

Non-contact determination of Rail Neutral Temperature (RNT) and state of stress
in continuously welded steel railway rail using robust dot-peen displacement tagging

by

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B.Tech., Institute of Technology, Nirma University, 2010
M.Eng., University of Windsor, 2012

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Alan Levin Department of Mechanical and Nuclear Engineering
Carl R. Ice College of Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2025

ABSTRACT

It is well-known that the stresses induced by temperature extremes can lead to buckling and breakage of Continuously Welded Steel Railway Rail (CWR). Furthermore, there is currently no proven non-contact technology for accurately assessing and monitoring the state of rail stress. CWR can be subjected to very high stress levels when the temperature of the rail differs from the installation temperature, referred as the “Rail Neutral Temperature (RNT),” corresponding to zero stress in the rail.

The objective of this research is to develop and demonstrate a new approach using non-contact technology for monitoring the rail neutral temperature and the state of rail stress. This is achieved through simultaneous non-contact measurement of rail axial displacement and temperature. A new prototype sensor has been developed by the Technology Development Institute (TDI) at Kansas State University (KSU) based on existing robust field-hardened non-contact strain-measurement technology. Steel rail displacement (strain) tagging is attained using a robust dot-peen pattern with commercially available portable dot-peen equipment.

The capability of the prototype sensor system to accurately assess the mechanical stress in steel rail is first demonstrated using a special-purpose laboratory testbed. This facility is capable of imposing mechanical loading in excess of 150,000lbf, while also subjecting the section of steel railroad rail to controlled thermal strain conditions. The viability of monitoring the state of rail stress is demonstrated under mechanical and thermal laboratory conditions representing extremes of what might be encountered in a field environment. Such conditions correspond to significant departures from a given baseline (rail neutral) strain condition in the testbed.

The unique application of this new technology represents a completely new paradigm for assessment of rail stress in track. It is based on the concept that whenever track is cut/replaced for

maintenance, the baseline conditions of the rail will be assessed and “tagged” to this section of rail. Over time, a growing network of these baseline sections of track will develop, allowing an ever-increasing database of measurement stations that can be accessed for periodic monitoring of the state of rail stress using the new sensor technology. The results presented in this dissertation represent the first steps in proving the capability of the method, prior to actual application in the field environment.

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Nomenclature and List of Abbreviations

CWR – Continuously Welded Rail

T_{RN} – Rail Neutral Temperature (RNT)

DRNT – Desired Rail Neutral Temperature

FRA – Federal Railroad Administration

ε - Strain

ε_T – Thermal Strain

ε_m – Mechanical Strain

ε_x – Strain in x-direction

ε_y – Strain in y-direction

σ – Stress

σ_T – Thermal Stress

σ_m – Mechanical Stress

σ_x – Stress in x-direction

σ_y – Stress in y-direction

E – Young's Modulus (Modulus of Elasticity)

T – Temperature

α – Thermal Expansion Coefficient (CTE)

T_0 – Ambient Temperature

T_i – Initial Temperature

A_C – Cross-sectional area

A_S – Surface area

RUD – Rail Uplift Device

ASTM - American Society for Testing and Materials

AREMA – American Railway Engineering and Maintenance-of-Way Association

R – Electrical Resistance

K – Sensitivity Coefficient of Resistance Strain Gage

ρ_r – Resistivity of the Material

L - Length

DIC – Digital Image Correlation

CCD – Charge-Coupled Device

FEA – Finite Element Analysis

ν – Poisson’s Ratio

λ_B – Bragg Wavelength

n_{eff} – Modal Index

Λ – Grating Period

FBG - Fiber-Bragg Sensors

CST – Continuous Scanning/Traversing

TRL – Technology Readiness Level

LSI – Laser Speckle Imaging

LED – Light Emitting Diode

NCC – Normalized Cross-Correlation

CMOS – Complementary Metal-Oxide-Semiconductor

kip – Kilo Pound

lbf – Pound Force

NCPM – Non-Contact Precision Measurement

IR – InfraRed

W – Watts

Bi – BIOT Number

q – Heat Transfer

k – Thermal Conductivity of the Material

h – Convective Heat Transfer Coefficient

L_C – Characteristic Length

m – Meter

K – Kelvin

ft – Feet

F – Fahrenheit

C – Celsius

hr – Hour

BTU – British Thermal Unit

P - Perimeter

C_p – Specific Heat Capacity

α_T - Thermal Diffusivity

ρ – Density of a Material

L_{eff} – Effective Length

t_L – Diffusion Time or Thermal Time Constant

T_{SS} – Steady State Temperature

V – Volume

M – Mass of the Body

H – Height

q_0'' – Heat Flux

P_H – Power

τ – Time Constant

$\ln$ – Natural Log (Logarithm)

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Dedication

To my lovely wife and precious daughter who supported and encouraged me in all my endeavors. Without your help, I wouldn't be able to achieve this milestone.

