Development and Verification of a Test System to Quantify Strain of an Optical Displacement Indicator and the Design of a Strain Indicating Prototype

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DEVELOPMENT AND VERIFICATION OF A TEST SYSTEM TO QUANTIFY STRAIN OF AN OPTICAL DISPLACEMENT INDICATOR AND THE DESIGN OF A STRAIN INDICATING SCREW PROTOTYPE

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Bioengineering

by
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December 2013

Accepted by:
Dr. John DesJardins, Committee Chair
Dr. Jeffery Anker
Dr. Hai Yao
ABSTRACT

Internal fixation, such as screws and plates, are often used to treat a variety of fracture types. Orthopedic screws can be used alone or with plates to apply constraint and increase rigidity of the fractured bone to promote proper healing. Some common complications with internal fracture fixators include malunion, nonunion, implant loosening and infection. With an ability to non-invasively track the strain on orthopedic devices implanted in tissue, clinicians would be able to estimate loading on the devices and in turn possibly monitor bone healing, implant loosening and/or infection in vivo. Current clinical solutions for measuring strain on orthopedic devices include radiographs and instrumented devices, both wired and wireless. The problems with these methods being used in vivo include cost, accuracy, and risk of infection. The purpose of the research presented in this thesis is to first develop and verify a test system that has the ability to quantify strain of an optical displacement indicator. Next, a strain indicating screw prototype will be designed that incorporates the optical displacement indicator.

A series of four dog bone specimens were tested using a bi-axial tabletop servohydraulic testing system (Instron 8874, Grove City, PA). An optical displacement indicator and foil strain gauge were attached to the specimens during uniaxial tension testing. Throughout the test, photos were taken of the indicator while time and strain from the foil gauge were collected through LabView. The time, cross head position and load of the Instron were also recorded through Wave Matrix. After each test, the data was compared and system improvements were implemented until the methods were
optimized and noise was minimal. A series of prototypes that incorporated the optical
displacement indicator were then designed and tested using this methodology.

The methodology was successfully verified and a working prototype of a strain
indicating screw was constructed. Future work will combine these methods with a
luminescent optical displacement indicator and laser spectroscopy in order to non-
invasively track strain through several centimeters of tissue.
DEDICATION

I dedicate this work to my family and friends that were there with support and encouragement along the way.
ACKNOWLEDGMENTS

I would first like to thank my advisor and mentor, Dr. John DesJardins, for not only his help and guidance with this work, but throughout my career as a member of the Laboratory of Orthopedic Research and Design. I would also like to thank my committee members, Dr. Jeffery Anker and Dr. Hai Yao for their support and efforts in completing this work. I had the benefit of many extremely helpful lab colleagues throughout this project as well that I am very thankful for. Lastly, thank you to my research partner, Melissa Rogalski; I would have been lost without you.
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CHAPTER ONE

GENERAL INTRODUCTION

Bone is a dynamic biological tissue composed of metabolically active cells that are integrated into a rigid framework. It is responsible for several basic functions such as support and protection, movement, hemopoiesis and storage of mineral and energy reserves. The healing potential of bone is influenced by a variety of biochemical, biomechanical, cellular, hormonal, and pathological mechanisms. A continuously occurring state of bone deposition, resorption, and remodeling facilitates the healing process. The failure of proper healing may result in the fatigue and failure of supporting instrumentation and persistence or worsening of symptoms. Currently there is no method of visualizing stress and strain on internal fixation devices non-invasively. Being able to visualize these stresses and strains would provide monumental advantages to current methods of monitoring and treating damaged and healing bone.

Bone Components and Structure

Approximately one-third of the dry weight of bone is composed of organic components including collagen fibers and different protein-carbohydrate molecules. The other two-thirds consist of inorganic components including a mixture of calcium salts, primarily calcium phosphate (65-70% of the weight). The cellular components of bone consist of osteogenic precursor cells, osteoblasts, osteoclasts, osteocytes, and the hematopoietic elements of bone marrow. The combination of these components allow bone to derive its remarkable properties and result in a structure that is strong and
durable, but not brittle. Its organic portions provide some flexibility and tensile strength while the inorganic portions provide compressional strength.\textsuperscript{26}

There are three primary types of bone: woven bone, cortical bone, and cancellous bone.\textsuperscript{11,37} Although woven bone forms the embryonic skeleton and then is largely absent from normal bone after four years of age, it is seen in the fracture callus of both children and adults.\textsuperscript{37} It does not contain lamellae and is composed of randomly arranged collagen bundles and irregularly shaped vascular spaces lined with osteoblasts. The irregularly shaped vascular spaces lead to an irregular mineralization pattern which results in woven bone being mechanically weak. This is why woven bone is normally remodeled and replaced with cortical or cancellous bone.

Cortical bone, also called compact or lamellar bone, is solid and relatively dense. It is remodeled from woven bone by means of vascular channels that invade the embryonic bone from its periosteal and endosteal surfaces. It forms the internal and external tables of flat bones and the external surface of long bones. The primary structural unit of cortical bone is an osteon, also known as a haversian system. Osteons consist of cylindrical shaped lamellar bone that surrounds longitudinally oriented vascular channels called haversian canals. Horizontally oriented canals, or Volkmann canals, connect adjacent osteons. The mechanical strength of cortical bone depends on the tight packing of the osteons.\textsuperscript{26}

Cancellous bone, also called spongy or trabecular bone, is porous and forms an open lattice of narrow plates of bone, called trabeculae. It lies between cortical bone surfaces and contains no osteons. Instead, it consists of a network of honeycombed
interstices containing hematopoietic elements and bony trabeculae.\textsuperscript{22} The trabeculae are predominantly oriented perpendicular to external forces to provide structural support but the meshwork of crisscrossing bars and plates of bone pieces the trabeculae form provide resistance to stresses applied in many directions.\textsuperscript{21,26,46} Cancellous bone is continually undergoing remodeling on the internal endosteal surfaces.

\textit{Physiologic Basis of Bone Remodeling and Fracture Healing}

Physiological bone remodeling is a process responsible for bone resorption and formation necessary to repair damaged bone, alter the shape of the bone in response to mechanical forces and to also maintain mineral homeostasis.\textsuperscript{35} This process occurs at both the periosteal and endosteal surfaces of a bone and starts before birth and continues until death. Bone remodeling consists of four sequential phases: activation, resorption, reversal and formation. The first phase, activation, involves the detection of a signal to initiate remodeling. This signal can take several forms such as direct mechanical strain on the bone, structural damage or hormone action on bone cells in response to systemic changes in homeostasis.\textsuperscript{35} Changes in stresses on the bone are thought to be sensed by osteocytes and translated into biological signals that initiate bone remodeling.\textsuperscript{5} Osteocyte apoptosis and increased osteoclastogenesis is a result of any damage to the bone matrix or limb immobilization.\textsuperscript{1,44} Osteocytes secrete transforming growth factor β (TGF-β) which inhibits the formation of osteoclasts, meaning the death of osteocytes allows osteoclast formation to occur.\textsuperscript{20} The parathyroid hormone (PTH) is a calcitropic hormone responsible for generating an endocrine remodeling signal to maintain calcium homeostasis. Binding of PTH on the surface of osteoblastic cells activates protein kinase
A, protein kinase C and calcium intracellular signaling pathways. This induces a wave of transcriptional responses that control secretion of molecules that recruit osteoclast precursors, induce osteoclast differentiation and activation, and establish bone resorption.41

