92	43.130	77.827	108.813	140.617	185.660
93	43.127	77.800	108.827	140.610	185.733
94	43.133	77.893	108.810	140.623	185.750
95	43.140	77.933	108.793	140.607	185.767
96	43.130	77.853	108.857	140.627	185.733
97	43.133	77.800	108.833	140.623	185.673
98	43.133	77.873	108.810	140.630	185.800
99	43.137	77.937	108.793	140.620	185.737
100	43.130	77.877	108.820	140.623	185.787
101	43.133	77.807	108.837	140.650	185.707
102	43.137	77.853	108.820	140.627	185.757
103	43.143	77.937	108.803	140.613	185.810

104	43.133	77.897	108.827	140.723	185.760
105	43.133	77.813	108.830	140.697	185.777
106	43.137	77.850	108.813	140.723	185.773
107	43.137	77.930	108.813	140.710	185.760
108	43.140	77.910	108.830	140.693	185.767
109	43.133	77.823	108.833	140.697	185.817
110	43.137	77.837	108.817	140.710	185.727
111	43.137	77.920	108.813	140.680	185.827
112	43.137	77.920	108.827	140.723	185.800
113	43.137	77.833	108.847	140.703	185.763
114	43.140	77.827	108.827	140.763	185.803
115	43.140	77.917	108.820	140.723	185.767
116	43.137	77.937	108.837	140.720	185.830
117	43.140	77.850	108.847	140.687	185.807
118	43.143	77.823	108.827	140.727	185.790
119	43.140	77.897	108.823	140.723	185.773
120	43.137	77.943	108.837	140.730	185.857
121	43.137	77.880	108.847	140.707	185.803
122	43.140	77.827	108.827	140.720	185.820
123	43.140	77.880	108.830	140.727	185.817
124	43.133	77.940	108.850	140.717	185.813
125	43.140	77.890	108.850	140.727	185.837
126	43.150	77.823	108.833	140.730	185.830
127	43.137	77.870	108.827	140.740	185.827
128	43.130	77.933	108.850	140.707	185.797
129	43.140	77.900	108.850	140.757	185.817
130	43.140	77.840	108.823	140.740	185.827
131	43.140	77.853	108.833	140.767	185.823
132	43.137	77.933	108.857	140.730	185.853
133	43.140	77.917	108.850	140.750	185.830
Average	**43.130**	**77.860**	**108.790**	**140.580**	**185.660**

7.4. Strain gauge four (SG 4) data

Strain gauge 4: Average Strain Values					
	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Samples	**133**	**133**	**133**	**133**	**133**
Units	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**
Min	**-31.74**	**-63.09**	**-87.14**	**-114.68**	**-149.31**
Max	**-31.62**	**-62.64**	**-86.58**	**-113.98**	**-148.38**
Mean	**-31.69**	**-62.9**	**-86.91**	**-114.4**	**-148.97**
STD	**0.04**	**0.1**	**0.16**	**0.19**	**0.23**
1	-0.005	-0.002	0.002	-0.005	0.007
2	0.002	-0.032	0.008	-0.005	-0.001
3	-0.614	0.021	0.024	-0.009	-0.181
4	-0.732	0.135	-0.930	-0.600	-0.294
5	-0.985	-1.023	-0.936	-0.958	-0.612
6	-1.068	-1.427	-1.014	-0.971	-0.929
7	-2.461	-23.217	-1.075	-0.973	-0.954
8	-12.987	-37.905	-2.127	-1.011	-0.995
9	-25.877	-39.419	-13.678	-20.883	-0.981
10	-31.233	-40.360	-22.797	-53.543	-1.775
11	-31.473	-42.544	-38.400	-80.253	-49.351
12	-31.447	-59.027	-75.403	-109.583	-82.117
13	-31.437	-60.593	-85.123	-112.343	-118.380
14	-31.463	-62.753	-85.727	-112.360	-139.793
15	-31.577	-62.360	-85.820	-113.570	-145.340
16	-31.573	-61.880	-85.913	-113.327	-147.303
17	-31.580	-62.153	-86.040	-113.337	-147.790
18	-31.583	-62.177	-86.053	-113.507	-147.777
19	-31.590	-62.460	-86.130	-113.657	-147.813
20	-31.593	-62.437	-86.100	-113.653	-147.900
21	-31.580	-62.500	-86.243	-113.697	-148.060
22	-31.593	-62.607	-86.267	-113.723	-148.127
23	-31.600	-62.570	-86.363	-113.793	-148.170
24	-31.597	-62.607	-86.407	-113.837	-148.160
25	-31.600	-62.653	-86.463	-113.863	-148.243
26	-31.597	-62.693	-86.480	-113.887	-148.263
27	-31.620	-62.660	-86.453	-113.927	-148.313