To all my family members: father and mother who supported me in all my decisions.

To the professors: Terry Beck and Robert Peterman, who taught me, motivated me and believed in me to finish this project.

Chapter 1 – Introduction

1.1 Background

Railway has been an integral part of the U.S. economy for more than a century, being one of the major commodity transporters and a key player in the development of the country. With growing technology and consumer demands, railway needs to adapt to higher speeds while providing safe transportation. Hence, the need for continuously welded tracks that can provide not only safe operation, but also higher speeds along with lower track down time for maintenance and repairs. In addition to these good things, however, can come potential challenges that need to be addressed periodically to avoid any major long-term issues.

Track failures resulting from hot weather buckling and cold weather breakage associated with Continuously Welded Rails (CWR's) represent one such challenge that has affected the rail industry. The inability to readily determine the state of stress in continuously welded railway rails has long plagued the rail industry, and the solution to this problem is considered by many to be the “holy grail” of the railroad industry.

In the past, railway tracks (non-welded) were bolted together with fishplates and the gap between fishplates allowed for thermal expansion or contraction. This gave enough room for rails to expand and contract; but the maintenance cost was higher with lower train speeds. Since the introduction of CWR's, the rail speed has increased because of no mechanical (bolted) joints and lower rail maintenance. However, because there are no gaps or joints to allow for rail expansion or contraction, the chances of buckling and breakage have increased, causing an alarm to initiate new research for the purpose of increasing rail safety.

The current research is aimed at the development and application of a non-contact strain-measurement technique to quickly and non-destructively determine the state of stress in steel

railroad rails. Excessive compressive stresses caused by the restraint of rail on hot days can lead to sudden buckling of track ([Figure 1.1](#)). Conversely, excessive tensile stresses induced by very cold temperatures can lead to rail breakage/fracture ([Figure 1.2](#)). It should be noted that both of these situations can be enhanced, and even activated, by local climate conditions, as well as when the rail is subjected to train loading, and can lead to derailments if undetected.



Figure 1.1 Buckling in Hot Weather¹

¹ <https://www.governing.com/infrastructure/the-havoc-extreme-heat-wreaks-on-our-aging-infrastructure>



Figure 1.2 Fracture in Cold Weather²

1.2 The Rail Neutral Temperature Concept

Continuous welded steel rail can be subjected to very high stress levels in track when the temperature of the rail differs from the installation temperature, commonly referred to as the “Rail Neutral Temperature (referred as RNT),” which corresponds to the temperature at which the rail stresses are neutral (zero). This influence of temperature on the rail stress is illustrated in [Figure 1.3](#). Any changes in the tension or compression in the rail causes the stress in the rail to change which can be represented in terms of RNT, the term used by major railroads in the US.