The second phase, or resorption phase, begins when osteoblasts respond to the above signals and recruit osteoclast precursors to the remodeling site. In response to PTH, OPG expression is reduced and CSF-1 and RANKL production is increased to promote the formation and activity of osteoclasts. The CSF-1 cytokine promotes proliferation, survival and spreading of osteoclast precursors. RANKL additionally coordinates the differentiation of osteoclast precursors to multinucleated osteoclasts, promotes resorption activity, and prolongs the life of the mature cells.8 Before the osteoclasts can attach, matrix metalloproteinases (MMPs), must degrade the unmineralized osteoid that lines the bone surface and expose RGD adhesion sites.35 Osteoclasts anchor to these RGD adhesion sites and create a microenvironment beneath the cell that is sealed. Hydrogen ions are pumped into the sealed zone, and dissolution of mineralized matrix occurs in this acidic space, producing Howship’s lacunae on the surface of trabecular bone and Haversian canals in cortical bone.10,42 The organic bone matrix that is left is then degraded by a collection of collagenolytic enzymes that work best at a low pH.38 The resorption phase is completed after the osteoclasts undergo apoptosis.10

The third phase, or reversal phase, occurs when bone resorption transitions to bone formation. Mononuclear cells including monocytes, osteocytes released from bone
matrix and preosteoblasts gather in resorption cavities and prepare the bone surface for subsequent osteoblast-mediated bone formation. The specific molecules involved in this reversal phase are still unknown but has been proposed by Smit et al to be mediated by the strain gradient in the lacunae. As osteoclasts resorb cortical bone in a cutting cone, strain is highest at the base of the lacunae and less in surrounding bone at the edges. The strain gradient may lead to activation of osteoclasts by reduced strain and osteoblasts by increased strain.\textsuperscript{39,40} A system that is able to monitor and measure strain will help in determining which cells are being activated and therefore the phase of healing the bone is experiencing.

The final phase is the formation phase. During this phase, osteoblasts synthesize new collagenous organic matrix and regulate the mineralization of this new matrix. This is done by releasing membrane-bound matrix vesicles that concentrate calcium and phosphate while enzymatically destroying mineralization inhibitors such as pyrophosphate and proteoglycans.\textsuperscript{2} Osteoblasts surrounded by matrix become osteocytes with an extensive canalicular network connecting them to bone surface lining cells, osteoblasts and other osteocytes. Approximately 50 to 70\% of osteoblasts undergo apoptosis at the completion of this phase. This results with the balance becoming osteocytes. Osteocytes serves as a blood-bone barrier by regulating influx and efflux of mineral ions into and out of bone extracellular fluid, but maintain the ability to redifferentiate into osteoblasts when exposed to PTH or mechanical forces.\textsuperscript{16} The end result of this process is the production of a new osteon and the preservation of the bones mechanical strength, or load versus displacement. At this stage, fixation devices will be
experiencing minimal strain. By non-invasively monitoring this, clinicians will be able to determine when the healing process is complete and therefore the best time to remove the supporting devices.

A bone is said to be fractured if there is a break in its continuity, which is usually due to trauma. During a fracture, the mechanical strength of the bone is compromised. Similar to the remodeling process described above, fracture healing is a dynamic pathobiological process that is governed by a variety of systemic and local factors. The type of fracture and treatment control weather primary or secondary fracture healing occurs. If the fracture is anatomically reduced at the micrometric level, primary or osteonal healing occurs. Osteoclasts create cutting cones and primarily cross the fracture site. This requires very high stability and therefore is the rarest type of healing. More frequently, secondary healing occurs. It can be categorized in three distinct but overlapping phases with an overall goal to restore bone structure, composition and function. In the first stage, known as the inflammatory stage, begins immediately following the bone fracture. A hematoma occurs at the fracture site and continues to develop during the first few hours and days. The hematoma provides two factors important for successful fracture healing: a small amount of mechanical stability to the fracture site and the recruitment of osteoblast and chondrocyte precursors to the fracture site in large numbers. These precursors can then start to differentiate into osteoblasts and chondrocytes to begin producing new matrix. Inflammatory cells such as macrophages and osteoclasts are also recruited to the fracture site to remove damaged and necrotic tissue. Due to the fracture disrupting the periosteum surrounding the bone, more
precursor cells from the periosteum will be introduced into the fracture site. The primary nutrient and oxygen supply of this early process is provided by the exposed cancellous bone and muscle.\textsuperscript{7,14} This will begin the formation of granulation tissue, ingrowth of vascular tissue, and migration of mesenchymal cells.\textsuperscript{4} Both intramembranous and endochondral ossification may occur at the fracture site. The use of anti-inflammatory or cytotoxic medication during the first week may alter the inflammatory response and inhibit bone healing.\textsuperscript{7,14}

During the repair stage, osteogenesis continues and the resulting proliferation of woven bone tissue will produce a fracture callus to bridge the fracture gap. Fibroblasts begin to lay down a stroma that helps support vascular ingrowth. Vascular ingrowth can be inhibited by many factors such as nicotine, malnutrition, diabetes, rheumatoid arthritis and osteoporosis. As vascular ingrowth progresses, a collagen matrix is laid down while osteoid is secreted and subsequently mineralized, which leads to the formation of a soft callus around the repair site. In terms of resistance to movement, this callus is very weak in the first 4 to 6 weeks of the healing process and requires adequate protection in the form of bracing or internal fixation. During this time, external mechanical stimuli have the greatest effect on fracture healing. Too much motion will result in a non-union, or the healing of a fracture site with an unstable fibrous union instead of bone. To prevent non-unions, different types of fracture fixation devices are used and will be discussed later. Between six to twelve weeks, the callus ossifies, forming a bridge of woven bone between the fracture fragments.\textsuperscript{4,22} A system that monitors strain could be used to monitor displacement as well. This displacement measurement could be used to ensure
that the fracture is experiencing optimal micromotion needed to avoid non-union and results in a fast recovery.

Fracture healing is completed during the remodeling stage in which the healing bone is restored to its original shape, structure, and mechanical strength. The healed bony callus is formed of woven bone and primary bone. The base material of the callus usually has lower strength and stiffness than mature lamellar bone. The large mass of bone in the callus gives it its strength. While maintaining its mechanical integrity, the callus mass is reduced through remodeling. Remodeling of the bone occurs slowly over months to years and is facilitated by mechanical stress placed on the bone. Adequate strength is typically achieved in 3 to 6 months. This strength, or load versus displacement, can be quantified using a system that can measure strain in-vivo.

**Influence of Load and Strain on Bone Remodeling/Healing**

Until death, bone continually rebuilds and remodels itself. It possesses the ability to alter its structure based on the magnitude and direction of the loading force it is experiencing. In response to mechanical stress, bone has the ability to increase its strength over a period of time by increasing the amounts of mineral salts deposited and collagen fibers synthesized. Stress also increases the production of the hormone calcitonin, which helps inhibit bone resorption by osteoclasts and encourage bone deposition by osteoblasts. In contrast, lack of mechanical stress weakens bone through both demineralization of the bone matrix and reduction of collagen formation. Research has shown that regular weight-bearing exercise can increase total bone mass in adolescents and young adults prior to its reduction later in life.
The osteogenic potential, influenced by blood supply, hormones, or growth factors and the biomechanical conditions at the fracture site are the two most important factors guiding the healing process. Given a sufficient vascularity, the course of fracture healing is mainly influenced by interfragmentary movement which is determined by the applied load and the stability of the fixation. As the fracture site is exposed to an axial loading force, bone is generally laid down where it is needed and resorbed from where it is not needed. This is why secondary fracture healing benefits from micromotion.

The biomechanical environment is characterized by osteoblasts and osteocytes that sense the mechanical signal and express biological markers that affect the repair process. In-vivo studies have shown that strain-activated osteoblastic cells increase the presence of the osteoblastic marker bone-specific alkaline phosphatase (AP), TGF-β1, and basic fibroblast growth factor (bFGF). The expression of bone morphogenetic proteins (BMPs) is also influence by mechanical strain. Previous studies have shown an upregulation of IGF-1, BMP-2 and BMP-4. Mechanical stimulation activates and mediates the expression of these genes by activation of specific signal transduction pathways by phosphorylation and dephosphorylation. This mechanical stimulation is detected by the deformation of the cell membrane, changing the conformation of membrane proteins like stretch-activated cation channels and integrins. The result is the binding of specific transcription factors to the promoter of the target gene.