28	-31.610	-62.673	-86.480	-113.910	-148.283
29	-31.603	-62.677	-86.530	-113.947	-148.340
30	-31.607	-62.743	-86.537	-113.983	-148.337
31	-31.617	-62.710	-86.520	-113.963	-148.443
32	-31.623	-62.730	-86.540	-113.987	-148.380
33	-31.623	-62.643	-86.580	-113.983	-148.507
34	-31.630	-62.767	-86.593	-114.007	-148.380
35	-31.620	-62.710	-86.583	-114.017	-148.630
36	-31.620	-62.770	-86.590	-114.060	-148.420
37	-31.633	-62.697	-86.627	-114.033	-148.597
38	-31.623	-62.710	-86.630	-114.063	-148.540
39	-31.623	-62.770	-86.633	-114.090	-148.617
40	-31.630	-62.783	-86.640	-114.047	-148.617
41	-31.637	-62.683	-86.680	-114.087	-148.577
42	-31.630	-62.697	-86.663	-114.133	-148.637
43	-31.630	-62.760	-86.660	-114.123	-148.607
44	-31.627	-62.803	-86.677	-114.157	-148.647
45	-31.637	-62.803	-86.707	-114.140	-148.663
46	-31.643	-62.753	-86.700	-114.150	-148.670
47	-31.637	-62.800	-86.693	-114.157	-148.693
48	-31.640	-62.837	-86.713	-114.183	-148.667
49	-31.647	-62.827	-86.740	-114.187	-148.700
50	-31.653	-62.807	-86.727	-114.227	-148.753
51	-31.650	-62.760	-86.720	-114.223	-148.723
52	-31.647	-62.793	-86.723	-114.247	-148.713
53	-31.653	-62.803	-86.757	-114.207	-148.777
54	-31.660	-62.853	-86.773	-114.217	-148.710
55	-31.657	-62.880	-86.747	-114.230	-148.793
56	-31.653	-62.883	-86.773	-114.243	-148.773
57	-31.660	-62.857	-86.797	-114.250	-148.830
58	-31.657	-62.837	-86.823	-114.250	-148.797
59	-31.663	-62.863	-86.770	-114.273	-148.837
60	-31.660	-62.853	-86.790	-114.273	-148.853
61	-31.670	-62.850	-86.817	-114.290	-148.823
62	-31.673	-62.773	-86.807	-114.283	-148.860
63	-31.677	-62.867	-86.803	-114.287	-148.850
64	-31.670	-62.833	-86.823	-114.317	-148.860
65	-31.667	-62.817	-86.837	-114.307	-148.863

66	-31.693	-62.870	-86.843	-114.313	-148.903
67	-31.683	-62.870	-86.823	-114.327	-148.847
68	-31.677	-62.820	-86.847	-114.320	-148.903
69	-31.683	-62.890	-86.880	-114.343	-148.920
70	-31.690	-62.837	-86.873	-114.337	-148.893
71	-31.697	-62.863	-86.857	-114.357	-148.933
72	-31.683	-62.860	-86.877	-114.350	-148.887
73	-31.687	-62.897	-86.910	-114.363	-148.930
74	-31.700	-62.780	-86.900	-114.347	-148.957
75	-31.700	-62.840	-86.893	-114.393	-148.953
76	-31.693	-62.797	-86.907	-114.367	-148.957
77	-31.690	-62.870	-86.930	-114.383	-148.927
78	-31.700	-62.843	-86.930	-114.393	-148.980
79	-31.700	-62.837	-86.913	-114.393	-148.977
80	-31.690	-62.817	-86.940	-114.413	-148.990
81	-31.693	-62.903	-86.953	-114.397	-148.957
82	-31.710	-62.857	-86.947	-114.457	-149.023
83	-31.707	-62.927	-86.933	-114.413	-149.017
84	-31.697	-62.900	-86.953	-114.437	-149.003
85	-31.703	-62.937	-86.970	-114.413	-149.043
86	-31.707	-62.893	-86.963	-114.413	-149.027
87	-31.713	-62.930	-86.947	-114.440	-149.063
88	-31.710	-62.903	-86.973	-114.443	-149.017
89	-31.703	-62.970	-86.987	-114.463	-149.057
90	-31.713	-62.983	-86.973	-114.440	-149.083
91	-31.720	-62.923	-86.960	-114.453	-149.080
92	-31.710	-62.927	-86.987	-114.443	-149.023
93	-31.713	-63.007	-87.003	-114.443	-149.087
94	-31.700	-62.963	-86.987	-114.470	-149.113
95	-31.710	-62.953	-86.980	-114.457	-149.127
96	-31.713	-62.983	-86.997	-114.483	-149.100
97	-31.713	-62.910	-87.013	-114.480	-149.057
98	-31.713	-62.910	-87.007	-114.497	-149.173
99	-31.720	-62.897	-87.000	-114.493	-149.127
100	-31.713	-62.943	-87.017	-114.503	-149.163
101	-31.710	-62.910	-87.033	-114.520	-149.087
102	-31.713	-62.903	-87.027	-114.510	-149.147
103	-31.717	-62.880	-87.017	-114.493	-149.183