² <https://x.com/T1SydneyTrains/status/1216827151359438848/photo/1>

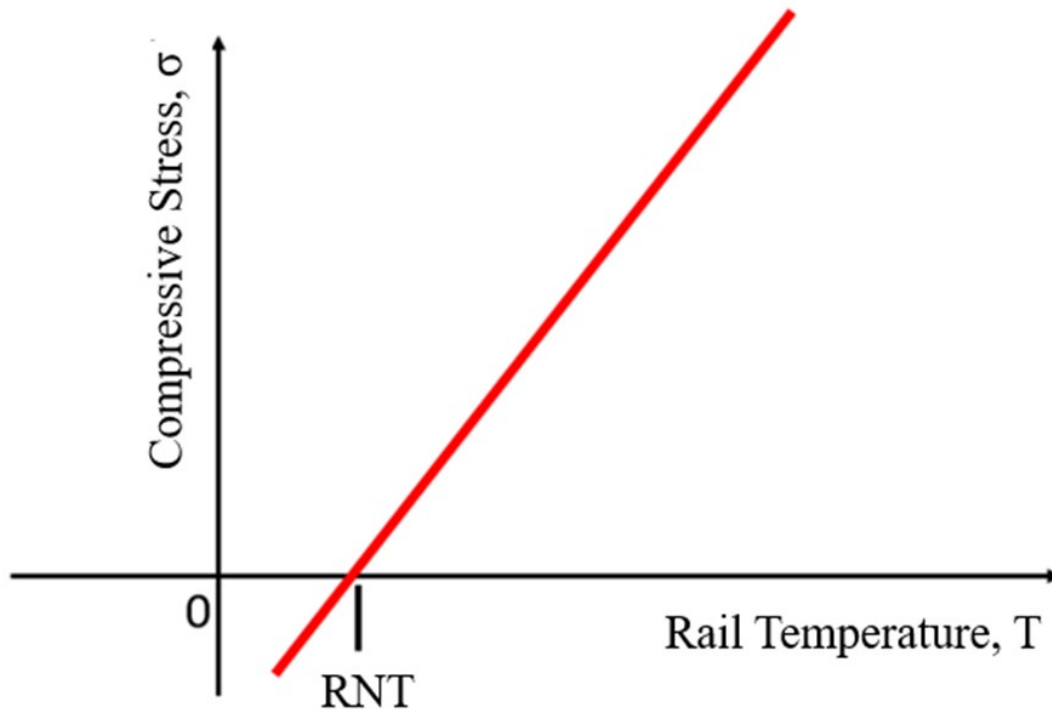


Figure 1.3 The Rail Neutral Temperature

Clearly, there is a need for a robust and reliable technique for accurate assessment and in-track monitoring of the “state of stress” of a section of steel railroad rail, which will represent the departure from the rail neutral (zero stress) condition established at the time of installation. Rails get installed at a DRNT (Desired Rail Neutral Temperature) depending on the temperatures in their respective geographic location. Any changes in the tension or compression in the rail causes the stress in the rail to change which can be represented in terms of RNT.

In cold weather, the RNT can drop below the DRNT, and the rail can contract, causing rail to crack and fracture. If detected in time, the fractured rails are less of a concern because they can be managed via temporary supports, speed restrictions or repairs[\[13\]](#). The FRA noted that if the

rail is properly anchored or appropriately connected to ties via fasteners, the pull apart gap is typically less than 4” and that trains can still traverse this gap relatively safely compared to buckled rails. Additionally, crack propagation can be detected using various Non-Destructive Testing’s. Also, signaling systems may be able detect cracked rails[27].

In hot weather, the rail expands leading to compressive forces, which can cause rail buckling if these forces are over limiting stress. The buckling will occur when the lateral resistance offered by ties and ballast is undermined by the compressive stresses in the rail, in other words loss of lateral stability[13,27].

The relationship between rail stress and temperature can be defined as follows:

$$\epsilon_{\text{Thermal}} = \alpha (\Delta T) \quad (1.1)$$

$$\sigma = E \epsilon \text{ (Hooke's Law)} \quad (1.2)$$

Combining equation 1.1 and 1.2 yields,

$$\Delta T = (T_{\text{RN}} - T) = \frac{\sigma}{E\alpha} \quad (1.3)$$

Where, T_{RN} is Rail Neutral Temperature, T is Current Rail Temperature, σ is Stress, E is Young’s Modulus (Modulus of Elasticity) and α is Thermal Expansion Coefficient of the Steel Rail.

When ΔT is positive the rail is in tension, while on the other hand if ΔT is negative, the rail is in compression[13].

To determine Rail Neutral Temperature (RNT), Equation (1.3) can be rearranged as follows:

$$T_{\text{RN}} = \frac{\sigma}{E\alpha} + T_{\text{R}} \quad (1.4)$$

In addition to mechanical and thermal stresses, there are various types of stresses that can affect the rail and play a role in RNT changes. Some of the major contributors are: Residual Stresses, Welding Stresses, Bending Stresses and Contact Stresses[13,28].

- **Residual Stresses:** Residual stresses are generated during the cold roller straightening of the rail (during manufacturing). The forces can be tensile and compressive in nature on different sections across the cross-section of the rail, so they do not add any resultant force overall[[13,28,31](#)].
- **Welding Stresses:** While welding CWR's, the track is tensioned to get the DRNT for installation. However, if the rail has porosity or already existing defects, it may initiate crack or propagate already existing cracks while performing track tensioning[[13,28](#)].
- **Bending Stress:** These type of stresses occurs when the rails are installed on bends or curves. When the train passes over the tracks, it causes the rails to bend creating cyclic vertical stresses[[13,28,31](#)].
- **Contact Stresses:** Major contributors for rail stresses are contact stresses. As a train passes over the tracks, the wheels repeatedly come in contact with the rail generating cyclic loading and unloading causing the rails to stress and de-stress. Plastic deformation can occur in the head where the wheels are in contact with the rail due to compressive stresses[[13,28,31](#)].