Perren introduced the importance of load and the resulting strain in the fracture healing cascade. Fracture gap strain is defined as the relative displacement of the fracture gap divided by the initial fracture gap. Perren found that when fracture gap
strain is less than 2%, primary fracture healing will occur. When the strain is greater than 2% but less than 10%, a callus is formed and the fracture will heal by secondary healing. Any strain larger than 10% will result in rupture of the fracture gap callus and nonunion will occur. These strains apply for simple fractures and comminuted fractures although comminuted fractures can tolerate more displacement due to the overall motion being shared between many fracture gaps.

**Internal Fracture Fixation Devices**

Fracture repair, which aims at regaining the functional competence of a bone, can be accomplished by many ways, such as natural healing, external fixation and internal fixation. External fixation uses an external frame with transdermal pins inserted into bone pieces on both sides of the fracture. For the purpose of this paper, internal fixation will be discussed. Internal fixation includes the use of screws, plates, pins, nails and/or wires. This method of fixation is advantageous over external fixation due to the ability to achieve more mechanical stability and less chance of transdermal infection. The fracture pattern determines the ideal method of fixation for fracture healing. Although the concept of internal fixation dates back to the mid 1800’s, the use of plates and screws was first documented in the 1880’s and 1890’s.²³

Bone screws are a basic part of modern internal fixation in which they can be used independently or in combination with other devices. When used independently, interfragmentary lag screws are used. These provide static compression across two bone surfaces. The two basic types of screws available are cortical and cancellous screws. Cortical screws are designed for compact diaphyseal bone while cancellous screws are
designed for trabecular metaphyseal bone, where the bone is softer. Cortical screws have a smaller thread diameter, decreased pitch, and a shallower thread than cancellous screws. Cancellous screws typically have a larger thread diameter, pitch and a greater difference between major and minor shaft diameters to increase the surface area for bone purchase.

Another type of screw used is a dynamic locking screw. It was designed to reduce the stiffness of locked plate constructs. It is composed of an outer sleeve with threads that engage the bone and an inner pin with threads that lock to the plate. The inner pin is designed in a way that allows movement within the outer sleeve, while the plate-screw interface and bone-screw interface remain constant. Doberle et al\textsuperscript{15} conducted a mechanical study and reported that dynamic locking screws reduced the axial stiffness by 16\% and increased interfragmentary motion at the near cortical side from 282\textmu m with a standard locked screw to 423\textmu m. Although the motion increased, it is still less than the 500\textmu m limit determined by Ganesh et al that will be discussed next.\textsuperscript{43}

Fracture fixation by bone-plate is intended to provide immobilization at the fracture site and reduce the fracture gap, thus allowing primary bone healing for micro-movement under about 500 microns.\textsuperscript{43} The role of a bone-plate is to hold the fractured bone segments in position, without allowing tensile stresses at the fractured interface. Instead, compressive stresses induced on the fracture gap will accelerate the healing process. The efficiency of the plate and screws is determined by three main factors: the degree of bone contact at the fracture gap, stability in terms of reduced movement at the fracture gap, and sufficient stress-shielding of the bone at the fracture gap. If these
factors are not met, complications will likely occur. The complications associated with plate fixation include loosening of screws under loading, damage to vascularity beneath the plate, and excessive shielding of stresses from the bone.\textsuperscript{43}

Plates range from standard straight plates of all sizes with locking and standard screws, to anatomically specific plates that act as fixed-angle devices. The screw holes are generally shaped with an angle of inclination on one side away from the center of the plate. When tightened, the screw head slides down the inclination, causing movement of the bone fragment relative to the plate. As one bone fragment approaches the other at the fracture, compression occurs. The shape of the holes in the can allow for up to 25° of inclination in the longitudinal plane and 7° inclination in the transverse plane for screw insertion. In order to combat stress-shielding and damage to vascularity, limited-contact plates were designed. These plates can decrease the surface area of the plate-to-bone contact by 50%.

Depending on the type and location of fracture, the plate length and screw position can be altered to increase or decrease the mechanical stiffness. Increasing the length of the plate will decrease the pullout force acting on the screws. This is due to the increased lever arm. For comminuted fractures, the general rule of thumb is use a plate that is at least twice as long as the length of comminution.\textsuperscript{6} In this case, usually half or fewer of the available plate holes are occupied with screws. Placing screws too close to the fracture site creates a potential for stress concentration and failure of the plate. Screws placed farther from the fracture site better distribute the force through the plate
but increase interfragmentary motion at the far cortex. This balance between rigidity and micromotion is crucial to optimize the rate of healing.

**In-vivo Strain on Orthopedic Device Surfaces**

In order to obtain the right balance of rigidity and micromotion, there are many combinations of plates and screws that can be used depending on the type, location and severity of the fracture. As the screw is inserted, axial tension is generated through it when the screw head makes contact with the cortex or fixation device. This causes compression and stability of the bone fragments. Depending on the location of the fracture, orthopedic screws can generate up to 3000 newtons of compression force. As time goes on, this force will decrease as the bone is remodeled to the stress. The fracture healing process is generally completed before substantial loss of compression occurs. Measuring strain in orthopedic screws would be a complimentary measurement to monitor implant loosening and infection.

As the name implies, compression plates can be bent and applied to the tension side of eccentrically loaded bone to produce compression across the whole fracture. This method provides absolute stability for two-part fracture patterns and is typically used for simple fracture patterns with low obliquity, due to insufficient room for a lag screw. A max force of about 600 newtons is generally applied, whereas more force can cause the far cortex of the fracture to open. An orthopedic plate that has the ability to display strain would in turn allow clinicians to monitor fracture gap strain as the healing process progresses.
Current Methods to Measure Strain and their Advantages and Disadvantages

The relationship between stress and strain is one of the most fundamental concepts from the study of mechanics of materials. The ability to measure normal strain, or the deformation per unit length, allows researchers to apply known loads to materials to calculate stresses and characterize the material properties such as the modulus of elasticity. Although the earliest strain measurement devices were mechanical in nature, there are now both optical methods and electrical devices. These measurement methods are either full-field or point measurements.

Some of the full-field methods currently used include grids and rulings, photoelasticity, and optical interferometry. Grids and rulings allow for visual confirmation of the change in displacement, which can then be divided by the original length to calculate the resulting strain. Although this is effective at large scale changes, the accuracy is limited to the markings on or around the test specimen.

Photoelasticity is an experimental method used in determining the stress distribution in a material. It is typically used when mathematical methods become extremely complex because it gives an accurate picture of stress distribution including around discontinuities in a material. This method is an important tool for determining critical stress points and used for determining stress concentrations in irregular geometries. Photoelasticity is based on the property of double refraction, a property where a ray of light passing through a material experiences two refractive indices. Upon the application of stresses, photoelastic materials exhibit double refraction, and the magnitude of the refractive indices at each point in the material is directly related to the
state of stresses at that point. A polariscope is used to analyze the double refraction and can calculate maximum shear stress and its orientation.\textsuperscript{17} Although this method is used for many industrial applications, all of the instrumentation and the requirement of a photoelastic material inhibits this technique from being used for calculation of in-vivo implant stress distributions.