104	-31.717	-62.973	-87.030	-114.613	-149.140
105	-31.717	-62.987	-87.050	-114.557	-149.160
106	-31.723	-63.020	-87.033	-114.587	-149.167
107	-31.720	-62.950	-87.030	-114.577	-149.153
108	-31.720	-62.970	-87.053	-114.563	-149.153
109	-31.717	-62.933	-87.060	-114.580	-149.207
110	-31.717	-62.973	-87.040	-114.590	-149.120
111	-31.717	-63.007	-87.040	-114.560	-149.220
112	-31.723	-62.960	-87.053	-114.613	-149.193
113	-31.723	-62.977	-87.077	-114.580	-149.170
114	-31.717	-62.983	-87.067	-114.560	-149.207
115	-31.730	-63.023	-87.063	-114.613	-149.177
116	-31.720	-63.020	-87.120	-114.603	-149.243
117	-31.733	-63.053	-87.093	-114.563	-149.220
118	-31.727	-63.030	-87.083	-114.617	-149.207
119	-31.723	-62.950	-87.083	-114.610	-149.193
120	-31.730	-63.037	-87.097	-114.623	-149.270
121	-31.727	-62.983	-87.113	-114.597	-149.233
122	-31.740	-63.013	-87.093	-114.613	-149.247
123	-31.733	-62.987	-87.103	-114.627	-149.250
124	-31.723	-62.997	-87.120	-114.620	-149.263
125	-31.740	-63.020	-87.123	-114.633	-149.280
126	-31.740	-63.037	-87.103	-114.647	-149.277
127	-31.737	-63.040	-87.113	-114.653	-149.280
128	-31.727	-63.027	-87.130	-114.623	-149.253
129	-31.740	-63.003	-87.133	-114.680	-149.273
130	-31.743	-63.050	-87.120	-114.647	-149.297
131	-31.737	-63.087	-87.117	-114.680	-149.293
132	-31.733	-63.090	-87.137	-114.647	-149.310
133	-31.740	-63.087	-87.140	-114.667	-149.303
Average	**-31.690**	**-62.900**	**-86.910**	**-114.400**	**-148.970**

7.5. Strain gauge five (SG 5) data

Strain gauge 5: Average Strain Values					
	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Samples	133	133	133	133	133
Units	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)
Min	-101.84	-210.96	-309.27	-402.01	-496.11
Max	-101.04	-209.68	-307.49	-399.38	-493.08
Mean	-101.32	-210.12	-307.87	-400.45	-494.18
STD	0.18	0.31	0.35	0.73	0.76
1	-0.032	-0.225	-0.021	0.015	-0.013
2	-0.061	-0.249	-0.084	-0.009	-0.056
3	0.113	-0.188	-0.564	0.602	-0.071
4	1.237	0.137	0.947	0.168	0.173
5	1.393	0.198	-1.926	-0.593	-0.828
6	1.597	-0.158	-1.953	-0.790	-1.349
7	1.425	-0.015	-71.048	-1.368	-6.517
8	-0.313	-0.434	-96.168	-69.857	-103.628
9	-25.537	-0.856	-100.060	-235.173	-197.883
10	-44.776	-1.646	-105.017	-334.770	-346.967
11	-56.454	-5.082	-162.976	-406.770	-433.893
12	-73.600	-49.237	-202.945	-405.610	-478.960
13	-89.217	-153.037	-205.809	-419.220	-507.813
14	-99.407	-195.747	-242.277	-417.273	-508.290
15	-98.323	-205.307	-280.323	-413.300	-520.360
16	-103.570	-204.930	-296.133	-410.603	-513.180
17	-103.300	-207.910	-309.237	-411.497	-508.187
18	-102.787	-218.527	-311.477	-410.113	-510.323
19	-102.563	-217.857	-316.843	-410.277	-509.150
20	-102.520	-215.460	-312.453	-409.020	-508.360
21	-102.330	-212.570	-312.163	-405.577	-506.323
22	-101.877	-210.887	-312.563	-402.810	-503.780
23	-101.920	-211.187	-311.950	-402.013	-502.300
24	-101.997	-211.377	-311.610	-401.940	-502.257
25	-101.963	-211.183	-311.730	-402.130	-501.560
26	-101.800	-211.130	-311.360	-402.093	-501.360
27	-101.743	-211.090	-310.930	-402.230	-500.963