1.3 Literature Review – RNT Measurement Techniques

RNT tracking and conformance is a very critical part of railway track maintenance since it dictates the stability of the track system to run trains successfully and safely at high speeds. There are a number of techniques to measure RNT, including destructive and non-destructive methods. An excellent review of RNT measurement techniques was given by Nicholas, et. al. [[13](#)], covering lot of these so mentioned techniques. Some commonly known and frequently used are mentioned below.

1.3.1 Rail Cutting Method

This method was used widely before 2003 and is rooted in the fact that when the rail is unclipped from the ties and cut, the rail will either compress or expand based on inherent stresses. The basic steps involve cutting the rail between two marked points and then measuring the resulting elongation to deduce the RNT[28]. The procedure is shown in [Figure 1.4](#).

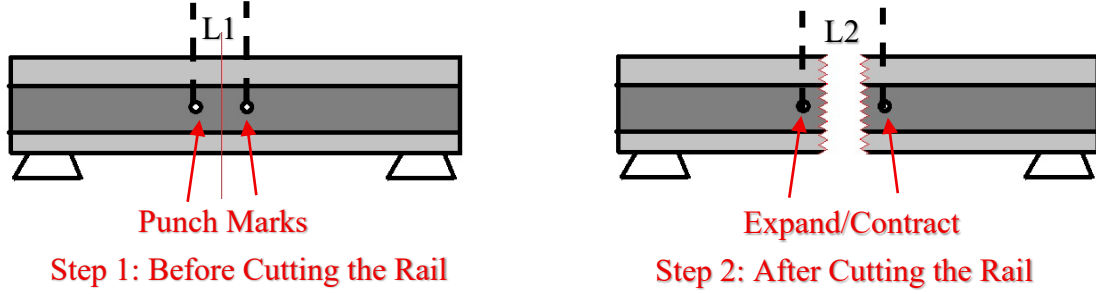


Figure 1.4 Rail Cutting Method for RNT/Thermal Stress Determination

The location of the cut must be 50m from the end of the CWR rail or 50m from a switch[13,28]. Mean rail temperature, T_R , is also measured within this 50m distance on each side of the cut for highest accuracy temperature capture[28]. Punch marks are placed at a distance of 100mm on both sides of the rail cutting location and the distance between punch marks is measured using sliding caliper before and after the cut is introduced[13,28]. The unclipped rail is supported on the roller for free slide, so the displacement is not restricted for displacement of the cut sections[13]. The RNT can be deduced using equation (1.5) below.

$$\Delta L = \alpha L (T_{RN} - T) \quad (1.5)$$

Where, T_{RN} is Rail Neutral Temperature, T is Current Rail Temperature, α is Thermal Expansion Coefficient of the Steel Rail, L is Rail Length Over Which the Stress Relaxation Occurs and ΔL = Change in Length (Elongation).

If ΔL is positive that means RNT is higher than rail temperature and there is tension in the rail while negative ΔL represents compression in the rail with RNT lower than rail temperature[28].

Some drawbacks of this method are given below.

- It is a destructive method[13,28].
- There are location restrictions. The location has to be at least 50 m from the end of CWR or switch. Also, it is a time-consuming process, so the track needs to be out of order for a period of time. [13,28]
- It is challenging to obtain an accurate Rail Relaxation Length “L”, because of non-linear relationship between rail relaxation length and RNT.
- The accuracy of this method is quoted to be $\pm 2^\circ\text{C}$ for UIC 60 rails (121.2lbs/yd). Errors up to 15°C have been reported especially when the stress relaxation length is not measured accurately[13,29].

1.3.2 Rail Lifting Methods

This is one of the documented methods since 1987 and has been tried and tested with lots of variations to it. The method relies on the fact that holding the rail at two distant points and applying load in the middle of this distinct points, the rail acts as a beam and the deflection is dependent on the longitudinal force in the rail[20,28-31]. In other words, the method is based on the relationship between the tensile and compressive force in the rail, and the force required to displace the rail a certain distance. The larger the thermal stress the higher the force required to deflect the rail. [13,30]

The procedure involves unclipping 30m of rail track, elevating the rail onto two simple supports positioned 10m away at both sides of the center point, and applying deflection by

incrementally lifting the rail head through the hydraulic jack while applying a load up to 10KN. As the load is applied, the force and displacement profile are captured[[13,15,28,29,31](#)]. The RNT is then calculated using equation (1.6) below.

$$T_{RN} = \frac{(F_{start} + F_{end})}{2AE\alpha} + T_0 \quad (1.6)$$

where T_0 is the ambient temperature, F_{start} and F_{end} are rail loading applied at the start and end of the measurement, α is the Coefficient of Thermal Expansion (CTE) of the Steel Rail, E is the modulus of elasticity or Young's modulus, and A is the rail cross-sectional area. Accuracy of this method is around $\pm 3.5^\circ\text{C}$, with a rapid measurement time of one measurement per hour[[13,20,28,31](#)].