Optical interferometry is based upon the principles of constructive and destructive interference of light such that it produces alternating light and dark bands.\textsuperscript{18} Interferometers are widely used for the measurement of small displacements and surface irregularities. By combining the concepts of optical interferometry and the moiré effect, moiré interferometry is born with the possibility of higher sensitivity. The moiré effect occurs any time two similar arrays of equally spaced lines or dots are arranged in such a way that one array can be viewed through the other.\textsuperscript{12} The dark and light bands which result from the interference are known as moiré fringes.\textsuperscript{31} A slight motion of one of the objects creates large-scale changes in the moiré pattern. Moiré interferometry uses a combination of a reflective diffraction grating applied directly to the specimen with a virtual reference grating created by the interference of coherent laser light. The diffraction grating, which is required to be directly on the specimen for stress analysis, divides the single beam of light into multiple beams composed of smaller intensities that are captured by a camera.\textsuperscript{18} The sensitivity of this system is primarily controlled by the frequency of the reference grating. Similar to photoelasticity, interferometry can produce accurate results but the instrumentation restricts it from being used \textit{in-vivo}.
Some of the point measurement methods include clip-on extensometers and bonded electrical resistance strain gauges. Clip-on extensometers use knife-edges to accurately measure deformation in a defined section of a test specimen. They are used in applications where high precision strain measurement is required. The best resolution of a purely mechanical device is about 10µƐ.\textsuperscript{32} They have the advantage of being easily attached and removed as well as low cost; however the size can be a drawback when testing small/delicate samples. Also the knife-edges create stress concentrations that may cause pre-mature failure and as the edges dull over time they may be prone to slipping. Clip-on extensometers require wired instrumentation, therefore similar to previous methods mentioned, cannot be used in measuring strain \textit{in-vivo}.

Another common device used for point measurements of strain is the bonded resistance strain gauge. It consists of a grid of thin metallic foil bonded to a thin insulating backing. The electrical resistance of this grid material varies linearly with strain. The backing is attached to the test specimen with a cyanoacrylate adhesive so that when the specimen is loaded, the strain on its surface is transmitted to the grid material by the adhesive. The strain in the specimen is found by measuring the change in the electrical resistance of the grid material. The bonded resistance strain gauge is low in cost, can be made of various gauge lengths, and is only moderately affected by temperature changes. It is also small in terms of size and mass and has high sensitivity to both static and dynamic strains.\textsuperscript{32} The drawbacks of using a strain gauge \textit{in-vivo} include limited spots for application and also the requirement of transdermal wires in order to
measure the change in electrical resistance. The transdermal wires provide a site for infection to possibly occur.

All of the methods previously discussed prove to be accurate at measuring strain but all of them have their drawbacks that hinder them from measuring strain in-vivo. Some current methods that measure strain in-vivo include ultrasound of liquid filled cavities, cemented strain gauges onto bone or devices and wireless systems that use telemetry. Although these systems have recorded in-vivo strain values, they have a variety of limitations including being unsuitable for non-invasive use, the need for large data acquisition devices and increased risk of infection. These limitations present a need to develop a system with the ability to non-invasively track the strain on orthopedic devices implanted in tissue. Luminescence used in combination with moiré fringe strain gauges might accomplish this. In luminescence, an energy source causes electron atoms to transfer out of their lowest energy "ground" state into a higher energy "excited" state. The electron returns the energy in the form of light in order to return to its "ground" state. This technique will be used through tissue and the emitted light will be captured and analyzed. The strain on a device will cause the moiré fringes to shift, therefore revealing more of one color and less of the other. By being able to non-invasively track strain on device surfaces, clinicians will have the ability to both optimize the treatment of fractures and monitor bone healing. This research presented describes the development and verification of a test system to quantify strain of an optical displacement indicator and the design of a strain indicating prototype screw.
CHAPTER TWO

DEVELOPMENT AND VERIFICATION OF A TEST SYSTEM TO QUANTIFY STRAIN OF AN OPTICAL DISPLACEMENT INDICATOR

Materials and Sample Preparation

This study involved uniaxial tensile testing of a series of four dog bones as test specimens, with the goal of refining the experimental set-up and determining an appropriate calibration platform for use with an optical strain gauge system. A description of each specimen and the associated nomenclature can be seen below in Table 2.1. Figure 2.1 shows a dog bone specimen with the dimension locations. All specimens were made by Clemson University Machining and Technical Services.

<table>
<thead>
<tr>
<th>Specimen Name</th>
<th>Material</th>
<th>Gauge Length</th>
<th>Gauge Width</th>
<th>Gauge Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>316 stainless steel</td>
<td>135.00mm</td>
<td>20.03mm</td>
<td>1.87mm</td>
</tr>
<tr>
<td>SS2</td>
<td>316 stainless steel</td>
<td>130.00mm</td>
<td>19.97mm</td>
<td>1.89mm</td>
</tr>
<tr>
<td>SS3</td>
<td>316 stainless steel</td>
<td>130.00mm</td>
<td>20.07mm</td>
<td>1.87mm</td>
</tr>
<tr>
<td>D1</td>
<td>Delrin acetal resin</td>
<td>126.5mm</td>
<td>19.88mm</td>
<td>1.97mm</td>
</tr>
</tbody>
</table>

Table 2.1: Dimensions of the various test specimens used
All specimens were cut to shape using a Hurco VMX30 3-axis CNC mill (Indianapolis, IN). Specimen SS1 through SS3 were machined from a 316 stainless steel bar (McMaster Carr 88885K15) with a yield strength of 30ksi. Specimen D1 was machined from Delrin Acetal Resin (McMaster Carr 8739K27) with a tensile strength of 9-11ksi. Specimen SS1 and D1 seen below in Figure 2.2 had grip ends that were both wider and thicker than the center section. The specimen also had holes at varying distances for the ability to attach an optical displacement indicator using nuts and bolts in combination with thin pieces of stainless steel.
The gauge width was set to 20mm and Equation 2.1 below was used to determine the minimum and maximum thickness allowed to keep the tensile force between 5 kN and 10 kN while also staying under 90% yield.

\[
Yield\ strength \times \%\ yield = \frac{Tensile\ Force}{Cross\ sectional\ area}
\]  

(2.1)

75% yield was used on the specimen for an added safety factor for the initial test. The only unknown in the equation was the thickness used to determine the cross sectional area. The process for finding the required thickness can be seen below:
Known

- Width = 20mm

- Young’s Modulus = 193,000 MPa

- 75% Minimum yield strength = 155.25 MPa

- Minimum tensile force – 5000N

- Maximum tensile force – 10,000N

Calculating Minimum and Maximum Thickness

\[ 155.25 \text{ N/mm}^2 = \frac{5000\text{N}}{(20\text{mm}) (x \text{ mm})} \]

**Minimum Thickness** = 1.61 mm

\[ 155.25 \text{ N/mm}^2 = \frac{10,000\text{N}}{(20\text{mm}) (x \text{ mm})} \]

**Maximum Thickness** = 3.22 mm

After the calculations, it was determined that a thickness of 2.0mm would be sufficient for the testing being done. Final drawings were then turned into Clemson University Machining and Technical Services.

After the finished specimens were received, a Mitutoyo micrometer (NO. 293-768-30) was used in various spots to determine the actual width, thickness and gauge length of the specimen. The width and thickness was then used to calculate the cross sectional area. After an accurate cross sectional area was determined, calculations were made in combination with the material properties to determine the displacement needed
to achieve approximately 75% yield. Equation 2.2 used to calculate elongation can be seen below:

\[
\text{Elongation} = \frac{Tensile \ stress \times \text{Original length}}{\text{Modulus of Elasticity}}
\]  

\[
= \frac{(155.25 \ MPa)(135 \ mm)}{(193,000 \ MPa)} = 0.11 \ mm
\]

This elongation was used as a guideline for the total displacement of the first uniaxial tension test described in the next section.

An optical displacement indicator as seen in Figure 2.3 below was then attached.

The optical displacement indicator is composed of two separate components. The first is an array of black lines printed on a transparent plastic sheet with a line thickness and spacing of 500 microns. The second is an array of alternating cyan and magenta lines on paper, both 500 microns thick. The length of the paper and transparent plastic
can be cut to varying lengths depending on the desired gauge length. Both arrays are printed using an Epson Stylus Photo R200 ink jet printer (Long Beach, CA).