28	-101.843	-211.040	-310.403	-402.170	-500.417
29	-101.913	-211.073	-310.047	-402.247	-499.710
30	-101.740	-211.050	-309.637	-402.393	-499.177
31	-101.647	-210.993	-309.027	-402.137	-497.933
32	-101.800	-211.013	-308.813	-402.053	-496.943
33	-101.843	-210.957	-308.950	-402.003	-496.113
34	-101.720	-210.693	-309.270	-401.960	-494.900
35	-101.593	-210.620	-309.040	-402.007	-495.000
36	-101.667	-210.737	-308.877	-401.867	-494.960
37	-101.787	-210.887	-308.820	-401.837	-495.367
38	-101.650	-210.690	-308.560	-401.807	-495.193
39	-101.567	-210.507	-308.093	-401.690	-495.440
40	-101.557	-210.637	-308.123	-401.610	-495.877
41	-101.710	-210.767	-308.287	-401.657	-495.870
42	-101.630	-210.600	-308.200	-401.537	-495.687
43	-101.507	-210.483	-308.130	-401.433	-495.993
44	-101.487	-210.497	-308.360	-401.513	-495.743
45	-101.647	-210.633	-308.590	-401.497	-495.457
46	-101.583	-210.557	-308.407	-401.437	-495.367
47	-101.457	-210.433	-308.120	-401.357	-495.060
48	-101.440	-210.447	-308.140	-401.363	-494.770
49	-101.530	-210.593	-308.107	-401.313	-494.790
50	-101.583	-210.503	-307.953	-401.290	-494.877
51	-101.460	-210.297	-307.980	-401.200	-495.023
52	-101.340	-210.387	-308.247	-401.110	-494.897
53	-101.450	-210.530	-308.253	-401.153	-494.990
54	-101.560	-210.443	-308.063	-401.040	-495.390
55	-101.450	-210.300	-308.023	-401.073	-494.950
56	-101.330	-210.280	-308.030	-401.090	-494.887
57	-101.393	-210.407	-307.963	-400.997	-494.880
58	-101.517	-210.380	-307.803	-400.857	-494.700
59	-101.383	-210.250	-307.947	-400.787	-494.450
60	-101.333	-210.223	-308.097	-400.890	-494.657
61	-101.380	-210.390	-308.047	-400.890	-494.560
62	-101.453	-210.367	-307.930	-400.900	-494.543
63	-101.387	-210.237	-307.840	-400.767	-494.713
64	-101.267	-210.177	-307.933	-400.777	-494.713
65	-101.307	-210.307	-307.880	-400.760	-494.680

66	-101.387	-210.237	-307.833	-400.747	-494.570
67	-101.437	-210.153	-307.910	-400.743	-494.523
68	-101.337	-210.120	-308.013	-400.770	-494.417
69	-101.273	-210.240	-308.040	-400.693	-494.323
70	-101.323	-210.250	-307.817	-400.667	-494.227
71	-101.390	-210.130	-307.870	-400.633	-494.290
72	-101.383	-210.073	-307.817	-400.577	-494.243
73	-101.220	-210.167	-307.707	-400.493	-494.240
74	-101.323	-210.183	-307.803	-400.533	-494.270
75	-101.340	-210.093	-307.903	-400.480	-494.303
76	-101.310	-210.043	-307.810	-400.493	-494.290
77	-101.263	-210.113	-307.750	-400.570	-494.163
78	-101.237	-210.147	-307.773	-400.507	-494.213
79	-101.340	-210.117	-307.847	-400.407	-494.117
80	-101.327	-210.037	-307.687	-400.420	-494.027
81	-101.217	-210.070	-307.693	-400.433	-494.023
82	-101.263	-210.127	-307.813	-400.357	-494.067
83	-101.280	-210.117	-307.797	-400.407	-494.077
84	-101.333	-210.017	-307.680	-400.377	-493.933
85	-101.243	-210.043	-307.733	-400.327	-494.010
86	-101.213	-210.063	-307.763	-400.217	-494.103
87	-101.243	-210.050	-307.737	-400.217	-493.933
88	-101.320	-210.000	-307.627	-400.203	-493.843
89	-101.253	-209.983	-307.707	-400.200	-493.987
90	-101.187	-210.027	-307.807	-400.197	-493.887
91	-101.223	-210.077	-307.687	-400.177	-493.667
92	-101.303	-209.933	-307.610	-400.193	-493.773
93	-101.237	-209.967	-307.703	-400.143	-493.917
94	-101.203	-210.033	-307.693	-400.090	-493.730
95	-101.180	-210.017	-307.640	-400.083	-493.717
96	-101.240	-209.877	-307.593	-400.113	-493.837
97	-101.300	-209.903	-307.733	-400.003	-493.773
98	-101.243	-210.003	-307.707	-400.020	-493.617
99	-101.170	-209.940	-307.590	-400.060	-493.707
100	-101.193	-209.833	-307.660	-399.993	-493.710
101	-101.260	-209.870	-307.687	-399.987	-493.523
102	-101.193	-209.973	-307.650	-399.953	-493.530
103	-101.143	-209.910	-307.540	-399.953	-493.683