Below are couple different types of methods used in RNT measurement using the rail uplifting device:

The VERSE Method:

It is a type of rail lifting method and is known as Vertical Rail Stress Equipment (VERSE)³. The VERSE system shown in [Figure 1.5](#) consists of a clamp to lift the rail head with its built-in hydraulic jack[[15,28,29](#)].

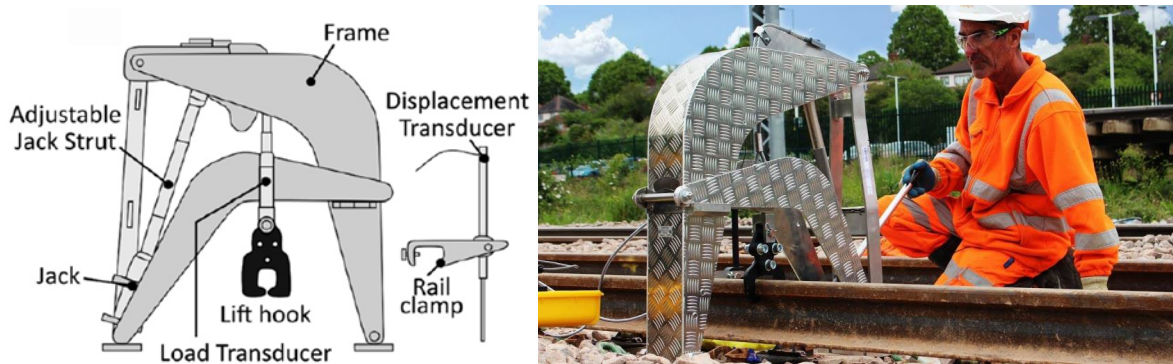


Figure 1.5 VERSE RNT Measurement System [[13,29](#)]

³ The associated hardware is supplied by Pandrol Ltd.

The Rail Uplift Device:

A new device called the Rail Uplift Device (RUD) was created by Kish and Samavedam[30]. A modified rail car, lifting the rail up after unclipping the rail from ties, is shown in Figure 1.6. The method is based upon the fact that the rail can be secured at two points with the inner wheels of the rail car and section of rail in between wheels can be lifted with a measured uplift force and unknown longitudinal force. For a fixed rail length, the uplift force required for a fixed vertical deflection corresponds to the inherent longitudinal force.[15,30]. As shown in Figure 1.6, δ_T is the deflection when the rail is in tension, δ_0 is deflection when there is no tension or compression in the rail and δ_C is deflection when the rail is in compression.

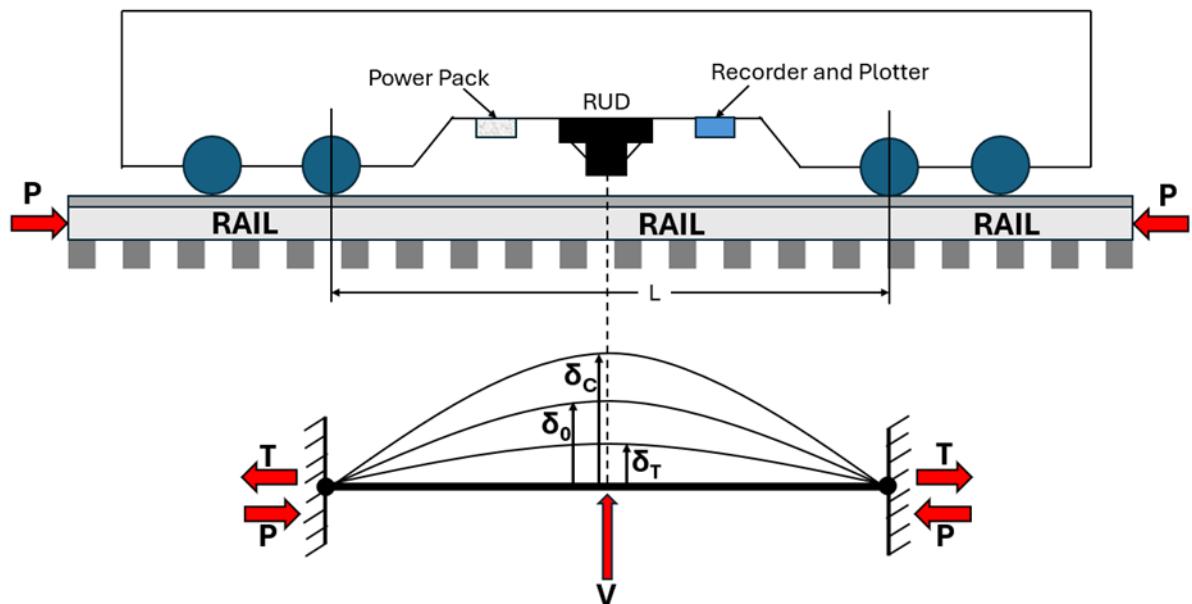


Figure 1.6 Rail Uplift Device Principle[30]

Testing at the TTC facility in Pueblo, Colorado showed good agreement with the theory[30].