As one array moves along the other, a color change can be visualized as seen below in Figure 2.4.

![Figure 2.4: Optical displacement indicator color change as one array moves along the other](image)

Omega uniaxial precision strain gauges (SGD-6/120-LY11, Stamford, CT) that are matched to steel were then bonded to the dog bone in the center of the gauge length as well but on the opposite side of the optical displacement indicator. This was done using a TT300 adhesive kit from Omega. The TT300 cement is a heat cured, two part epoxy adhesive that can be used to bond polyimide-backed strain gauges for strain measurement up to 200°C.

Specimen SS2 and SS3 were made and prepared using the same material and method as specimen SS1 described above. These specimens were made a uniform thickness throughout, instead of having thicker grips. The holes in the gauge length were also not incorporated. These specimens can be seen below in Figure 2.5.
The strain gauges on SS2 and SS3 were attached using Omega’s SG496 rapid cure strain gauge adhesive. The method for making the optical displacement indicators remained the same except the cyan and magenta were printed on the paper using an Epson Artisan 1430 ink jet printer.

Methods

Uniaxial Tension Test of D1 and SS1-3

Specimens D1 and SS1-3 were used for a variety of uniaxial tension tests conducted with an Instron 8874 axial-torsion fatigue testing system (Grove City, PA). For each test, the Instron testing system was set to record the time in seconds, the crosshead position in millimeters and the load in Newtons. The test setup can be seen below in Figure 2.6.
The specimen was first clamped into the bottom grip of the Instron and the load cell was balanced to account for the weight of the specimen. The top clamp was then closed and the resulting compression was removed.

A description of each test method and the corresponding nomenclature can be seen below in Table 2.2. The initial displacement used in method A was determined using the calculations above in Equation 2.2. After confirming the specimen was not being loaded past the yield strength, displacement was gradually increased in order to increase displacement of the optical displacement indicator. Test method D was a cyclic test in which tension and compression were applied at a linear rate, transferring immediately from one to the other. The number of cycles for this method varied from three to five.
<table>
<thead>
<tr>
<th>Method</th>
<th>Displacement</th>
<th>Rate</th>
<th>Cyclic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.12mm</td>
<td>0.002mm/s</td>
<td>No</td>
</tr>
<tr>
<td>B</td>
<td>0.135mm</td>
<td>0.003mm/s</td>
<td>No</td>
</tr>
<tr>
<td>C</td>
<td>0.159mm</td>
<td>0.003mm/s</td>
<td>No</td>
</tr>
<tr>
<td>D</td>
<td>0.16mm</td>
<td>0.004mm/s</td>
<td>Yes</td>
</tr>
<tr>
<td>E</td>
<td>1.8mm</td>
<td>0.03mm/s</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 2.2: Details of various uniaxial tests

Each test for the remainder of this thesis will be described by the name of the specimen, the letter of the corresponding method used and the trial. For example, a test using specimen SS1, method A for the second trial will be referred to as SS1-A2.

*Image Analysis*

A Nikon D7000 digital camera was used to capture photos of the optical displacement indicator. The photos were processed using a Matlab code as seen in Apendix A2 to quantify the amount of color change. The picture number and XY pixel range is input into the code which then outputs the mean amount of red, green and blue in each photo. From the mean values, $R'$, $G'$ and $B'$ are calculated using Equation 2.3 below.

$$R' = \frac{Red_{mean} - Red_{minimum}}{Red_{maximum} - Red_{minimum}}$$ (2.3)
In test SS3-D4, an optical displacement indicator with black lines extending over colored reference regions was used. For analysis, R’, B’, and G’ were calculated differently using Equation 2.4 below.

\[
R' = \frac{\text{Red}_{\text{mean}} - \text{Red}_{\text{magenta reference}}}{\text{Red}_{\text{cyan reference}} - \text{Red}_{\text{magenta reference}}}
\]  

(2.4)

After R’, B’ and G’ are calculated for each image, a ratio is determined for each photo using Equation 2.5 below:

\[
\text{Red: Green Ratio} = \frac{R'}{(R' + G')}
\]  

(2.5)

This ratio is then graphed versus the corresponding photo number in order to see how the optical displacement indicator changed color ratios throughout the uniaxial tension test. The ratios range from 0 to 1 with 0 corresponding to the least amount of red and 1 corresponding to the most amount of red. Test SS3-D4 used reference regions for analysis so the ratio is the actual ratio of red to green.
Strain Gauge Data Acquisition

In order to record the data from the strain gauge, the leads of the strain gauge were soldered to insulated wires that were connected to a NI 9944 120 ohm quarter bridge completion accessory. This then connected via Ethernet cable to a NI 9237 4-channel simultaneous bridge module. The module was plugged into a NI 9171 compact DAQ that was connected to a computer via USB. The computer contained a LabView program that recorded the time in seconds and strain measurements from the gauge. This program can be seen in appendix A-1.
CHAPTER THREE

DESIGN OF A STRAIN INDICATING SCREW prototype

Materials and Sample Preparation

After maximizing the accuracy and efficiency of the optical displacement indicator system, the system needed to be used in combination with a bolt to form the first prototype. The design of a strain indicating screw prototype started by modifying a normal 2.75 inch 3/8-16 allen head bolt. All machine work was done by Clemson University Machining and Technical Services. The prototype is composed of four separate pieces that were assembled upon completion. The first part is a 2.75 inch 3/8-16 allen head bolt that had a hole drilled through its vertical axis, starting at the bottom and coming out of the top of the head. This hole was then threaded to accommodate the second part, a M3x0.5 threaded rod. The threaded rod is fed through the bottom of the bolt until the tip comes out of head. The tip of the rod is modified into a “T” shape that will connect with the next part of the prototype, an optical displacement indicator. The transparency section of the optical displacement indicator also has a “T” shape cutout for the tip of the rod to fit in to. This allows the transparency to move back and forth as the rod is turned and also when the bolt is mechanically elongated. By being able to turn the rod going through the middle, the optical displacement indicator can be adjusted to the desired position before load is placed on it. In order to rigidly hold the transparency and paper in this vertical orientation, a fourth part was needed. This part is a hexagonal prism made of aluminum. The prism is inserted into the allen key depression in the head of the bolt. A hole in the center allowed the rod to come through the base of it. Any part of the
prism that protruded out of the allen key depression was cut in half in order to form a flat surface for the paper portion of the optical displacement indicator to be attached to. The paper was attached using super glue. The finished prototype can be seen below in Figure 3.1 and will be referred to as prototype 1 for the remainder of this thesis.

![Figure 3.1: Assembled prototype 1](image-url)
The next prototype designed, which will be referred to as prototype 2 for the remainder of this thesis, started as a block of 316 stainless steel instead of modifying an existing bolt like described above. Prototype 2 still used a threaded rod going through the central axis of the bolt but now used a wedge contained in the head of the bolt. This wedge has dove tails on either side that allow it to slide back and forth as the bolt is elongated or compressed. A series of drawings and photos can be seen below in Figure 3.2 of prototype 2.

![Figure 3.2: Prototype 2 showing from left to right; initial drawings, SolidWorks assembly, disassembled prototype and the assembled prototype](image)

The angle between the top of the wedge and the surface that contacts the threaded rod was made to be 35°. The inner rod was a M3x0.5 like the one used in the previous prototype. The side of the bolt head that held the spring between it and the wedge was fastened to the bolt using a 0-80 bolt.
In order to mechanically test prototype 1, a custom fixture was designed that would hold the bolt to the base of the Instron 8874 while still allowing visualization of the optical displacement indicator. The fixture, as seen below in Figure 3.3, was made by TIG welding plates of 4140 steel together.