104	-101.243	-209.810	-307.567	-399.927	-493.543
105	-101.260	-209.883	-307.743	-399.910	-493.477
106	-101.240	-209.967	-307.627	-399.913	-493.553
107	-101.093	-209.923	-307.527	-399.810	-493.693
108	-101.190	-209.790	-307.650	-399.877	-493.420
109	-101.260	-209.810	-307.710	-399.837	-493.513
110	-101.187	-209.920	-307.580	-399.770	-493.490
111	-101.097	-209.917	-307.490	-399.603	-493.560
112	-101.157	-209.807	-307.657	-399.730	-493.403
113	-101.167	-209.793	-307.673	-399.673	-493.433
114	-101.213	-209.883	-307.533	-399.733	-493.437
115	-101.067	-209.880	-307.540	-399.713	-493.490
116	-101.113	-209.713	-307.600	-399.690	-493.323
117	-101.203	-209.773	-307.627	-399.713	-493.513
118	-101.153	-209.880	-307.513	-399.693	-493.337
119	-101.130	-209.877	-307.707	-399.617	-493.293
120	-101.103	-209.733	-307.633	-399.633	-493.470
121	-101.173	-209.740	-307.643	-399.610	-493.360
122	-101.210	-209.833	-307.530	-399.567	-493.290
123	-101.090	-209.780	-307.567	-399.547	-493.313
124	-101.107	-209.680	-307.653	-399.537	-493.380
125	-101.180	-209.800	-307.623	-399.577	-493.383
126	-101.197	-209.780	-307.487	-399.483	-493.190
127	-101.127	-209.743	-307.573	-399.500	-493.440
128	-101.077	-209.710	-307.670	-399.487	-493.283
129	-101.147	-209.717	-307.553	-399.450	-493.253
130	-101.197	-209.750	-307.537	-399.440	-493.083
131	-101.143	-209.713	-307.620	-399.493	-493.250
132	-101.040	-209.723	-307.570	-399.410	-493.163
133	-101.110	-209.750	-307.513	-399.380	-493.230
Average	**-101.320**	**-210.120**	**-307.870**	**-400.450**	**-494.180**

7.6. Strain gauge six (SG 6) data

Strain gauge 6: Average Strain Values					
	Experiment A	Experiment B	Experiment C	Experiment D	Experiment E
Samples	133	133	133	133	133
Units	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)	Micro (m/m)
Min	-97.71	-199.52	-305.26	-431.88	-605.58
Max	-97.53	-199.38	-304.62	-430.62	-603.8
Mean	-97.63	-199.46	-304.95	-431.33	-605.04
STD	0.05	0.03	0.17	0.28	0.34
1	0.014	-0.044	-0.002	0.003	0.008
2	0.036	-0.014	-0.008	-0.034	0.022
3	-1.402	-0.207	0.140	-0.013	-0.510
4	-1.625	-1.607	-2.009	-1.308	-0.635
5	-2.312	-2.129	-2.035	-2.151	-1.354
6	-2.572	-2.776	-2.249	-2.137	-2.224
7	-7.235	-36.921	-2.551	-2.211	-2.251
8	-39.563	-56.844	-5.972	-2.467	-2.378
9	-79.663	-82.264	-44.747	-69.660	-2.436
10	-96.590	-131.092	-79.290	-193.836	-4.798
11	-97.290	-134.857	-132.927	-294.160	-189.790
12	-97.220	-162.640	-263.580	-411.177	-319.620
13	-97.113	-195.487	-299.283	-422.217	-477.010
14	-97.173	-197.907	-302.223	-423.550	-568.017
15	-97.557	-199.480	-303.097	-429.853	-591.493
16	-97.560	-199.020	-303.633	-429.140	-600.300
17	-97.557	-199.187	-303.787	-429.423	-603.210
18	-97.550	-199.193	-303.327	-429.697	-602.897
19	-97.583	-199.427	-303.660	-430.230	-602.523
20	-97.527	-199.467	-303.510	-429.780	-602.813
21	-97.570	-199.463	-303.973	-430.113	-603.563
22	-97.607	-199.433	-303.800	-430.120	-603.420
23	-97.573	-199.390	-304.307	-430.360	-603.653
24	-97.533	-199.453	-304.423	-430.440	-603.693
25	-97.557	-199.473	-304.500	-430.463	-603.900
26	-97.580	-199.440	-304.467	-430.523	-603.763
27	-97.573	-199.390	-304.423	-430.677	-604.160