Some drawbacks of this method are[13,15,28]:

- Firstly, 30m of rail must be unclipped before performing any test, making it unsuitable for tight arrangements.

- It is not good for rails that are already under compression or are at higher temperature than the RNT because the rail will buckle as soon as it is unclipped.
- The method does not need rail to be cut so it is in a sense a nondestructive method, but the method is labor intensive since the rail clips must be removed every time.

1.3.3 Hole-Drilling Method

This method has been used since 1934 and is an ASTM certified method for measuring surface residual stresses in components[33,34]. This is a semi-destructive method which involves drilling a hole and measuring the residual stresses in the object[34,36]. The drilled hole can be blind with a depth (a) equal to its diameter or (b) small compared to the thickness of the component or it can be a through hole. Rosette strain gages are typically employed around the bore to measure the strain variation[13,35].

University of California San Diego researchers have successfully measured rail thermal stresses by implementing the hole drilling method on US AREMA 136RE and 141RE rails⁴. Measurements were carried out on unconstrained and constrained rail sections (136RE and 141RE) to calculate thermal stress. Errors were reported at $\pm 5^{\circ}\text{C}$ during the initial study but further testing showed that this method may be able to determine the RNT within $\pm 2.78^{\circ}\text{C}$ accuracy with a 90% confidence interval.[13,36,37]. More information on UCSD research can be found in the documents on the study of the in-situ thermal stress measurement using a hole-drilling method by Zhu X, et. al. [36] and Thermal stress measurement in continuous welded rails using the hole-drilling method by Zhu X, et. al.[37].

⁴ 136RE and 142RE are standard rail cross-sections defined by American Railway Engineering and Maintenance-of-Way Association (AREMA). The numbers signify the weight of the rail in terms of lbs./yard. For more information, visit: <https://www.arema.org/>

Some drawbacks of this method are:

- Even though the method is quite accurate, drilling of holes on rails in the field for safety reasons[13].
- This method will measure total stress (residual + thermal) so the residual stress for that section of rail must be known prior to extract only thermal portion[28].
- This method required track closures to bore the holes and install the strain gages[13].

1.3.4 Deformation Techniques

By measuring deflection or strain, stress can be inferred easily. Some of the available methods include Strain Gages, Fiber Brag Sensor and Digital Image Correlation (DIC). [13,28].

Strain Gages:

A resistive strain gage, typically in an appropriate bridge circuit, produces an electrical signal proportional to the mechanical strain of the surface to which it is bonded. They come in a variety of sizes depending on the location they must be used on. A resistive strain gage is made of small wires that measure strain when the resistance of the wire changes during the process of displacement[39,40]. The resistance R varies with ρ , the resistivity of the material, L the length, and A the cross-sectional area of the conductor[13,28,38].

$$R = \frac{\rho L}{A} \quad (1.7)$$

Strain $\varepsilon = \left(\frac{\Delta R}{R} \right) \frac{1}{K}$, where ΔR is resistance variance, K refers to sensitivity coefficient of the resistance strain gage[38]. Stress can be calculated using Hooke's law in equation (1.2) after measuring the strain. Electrical resistance is temperature dependent, so temperature compensation is necessary for accurate results[28].

A new device based on a bi-directional strain method has been used to measure longitudinal rail stress and multi-point measurement. Total longitudinal rail stress can be estimated from the measured total longitudinal strain and total vertical strain using this new bi-directional strain measurement method. In general, this strain gage method has a resolution of $\pm 0.4^\circ\text{C}$ [28]. Some drawbacks of this method are [13,28]:

- Must be mounted on the rail when it is not installed (in stress free state) or thermal strain at the time of rail installation is required for baseline [13,20].
- It may not be the most practical method in the field because of rail weathering. Strain gages may get affected by rain, dust etc. in the field.