![Image of custom fixture](image1)

Figure 3.3: Custom fixture on the base of the Instron 8874 used for holding prototype 1 during uniaxial tension tests

A custom piece also had to be made in order for the hydraulic grip to safely and securely hold the prototype during testing. This piece can be seen below in Figure 3.4.

![Image of threaded piece](image2)

Figure 3.4: Threaded piece to connect the bolt to the Instron grip
It is made of 17-4 stainless steel and is able to thread onto the 3/8-16 bolt. The thin section is 5 mm thick and 25 mm wide to provide enough bulk material to be strong enough for tensile testing, yet thin enough to fit in the hydraulic grips that only open about 7.5 mm.

**Methods**

The experimental setup for the testing of prototype 1 can be seen below in Figure 3.5.

![Prototype 1 tensile test setup](image)

Figure 3.5: Prototype 1 tensile test setup

The test started by applying approximately 50N to the bolt and then holding the position for 30 seconds. The displacement then increased 0.1mm @ 0.004mm/s. After the full displacement was reached, the position held for 30 seconds.
Testing of prototype 2 consisted of attaching it to the fixture shown in Figure #.

The inner rod was set such that the head of the bolt was displaying approximately all red. From here, three pictures were taken and then the inner rod was turned in increments of 45°, taking three pictures at each position. This was done until the rod completed two full revolutions in one direction and then two full revolutions in the opposite direction. This test setup can be seen below in Figure 3.6.
CHAPTER 4

RESULTS

Uniaxial Tension Testing

The results of test SS1-A1, SS1-A2, and SS2-A1 are shown below in Figure 4.1. These tests did not see a color change due to both mean colors increasing or decreasing together during the test. The mean red and blue color is graphed against the photo number for each test.

Figure 4.1: Mean color vs. photo number of tests SS1-A1, SS1-A2 and SS2-A1 showing both mean colors were increasing or decreasing together resulting in no color change
The results for test D1-E1 are shown below in Figure 4.2 and 4.3. The optical displacement indicator was set to show about 50% of each color under zero load. Photos were taken every three seconds and all photos were saved.

![Optical Gauge Red:Blue Ratio](image)

Figure 4.2: Photo number vs. optical displacement indicator color ratio of test D1-E1 showing a complete color change throughout the test
Photos 6 and 20 are shown below in Figure 4.3. These pictures correlate with the complete color change values represented in Figure 4.2 above.

![Figure 4.3: Photos 6 and 20 from the D1-E1 test corresponding to the values in Figure 4.2 above](image)

The actual displacement of the Instron crosshead was 1.80 mm. With an optical gauge length of 47.50 mm and a specimen gauge length of 126.50 mm, the theoretical displacement of the optical gauge is 676 microns. The optical displacement indicator line thickness of 500 microns should result in a 135.2% color change. The color change calculated from the photos was 136%.
The results for test SS3-B1 and SS3-C1 can be seen below. The optical displacement indicator was aligned to show approximately 50% of each color while under zero load. Five pictures were taken before and after the test with the time interval being three seconds between pictures. Figure 4.4 below shows how the optical displacement indicator color ratio changed with load.

![Intron vs. Optical Displacement Indicator](image)

Figure 4.4: SS3-B1 Intron load vs. optical displacement indicator color ratio showing the agreement between the two devices

The actual displacement of the Intron crosshead was 126 microns. With an optical gauge length of 55.15mm and a specimen gauge length of 130.00mm, the theoretical displacement of the optical displacement indicator is 53 microns. The line thickness of 500 microns results in a 10.6% theoretical color change.
The results for SS3-C1 can be seen below. The test parameters remained the same as test SS3-B1 except the overall displacement was increased from 0.135mm to 0.159mm. Figure 4.5 below compares the Instron load with the change in color ratio.

![Intron vs. Optical Displacement Indicator](image)

Figure 4.5: SS3-C1 Intron load vs. optical displacement indicator color ratio showing the agreement between the two devices.

The actual displacement of the Instron crosshead was 149 microns. The theoretical displacement of the optical displacement indicator is 63 microns. The line thickness of 500 microns results in a 12.6% color change.
**Cyclic Testing**

Results for the series of cyclic tests, SS3-D1 through SS3-D4 can be seen below. SS3-D1 captured photos every four seconds with approximately six pictures before and after the test. The load from the Instron is overlapped with the strain from the strain gauge below in Figure 4.6. Figure 4.7 shows the load from the Instron overlapped with the color change of the optical displacement indicator.

![Intron vs. Strain Gauge](image)

**Figure 4.6:** SS3-D1 time vs. load from the Instron overlapped with time vs. strain from the strain gauge showing the agreement between the two devices
Figure 4.7: SS3-D1 time vs. load from the Instron with photo number vs. color ratio from the optical displacement indicator showing the maximum load corresponding to the minimum amount of blue each cycle.

The actual displacement of the Instron crosshead was 164 microns. The theoretical displacement of the optical displacement indicator is 70 microns. The line thickness of 500 microns results in a 14% theoretical color change.

With a strain gauge length of 6mm, the strain gauge should have resulted in an elongation of 8 microns. This elongation would result in a theoretical strain of 1262 µƐ. The maximum strain recorded from the gauge was 1257 µƐ.
Test SS3-D2 used the same parameters as SS3-D1, but decreased the time between each photo to three seconds. Black boards were also used behind the specimen, reducing the background lighting. The load from the Instron is overlapped with the strain from the strain gauge below in Figure 4.8. Figure 4.9 shows the load from the Instron overlapped with the color change of the optical displacement indicator.

Figure 4.8: SS3-D2 time vs. load from the Instron overlapped with time vs. strain from the strain gauge showing the agreement between the two devices
The actual displacement of the Instron crosshead was 165 microns. The theoretical displacement of the optical displacement indicator is 70 microns. The line thickness of 500 microns results in a 14\% theoretical color change.

With a strain gauge length of 6mm, the strain gauge should have resulted in an elongation of 7.6 microns. This elongation would result in a theoretical strain of 1262 \( \mu \varepsilon \). The maximum strain recorded from the gauge was 1263 \( \mu \varepsilon \).
Test SS3-D3 used the same parameters as SS3-D2, but decreased the time in between each photo to one second and reduced the number of cycles from five to three. Figure 4.10 below compares the strain gauge data with the optical indicator data. Green was used for analysis on this test instead of blue.

![Strain Gauge vs. Optical Displacement Indicator](image)

*Figure 4.10: SS3-D3 strain gauge vs. optical displacement indicator showing the decreased time between photos from SS3-D2 decreased the noise*

The actual displacement of the Instron crosshead was 165 microns. The theoretical displacement of the optical displacement indicator is 70 microns. The line thickness of 500 microns results in a 14% theoretical color change.
With a strain gauge length of 6mm, the strain gauge should have resulted in an elongation of 8 microns. This elongation would result in a theoretical strain of 1262 µƐ. The maximum strain recorded from the gauge was 1245 µƐ.

Test SS3-D4 had the same parameters as test SS3-D3 but used a new optical displacement indicator that had black lines extending over colored reference regions. The reference regions allowed the photo analysis to plot the actual ratio of color as opposed to 0 being the least red and 1 being the most red. Figure 4.11 below shows the optical displacement indicator color ratio change overlapped with the strain recorded from the strain gauge.

Figure 4.11: SS3-D4 strain gauge vs. optical displacement indicator with reference regions showing the agreement between the amount of red and the amount of strain
Based on the data recorded for this test, the actual displacement of the Instron crosshead was 164 microns. With a new optical displacement indicator gauge length of 44.3mm, the theoretical displacement is 56 microns. The line thickness of 500 microns should result in an 11.2% theoretical color change. The color change calculated from the photos was approximately 12%.