28	-97.520	-199.440	-304.493	-430.563	-603.940
29	-97.540	-199.453	-304.567	-430.663	-603.867
30	-97.583	-199.447	-304.553	-430.797	-603.883
31	-97.590	-199.410	-304.550	-430.713	-604.370
32	-97.587	-199.413	-304.553	-430.703	-603.923
33	-97.553	-199.420	-304.623	-430.683	-604.427
34	-97.580	-199.420	-304.787	-430.690	-603.803
35	-97.587	-199.450	-304.617	-430.780	-605.020
36	-97.570	-199.430	-304.637	-430.867	-603.837
37	-97.550	-199.440	-304.660	-430.713	-604.683
38	-97.560	-199.420	-304.630	-430.857	-604.773
39	-97.530	-199.447	-304.687	-430.967	-604.743
40	-97.533	-199.417	-304.653	-430.623	-604.563
41	-97.557	-199.410	-304.677	-430.840	-604.387
42	-97.617	-199.430	-304.693	-431.043	-604.667
43	-97.567	-199.453	-304.693	-430.927	-604.437
44	-97.537	-199.380	-304.693	-431.080	-604.567
45	-97.543	-199.437	-304.733	-430.930	-604.697
46	-97.573	-199.433	-304.713	-431.003	-604.660
47	-97.533	-199.457	-304.667	-430.973	-604.700
48	-97.583	-199.427	-304.743	-431.047	-604.567
49	-97.547	-199.377	-304.760	-431.023	-604.690
50	-97.557	-199.410	-304.737	-431.260	-604.867
51	-97.593	-199.447	-304.727	-431.183	-604.630
52	-97.567	-199.403	-304.720	-431.267	-604.713
53	-97.573	-199.457	-304.747	-431.040	-604.937
54	-97.580	-199.470	-304.810	-431.080	-604.457
55	-97.557	-199.447	-304.737	-431.117	-604.893
56	-97.613	-199.407	-304.803	-431.087	-604.730
57	-97.580	-199.430	-304.803	-431.193	-604.890
58	-97.620	-199.473	-304.800	-431.107	-604.767
59	-97.590	-199.503	-304.720	-431.190	-604.953
60	-97.597	-199.423	-304.780	-431.110	-605.050
61	-97.620	-199.450	-304.847	-431.267	-604.793
62	-97.617	-199.460	-304.800	-431.187	-604.920
63	-97.637	-199.490	-304.803	-431.160	-604.873
64	-97.587	-199.437	-304.857	-431.253	-604.900
65	-97.597	-199.480	-304.823	-431.197	-604.897

66	-97.647	-199.473	-304.843	-431.243	-605.147
67	-97.643	-199.443	-304.813	-431.197	-604.790
68	-97.630	-199.487	-304.850	-431.233	-605.003
69	-97.643	-199.487	-304.907	-431.283	-605.077
70	-97.660	-199.490	-304.937	-431.250	-604.950
71	-97.627	-199.457	-304.843	-431.317	-605.093
72	-97.657	-199.463	-304.880	-431.253	-604.730
73	-97.630	-199.463	-304.940	-431.320	-604.983
74	-97.657	-199.443	-304.953	-431.240	-605.087
75	-97.697	-199.480	-304.927	-431.383	-605.000
76	-97.670	-199.483	-304.943	-431.270	-604.997
77	-97.657	-199.470	-305.027	-431.303	-604.843
78	-97.703	-199.423	-304.997	-431.320	-605.070
79	-97.667	-199.477	-304.980	-431.263	-605.010
80	-97.643	-199.490	-305.010	-431.410	-605.087
81	-97.637	-199.473	-305.053	-431.280	-604.883
82	-97.683	-199.443	-305.040	-431.340	-605.210
83	-97.683	-199.493	-305.000	-431.300	-605.113
84	-97.623	-199.493	-305.047	-431.447	-605.023
85	-97.637	-199.473	-305.037	-431.277	-605.130
86	-97.643	-199.457	-305.037	-431.287	-605.023
87	-97.647	-199.473	-305.010	-431.377	-605.237
88	-97.647	-199.480	-305.050	-431.423	-604.987
89	-97.637	-199.440	-305.077	-431.533	-605.147
90	-97.653	-199.430	-305.077	-431.320	-605.330
91	-97.670	-199.477	-304.997	-431.340	-605.220
92	-97.637	-199.433	-305.067	-431.320	-604.910
93	-97.647	-199.463	-305.047	-431.340	-605.297
94	-97.670	-199.417	-305.050	-431.347	-605.377
95	-97.677	-199.470	-305.013	-431.317	-605.360
96	-97.613	-199.423	-305.070	-431.470	-605.213
97	-97.640	-199.467	-305.107	-431.347	-604.957
98	-97.663	-199.517	-305.080	-431.417	-605.550
99	-97.673	-199.497	-305.037	-431.357	-605.263
100	-97.647	-199.497	-305.057	-431.387	-605.490
101	-97.617	-199.443	-305.073	-431.513	-605.010
102	-97.680	-199.457	-305.110	-431.437	-605.263
103	-97.677	-199.467	-305.067	-431.357	-605.533