Digital Image Correlation:

Digital Image Correlation or DIC is a well-known technique for displacement measurement using a fixed CCD camera. If one camera is used, it is called 2D DIC with the displacement occurring only within the plane perpendicular to the camera. However, that may not be the case for general displacements. Using more than one camera, now well-known as 3D or stereo-DIC, provides stereoscopic displacement measurement capability. With DIC the surface under investigation is marked with a displacement “tag” such as speckle paint to track the features, and images are taken before and after displacement/strain [62]. This requires a scaling relationship (camera calibration) between pixels and displacement (e.g., millimeters). The captured images are subdivided into subsets with a unique gray level distribution [12,13,63]. The subsets are then computed mathematically using some type of pixel correlation algorithm to yield displacement; for example, Normalized Cross-Correlation [62].

Recent research was conducted by Knopf, K. et. al. at University of South Carolina to measure RNT and state of rail stress using DIC techniques. The research included FEA

analysis, followed by laboratory testing to confirm the FE analysis results. Two separate rail segments, one unconstrained and one partially constrained, were used to conduct testing. FEA analysis suggested that the rail head curvature change is proportional to change in temperature between two ties, and the direction of curvature change is different dependent upon the temperature being above or below its RNT state[14,20].

Laboratory tests were performed using the DIC method with temperature change being used as thermal loading steps to confirm the FEA analysis results. A linear relationship between curvature of the head and temperature was developed, allowing a plot to be created which was then used to estimate the RNT (y-intercept). The longitudinal stress was then calculated using the following, after plotting the temperature-strain relationship[14,20]:

$$\sigma_x = (\epsilon_x - \epsilon_y) \frac{E}{(1+\nu)} + \sigma_y \quad (1.8)$$

As per the author, the method is reference free and it can estimate the RNT within $\pm 1^\circ\text{F}$; however, there are some factors that may have an effect on the final results[14,20]. For example, the assumption was that the head deformation at RNT was zero, which may not be the case, and also that the head will deform always at the same rate, which may also be not the case because of weathering, and wear and tear introduced with continuous train motion.

Some drawbacks of this method are given below[14,20].

- The method being non-disruptive, requires a set of readings to plot temperature, curvature and strain to estimate RNT and calculate longitudinal stress.
- Also, speckle paint was applied to the rail for displacement measurement. This may not be a feasible option, since the rail is subject to weathering in the field, and the surface structure/features may change significantly over the time period associated with

the measurement. Hence, this method may be only a short-term measurement technique.

Fiber-Bragg Sensor:

Fiber-Bragg (FBG) sensors are similar to strain gages but are an optical version of them with longer service life, higher precision, light in weight, and electromagnetic interference shielding[13,41,42,43]. They are capable of measuring parameters such as strain and temperature[43].

Fiber-Bragg sensor are tiny single mode devices with periodic refractive index variation output capabilities. The reflection wavelength is highly responsive to temperature change and strain with corresponding wavelength-shift of 10pm/K and 1pm/microstrain. It is a typical optical fiber cable with a grated core that acts as reflectors of optical light. Discontinuity because of grating causes the propagating light to reflect at different wavelengths[13,44]. This happens at the Bragg wavelength, λ_B and is defined mathematically by Equation (1.9),

$$\lambda_B = 2 n_{\text{eff}}\Lambda \quad (1.9)$$

where n_{eff} is the modal index and Λ is the grating period.[42,44]

There has been some research and testing performed on the fiber optic Bragg grating sensing system for health monitoring in railways. One example is the system designed and tested by The Hong Kong Polytechnic University in collaboration with KCRC. The FBG sensors were installed on tracks to measure strain which was then used to count axels, speed and weight. Additionally, the FBGs were installed on a train body that can be used to assess structural integrity of train body shells and also assess track conditions.[43]

In other research, laboratory testing was conducted with the Hetero-Cladding FBG sensor in China. In this test, two FBGs were constrained in a single optical fiber cable but with

different cladding diameters. Because of this cross-sectional difference, the temperature sensitivity is the same, but strain sensitivity is different for each FBG. This feature of identical temperature sensitivity and different strain sensitivity is used to measure longitudinal force by the relative wavelength difference between two FBGs. Laboratory research indicates that the maximum differences between the theoretical values and the test results were about 4.8% and 2.4% respectively (without and with temperature correction)[42].

Some drawbacks of this method are[13]:

- High cost compared to strain gages with similar accuracy[13,41].
- Still a new technology, so unconventional from a usage and training standpoint [41].

1.3.5 Displacement Methods

Position change (displacement) between two points can be measured instead of strain to calculate stress [28].