With a strain gauge length of 6mm, the strain gauge should have resulted in an elongation of 8 microns. This elongation would result in a theoretical strain of 1262 µƐ. The maximum strain recorded from the gauge was 1247 µƐ.
Prototype Testing

The displacement versus load of the unmodified 3/8-16 bolt and Prototype 1 can be seen below in Figure 4.12. The same method described in Section 3 was used for both specimens (0.1 mm at 0.004 mm/s). Figure 4.13 shows the optical displacement indicator data.

![Uniaxial Tension Test of Unmodified vs. Prototype 1](image)

Figure 4.12: Position vs. Load of prototype 1 and unmodified 3/8-16 stainless steel bolt showing the unmodified bolt had an increased stiffness.
Figure 4.13: Photo number vs. color ratio of prototype 1 optical displacement indicator showing there was not enough strain induced on the prototype to see a change in color.
The results of the test described in Section 3 for prototype 2 can be seen below in Figure 4.14 and Figure 4.15. The average standard deviation in color between each set of three photos was determined to be 1.05%. Figure 4.14 compares the revolutions vs. average color for the two complete revolutions both forward and backward. Figure 4.15 compares the average color with the corresponding revolution in degrees on the forward and backward revolution.

![Prototype 2 Revolution Test](image)

Figure 4.14: Inner rod revolutions vs. optical displacement indicator color ratio of prototype 2 showing the internal wedge was moving properly, both forward and back
Figure 4.15: Photos from 90° (left), 225° (middle) and 315° (right) showing the gradual color change of prototype 2 during the revolution test
CHAPTER 5
DISCUSSION

Optical Displacement Indicator

Many system improvements were implemented throughout the series of uniaxial tests in order to improve accuracy and reduce noise of the optical displacement indicator. These system improvements include better optical displacement indicator attachment, increased distance between optical indicator attachment points, decrease of time between photos, include photos before and after the test, block background light, start optical half blue/half red, addition of black and colored reference regions, and the addition of a +6 lens to decrease the distance between the camera and the optical displacement indicator from about 18 inches to 4 inches.

By increasing the distance between the optical displacement indicator attachment points, the indicator would show a greater color change for a given specimen displacement. Test D1-E1 was conducted in order to see how the optical displacement indicator results looked when experiencing enough displacement to go through a full color change. The optical displacement indicator was set to show approximately 50% of each color under zero load. The total displacement for this test was increased to 1.8mm. With an increased optical displacement indicator gauge length of 47.50 mm and a specimen gauge length of 126.50 mm, the theoretical displacement of the optical displacement indicator is 676 microns. The line thickness of 500 microns should result in a 135.2% color change. The color change calculated from the photos was 136%. The colors in the photos in Figure 4.3 correspond to their values on the graph in Figure 4.2.
The noise was minimal compared to the previous tests so the total specimen elongation and distance between optical displacement indicator attachment points were both increased for the remainder of the uniaxial tests on specimen SS3. The results for tests SS3-B1 and SS3-C1 shown in Figure 4.4 and Figure 4.5 are less noisy and follow the load of the Instron better than the previous stainless steel tests. These tests used increased specimen elongation and a new optical displacement indicator with 55.15mm between attachment points as opposed to the previous 33.20mm. The noise in the graphs was most likely due to poor focus of the camera on the optical displacement indicator.

For test SS3-D1, a cyclic method was used to confirm the optical displacement indicator followed the strain gauge for both tension and compression and also repeated cycles. Based on the results from test SS3-B1 and SS3-C1, the camera was focused better on the optical displacement indicator. Six photos were taken before and after the test so the graph of the photos would have flat regions before and after the color started to change. Figure 4.7 shows the photos follow the trend of the Instron load but were extremely noisy, even in the 6 photos before and after the test when the color shouldn’t have been changing. After looking at the photos, it was determined the noise was from the bright background causing the photo to become oversaturated. Also the camera was set to take a photo once every 4 seconds. The large gap in between each picture most likely contributed to the noise as well.

Based on the results from the previous test, SS3-D2 incorporated many system improvements. Black boards were used behind the specimen in order to eliminate any light from behind and the chance of over saturated photos. A +2 and a +4 lens were
added to the camera in order to move the camera closer to the specimen and achieve a better focus. The distance between the camera and specimen decreased from 18 inches to 4 inches. A comparison between photos from the previous test and this test can be seen below in Figure 5.1.

![Comparison of photos from SS3-D1 (left) and SS3-D2 (right) showing better focus when using the black boards and +6 camera lens](image)

Figure 5.1: Comparison of photos from SS3-D1 (left) and SS3-D2 (right) showing better focus when using the black boards and +6 camera lens

The time between each photo was also decreased to three seconds. The results for test SS3-D2, seen in Figure 4.9, had significantly less noise. The regions before and after the test were also flat as opposed to the previous test. Now that the system improvements showed promising results, the time between each photo needed to be decreased to at least one photo per second.

Test SS3-D3 used the same parameters and setup as SS3-D2, except the time between each photo was decreased to one second. The camera encountered problems saving all of the photos so only 206 out of 252 were saved. The noise significantly decreased again from the previous test as seen in Figure 4.10. Now that the noise was at
a minimum, the next test needed to be analyzed such that the actual percent color change could be calculated and compared to the theoretical percent color change.

Test SS3-D4 used the same parameters and setup as SS3-D3 except a new optical displacement indicator, shown below in Figure 5.2, was used that had black lines extending over cyan and magenta reference regions.

![Optical displacement indicator with black lines extending over cyan and magenta reference regions](image)

**Figure 5.2**: Optical displacement indicator with black lines extending over cyan and magenta reference regions used for test SS3-D4

The results for this test, seen in Figure 4.11, are noisier than the previous test. This was due to the time between each picture being increased to three seconds. The new optical displacement indicator was also aligned slightly crooked after looking at the photo below in Figure 5.3.
The optical displacement indicator being aligned slightly crooked caused the arrays to not line up perfectly, allowing color to show outside the width of the black lines. Based on the data recorded for this test, the actual displacement of the Instron crosshead was 164 microns. With a new optical displacement indicator gauge length of 44.3mm, the theoretical displacement is 56 microns. The line thickness of 500 microns should result in an 11.2% theoretical color change. The color change calculated from the photos was approximately 12%.
Strain gauge

As seen in Figure 4.6, the strain from the strain gauge was plotted against the load from the Instron. This was done to confirm both the strain gauge and the method of recording strain were being done properly. The strain gauge was responding properly to changes in load, but was not outputting the proper value of strain the material was experiencing. This is due to not scaling the strain gauge with known strains before running the tests. The strain gauge outputs increased strain linearly to increased displacement so a custom scale needs to be applied to each gauge before use. Without a custom scale, the values of strain will not correspond to the actual strain. This custom scale is applied using the LabView program, in which it scales the raw input values and then outputs the new scaled value. An example of this process can be seen below in Figure 5.4.

![Linear Scale Diagram]

Figure 5.4: Process for adding a scale to the Omega strain gauges so they output the actual strain
Tests SS3-D1 and SS3-D2 used the same specimen and strain gauge. In order to confirm the strain gauge was working properly, the specimens’ maximum strains and loads are compared below in Table 5.1.

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Strain Gauge Strain</th>
<th>Intron Strain</th>
<th>Intron Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS3-D1</td>
<td>563</td>
<td>1257</td>
<td>4687</td>
</tr>
<tr>
<td>SS3-D2</td>
<td>648</td>
<td>1263</td>
<td>5062</td>
</tr>
</tbody>
</table>

Table 5.1: Maximum strain and load from SS3-D1 and SS3-D2

The strain recorded from the strain gauge increased from SS3-D1 to SS3-D2 as well as the load recorded from the Intron. After confirming the strain gauge was behaving properly, tests SS3-D3 and SS3-D4 were used to compare the strain gauge results with the optical displacement indicator color change.