104	-97.680	-199.427	-305.100	-431.877	-605.220
105	-97.700	-199.473	-305.123	-431.583	-605.290
106	-97.653	-199.477	-305.063	-431.787	-605.290
107	-97.660	-199.407	-305.083	-431.650	-605.270
108	-97.673	-199.473	-305.130	-431.547	-605.257
109	-97.640	-199.467	-305.140	-431.633	-605.407
110	-97.673	-199.450	-305.093	-431.710	-604.983
111	-97.713	-199.463	-305.070	-431.503	-605.520
112	-97.637	-199.477	-305.077	-431.700	-605.320
113	-97.667	-199.480	-305.130	-431.597	-605.157
114	-97.663	-199.460	-305.053	-431.507	-605.337
115	-97.683	-199.467	-305.063	-431.673	-605.207
116	-97.663	-199.487	-305.260	-431.633	-605.463
117	-97.653	-199.453	-305.073	-431.513	-605.380
118	-97.647	-199.447	-305.100	-431.683	-605.313
119	-97.680	-199.440	-305.097	-431.617	-605.170
120	-97.633	-199.480	-305.117	-431.690	-605.583
121	-97.683	-199.450	-305.143	-431.603	-605.337
122	-97.657	-199.433	-305.113	-431.620	-605.420
123	-97.660	-199.443	-305.143	-431.623	-605.387
124	-97.670	-199.430	-305.137	-431.603	-605.400
125	-97.693	-199.470	-305.190	-431.667	-605.480
126	-97.680	-199.483	-305.133	-431.687	-605.463
127	-97.707	-199.470	-305.100	-431.687	-605.373
128	-97.683	-199.463	-305.187	-431.553	-605.287
129	-97.693	-199.467	-305.147	-431.833	-605.407
130	-97.663	-199.503	-305.133	-431.603	-605.410
131	-97.680	-199.470	-305.140	-431.733	-605.390
132	-97.643	-199.457	-305.170	-431.633	-605.567
133	-97.683	-199.503	-305.167	-431.653	-605.437
Average	**-97.630**	**-199.460**	**-304.950**	**-431.330**	**-605.040**

7.7. Strain gauge eight (SG 8) data

Strain gauge 8: Average Strain Values					
	Experiment A	**Experiment B**	**Experiment C**	**Experiment D**	**Experiment E**
Samples	**133**	**133**	**133**	**133**	**133**
Units	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**	**Micro (m/m)**
Min	**18.53**	**33.43**	**51.34**	**66.81**	**92.39**
Max	**18.69**	**33.55**	**51.55**	**70.45**	**92.75**
Mean	**18.64**	**33.48**	**51.47**	**70.05**	**92.6**
STD	**0.04**	**0.02**	**0.06**	**0.34**	**0.1**
1	-0.009	-0.016	-0.020	-0.028	-0.017
2	0.008	-0.018	-0.031	-0.040	-0.011
3	-0.029	-0.002	0.000	-0.029	-0.007
4	0.111	0.253	0.264	0.147	0.137
5	0.039	0.265	0.415	0.419	0.108
6	0.363	0.291	11.670	0.499	0.258
7	2.649	0.238	15.819	15.222	3.807
8	8.149	7.609	29.301	36.063	42.457
9	11.741	11.128	46.153	45.899	71.110
10	12.838	20.196	50.067	50.431	81.713
11	12.874	26.990	50.743	56.850	87.970
12	12.778	31.267	51.203	67.770	91.623
13	12.790	31.953	51.353	70.543	92.170
14	17.737	32.987	51.287	70.697	92.410
15	18.977	33.193	51.260	71.270	92.267
16	19.370	33.240	51.300	71.067	92.193
17	19.383	33.293	51.290	71.030	92.267
18	19.417	33.340	51.260	71.193	92.283
19	19.397	33.347	51.243	71.200	92.320
20	19.387	33.340	51.267	71.217	92.287
21	19.030	33.347	51.290	71.263	92.287
22	18.933	33.353	51.267	69.207	92.327
23	18.930	33.377	51.263	70.413	92.313
24	18.933	33.380	51.277	68.297	92.307
25	18.953	33.380	51.317	70.477	92.317
26	18.837	33.383	51.307	70.290	92.350
27	18.377	33.387	51.287	68.243	92.357

28	18.523	33.407	51.310	70.287	92.347
29	18.520	33.400	51.323	70.337	92.357
30	18.520	33.413	51.320	69.673	92.370
31	18.520	33.427	51.297	70.413	92.363
32	18.527	33.427	51.337	70.420	92.370
33	18.533	33.427	51.357	70.447	92.390
34	18.533	33.430	51.350	70.230	92.400
35	18.533	33.430	51.337	66.813	92.387
36	18.533	33.433	51.343	69.970	92.407
37	18.547	33.433	51.373	70.070	92.433
38	18.550	33.437	51.380	69.897	92.413
39	18.550	33.443	51.353	70.087	92.403
40	18.553	33.443	51.357	70.130	92.437
41	18.573	33.443	51.397	70.107	92.423
42	18.587	33.443	51.390	70.153	92.413
43	18.557	33.450	51.357	70.143	92.440
44	18.567	33.460	51.370	70.157	92.457
45	18.573	33.457	51.397	70.187	92.443
46	18.570	33.460	51.400	70.167	92.450
47	18.573	33.473	51.380	70.150	92.470
48	18.600	33.463	51.393	70.170	92.460
49	18.593	33.463	51.417	70.187	92.477
50	18.610	33.467	51.407	70.173	92.493
51	18.607	33.480	51.387	70.163	92.510
52	18.587	33.473	51.407	70.177	92.510
53	18.603	33.483	51.427	70.183	92.503
54	18.597	33.477	51.410	70.150	92.520
55	18.617	33.467	51.420	70.147	92.517
56	18.607	33.480	51.417	70.170	92.503
57	18.623	33.463	51.457	70.173	92.533
58	18.607	33.487	51.440	70.137	92.553
59	18.630	33.490	51.417	70.150	92.517
60	18.623	33.490	51.413	70.183	92.540
61	18.617	33.480	51.437	70.153	92.543
62	18.597	33.483	51.440	70.133	92.567
63	18.630	33.500	51.433	70.157	92.523
64	18.623	33.493	51.440	70.167	92.560
65	18.637	33.500	51.440	70.160	92.570

66	18.627	33.500	51.463	70.140	92.537
67	18.627	33.490	51.447	70.143	92.563
68	18.643	33.493	51.440	70.177	92.580
69	18.633	33.503	51.450	70.147	92.583
70	18.637	33.510	51.463	70.123	92.570
71	18.633	33.487	51.453	70.150	92.577
72	18.623	33.497	51.450	70.153	92.607
73	18.630	33.507	51.463	70.110	92.583
74	18.637	33.547	51.470	70.123	92.593
75	18.637	33.510	51.497	70.140	92.600
76	18.643	33.507	51.467	70.147	92.597
77	18.640	33.510	51.487	70.100	92.620
78	18.640	33.513	51.493	70.103	92.590
79	18.637	33.530	51.483	70.143	92.623
80	18.640	33.507	51.470	70.110	92.620
81	18.633	33.500	51.477	70.093	92.610
82	18.653	33.497	51.493	70.113	92.610
83	18.657	33.497	51.503	70.110	92.630
84	18.640	33.507	51.470	70.090	92.610
85	18.653	33.487	51.497	70.073	92.610
86	18.650	33.503	51.520	70.097	92.650
87	18.653	33.510	51.500	70.107	92.620
88	18.657	33.510	51.480	70.077	92.630
89	18.650	33.500	51.490	70.080	92.640
90	18.667	33.503	51.523	70.107	92.647
91	18.660	33.487	51.507	70.087	92.630
92	18.647	33.507	51.503	70.070	92.633
93	18.647	33.480	51.510	70.073	92.667
94	18.667	33.490	51.520	70.093	92.653
95	18.667	33.490	51.520	70.077	92.643
96	18.657	33.487	51.500	70.050	92.653
97	18.667	33.500	51.503	70.063	92.660
98	18.677	33.493	51.527	70.063	92.677
99	18.680	33.490	51.523	70.047	92.650
100	18.680	33.493	51.500	70.043	92.680
101	18.647	33.497	51.510	70.043	92.673
102	18.670	33.493	51.543	70.047	92.653
103	18.673	33.477	51.533	70.037	92.687

104	18.680	33.477	51.507	70.020	92.687
105	18.673	33.490	51.510	70.037	92.673
106	18.673	33.487	51.537	70.040	92.663
107	18.670	33.503	51.533	70.003	92.687
108	18.673	33.493	51.517	70.003	92.703
109	18.680	33.480	51.517	70.027	92.653
110	18.687	33.493	51.530	70.037	92.680
111	18.663	33.487	51.543	69.997	92.687
112	18.687	33.477	51.527	69.990	92.687
113	18.673	33.473	51.517	70.017	92.697
114	18.677	33.483	51.553	70.003	92.707
115	18.670	33.477	51.547	69.990	92.713
116	18.677	33.480	51.513	69.997	92.680
117	18.680	33.480	51.537	69.987	92.710
118	18.680	33.467	51.537	69.993	92.723
119	18.687	33.480	51.550	69.970	92.717
120	18.673	33.473	51.547	69.980	92.707
121	18.683	33.480	51.517	69.990	92.710
122	18.677	33.470	51.550	69.990	92.710
123	18.670	33.463	51.553	69.960	92.713
124	18.677	33.477	51.533	69.997	92.730
125	18.680	33.473	51.537	70.007	92.730
126	18.680	33.473	51.543	69.977	92.720
127	18.690	33.467	51.547	69.953	92.713
128	18.667	33.463	51.540	69.990	92.737
129	18.677	33.467	51.530	69.983	92.733
130	18.677	33.467	51.547	69.957	92.720
131	18.677	33.453	51.553	69.970	92.717
132	18.683	33.463	51.550	69.980	92.750
133	18.687	33.480	51.520	69.960	92.740
Average	**18.640**	**33.480**	**51.470**	**70.050**	**92.600**