**Optical vs. strain gauge**

After the methods had been optimized for gathering optical displacement indicator data, Figure 4.11 from test SS3-D4 shows the data being compared to the data recorded from the strain gauge. When the data is overlapped, the maximums and minimums correspond with each other. Based on the data recorded for this test, the actual displacement of the Intron crosshead was 164 microns. With an optical gauge length of 44.3mm and a specimen gauge length of 130mm, the theoretical displacement of the optical gauge is 56 microns. The optical gauge line thickness of 500 microns
should result in an 11.2% theoretical color change. The color change calculated from the photos was approximately 12%. This corresponds to a 7% error. This data shows that the optical displacement indicator can be used to determine changes in displacement and therefore the resulting strain can be calculated from this. Due to slight variations in the print on each optical displacement indicator, I recommend using a calibration process on each indicator before it is used. A photo should be taken of the indicator when it is set to show all cyan and all magenta. Sometimes full cyan and full magenta cannot be reached due to small voids in the black ink lines allowing the color underneath to show through.

**Prototype 1**

As seen in Figure 4.12, uniaxial tension tests showed that the unmodified bolt experienced a higher load than prototype 1 while using the same method. This is expected because the unmodified bolt has a higher cross sectional area that is being stressed. The cross sectional area of prototype 1 was 85% of the cross sectional area of the unmodified bolt. Based on the maximum loads from Figure 4.12, prototype 1 reached a maximum load that was 76% of the maximum load of the unmodified bolt. This difference can be the result of multiple things. The specific material composition of each bolt most likely varied. Although both bolts were 2.5 inches long, the thread lengths and distances from the bottom of the locking nut to the bolt head were different. The gauge length of prototype 1 was 4.5mm longer than the unmodified bolt. The increased gauge length results in less load for a given displacement. The course thread on each bolt also
made it difficult to be precise with the position of the locking nut and therefore the gauge length.

Due to the camera moving slightly while the test was being conducted, analysis was not accurate and extremely noisy. With the camera not being stable and 10 of the 64 photos saved being blurry and not focused, the photo analysis did not really show an overall trend. When the photos were looked at, half of them showed the visual gauge in a slightly different position. The camera slightly moving caused different photos of the optical displacement indicator to be taken at different angles, which most likely contributed to the noise as well.

In combination with the poor quality of the photos, enough load was not put on prototype 1 in order to induce strains the optical displacement indicator test system could measure. Geometries of future bolts need to be designed such that clinically relevant loads of 2000-3000N will produce sufficient strain the optical displacement indicator system can measure.
Prototype 2

The testing of the updated prototype showed that the percent color change was consistent with the number of revolutions the inside rod was turned. The internal rod pitch of 500 microns/revolution correlated to a 1/8\textsuperscript{th} revolution turn resulting in a vertical displacement of 62.6 microns. The angle of the wedge being 35° resulted in a 500 micron horizontal displacement for every 350 micron vertical displacement of the internal rod, or a mechanical advantage of 1.43. Each 1/8\textsuperscript{th} revolution will result in a horizontal displacement of the wedge of 89.2 microns. Dividing this by the optical gauge line thickness of 500 microns equals a color change of 17.84\% per 1/8\textsuperscript{th} revolution. Based on the data seen in Figure 4.14, the average color change per 1/8\textsuperscript{th} revolution was calculated to be 14.82\%. The 6.7\% error is due to each 1/8\textsuperscript{th} revolution being turned by hand. By having a handle that was unsymmetrical, precisely turning the inner rod 1/8\textsuperscript{th} of a revolution was hard to do consistently and repeatedly. It is recommended for future tests similar to this that a symmetrical handle and precise markings be used.
CHAPTER 6
CONCLUSION AND FUTURE WORKS

Throughout the series of uniaxial tests, a variety of system changes were
implemented in order to decrease noise from the optical displacement indicator data and
increase accuracy of the strain indicating test system. Optimal image focus, consistent
light intensity and minimal time between photos were crucial to both the noise and
accuracy of the system. The addition of +4 and +2 lenses to the camera along with
decreasing the distance from the indicator to the camera significantly improved focus.
The use of black boards behind the specimen also assisted in not only better focus, but
also increased consistency of light intensity in each photo. Decreasing the time between
photos from four seconds to one second also decreased the noise of the optical
displacement indicator system. Future tests need to continue to increase the sampling
rate, taking multiple pictures per second. Once the attachment method of the optical
gauge was improved and the system improvements described above were applied, the
photo analysis of the optical displacement indicator data proved to be accurate and follow
the same trend of the Instron and strain gauge data.

This concept being incorporated into the head of a prototype bolt showed
successful initial results. The indicator attached to the wedge inside the head of
prototype 2 moved properly in both directions when turning the internal rod by hand. For
future tests, prototype 2 needs to be put under a clinically relevant load of 2000-3000N as
photos are taken to ensure that the color is changing properly when being strained. In
order to eliminate skewed results from slight variations in material, the bolt should be mechanically tested before the modifications are made to it. After being modified, the prototype can be mechanically tested, similar to the setup used when testing prototype 1, and the results can be compared to the unmodified. After proper optical indicator behavior is confirmed, a dye and non-invasive visualization method need to be incorporated into the prototype design. The combination will allow various tests to be conducted in which the color change can be visualized and measured through a clinically relevant tissue thickness as the bolt is strained.

Beyond the concept of a strain indicating system for orthopedic plates and screws, there are many other directions the concept can be applied to for future testing. The concept incorporated into a tubular design would prove to be useful for applications other than bone. By making the external tube transparent and both tubes flexible, the system would be able to be routed in a variety of paths and maintain the ability to indicate strain when bending. This concept would be excellent for use with monitoring the healing of injured tendons, ligaments and muscles. Another concept that could be paired with the strain indicating system is the magnetic actuation of load. The ability to apply a known load and measure the corresponding displacement would allow clinicians to determine the modulus of elasticity or stiffness, a value that could be used to monitor healing as well.
APPENDICES

Appendix A

Strain to Text LabView Code

Figure A: LabView setup used to convert strain gauge output to a text file.
function [III, I, R, G, B, Rm, Gm, Bm] = imageanalloadarevised(S, x_range, y_range)

cd(uigetdir);
Fst = dir;
Fst = Fst(3:end);
% Fst = Fst(15:2:135);
if nargin<1,
   S = 1:size(Fst, 1);
end;
if nargin<3,
   x_range = 1029:2564;
   y_range = 495:1940;
end;
display('loading file')
for f = S,
   % display(f);
   disp(Fst(f).name);
   Iall(:, :, :, f) = I;
   Isub = I(y_range, x_range, :);
   for c = 1:3, for i = 1:5:(size(y_range, 2) - 1), for j = 1:5:(size(x_range, 2) - 1),
      Iavesub((i + 4)/5, (j + 4)/5, c) = mean(mean(Isub(i:i+4, j:j+4, c))); % end; end; end;
   III(:, :, :, f) = Iavesub / 255;
   III(:, :, :, f) = Isub;
   % clear I; clear Isub; clear Iavesub;
   clear Iall;
end;
R(:, :, :, f) = III(:, :, 1, :);
G(:, :, :, f) = III(:, :, 2, :);
B(:, :, :, f) = III(:, :, 3, :);
% for i = 1:S, R94(i) = mean(R94(:, i)); end;
% for i = 1:S, G94(i) = mean(G94(:, i)); end;
% for i = 1:S, B94(i) = mean(B94(:, i)); end;
figure; plot(R94, 'r'); hold; plot(G94, 'g'); plot(B94, 'b');
for i = S, Rm(i) = mean(mean(R(:, :, i))); end;
for i = S, Gm(i) = mean(mean(G(:, :, i))); end;
for i = S, Bm(i) = mean(mean(B(:, :, i))); end;
figure; plot(Rm, 'r'); hold; plot(Gm, 'g'); plot(Bm, 'b');

B: MATLAB program used to analyze the optical displacement indicator photos
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