Pfender Device:

This method is rooted in measuring rail base displacement and was first introduced in Hungary. Pair of balls are hammered on the rail surface on both sides with a base of 100mm (L) at an interval of 10 meters. The change in distance between each pair of balls is measured using a Pfender meter. Change in stress can be calculated using equation (1.10),[13,28]

$$\Delta\sigma = E \frac{\Delta L}{L} \quad (1.10)$$

Here, $\Delta\sigma$ is change in stress, ΔL is change in length, and E is Young's modulus.

The change in RNT can be defined as

$$\Delta T_{RN} = \frac{1}{\alpha} \frac{\Delta L}{L} \quad (1.11)$$

where α is coefficient of thermal expansion for steel rail.

The resolution of the Pfender device is about 0.002mm and the accuracy for measuring RNT is around $\pm 2^\circ\text{C}$ [28].

A drawback of this method is [13,28]:

- The sensor itself needs to be calibrated routinely because of thermal expansion of its components.

MS-02 Device:

The MS-02 device measures rail base elongation or compression within a fixed gage length, as shown in Figure 1.7 [28].

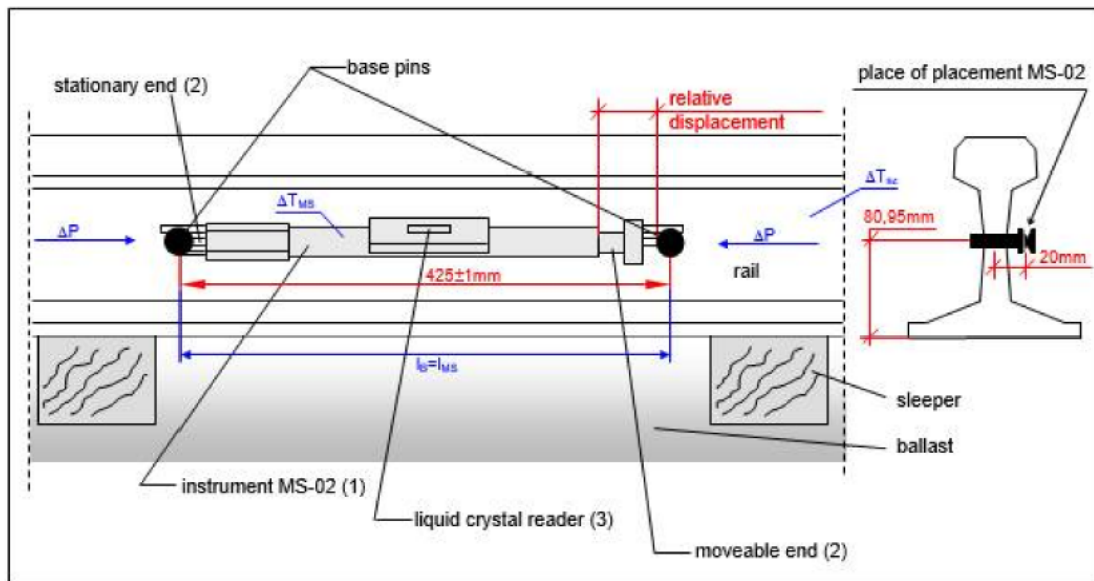


Figure 1.7 The MS-02 Measurement Device [45]

The procedure starts with drilling two 20mm holes on the rail neutral axis for each measurement set with a gage length of $425\text{mm} \pm 1\text{ mm}$ [45]. The device has one fixed tip and one movable tip that is used to align the device onto the attaching pins which mount the device to avoid measurement errors [13,28]. Relative displacement between the rail base and the device base due to the change in rail base temperature is measured to infer strain and later to

calculate stress. As per the design, the thermal expansion coefficient and thermal absorption of the device is kept similar to that of the rail. The accuracy reported is $\pm 3^{\circ}\text{C}$. [13,28,45]

A drawback of this method is [13,28]:

- Requires that the RNT is known at the time of installation.

Some other methods, apart from the key ones mentioned above that are used to measure stress and rail neutral temperature, include: The Magnetic Method [13,20,28,48,49,50,51,52,53], X-Ray Diffraction Methods [13,20,28,51,56], Electromagnetic Impedance/Piezoelectric [13,20,57,60,61], Ultrasonic/Ultrasound [13,20,28,46,47], Vibration [13,20,28,57,58,59]. Refer to the referenced papers for further details on the techniques.

To summarize, some of the methods mentioned above can measure rail neutral temperature with high accuracy (reported as $\pm 1^{\circ}\text{F}$). However, some of them are either destructive or semi-destructive methods (rail cutting, rail lifting) for measuring rail neutral temperature. These methods are very time-consuming since the rail will need to be replaced before the track is put back in service. Some methods are contacting (deformation measurement, ultrasonic, vibration and piezoelectric) which means there has to be some kind of rail contact which may affect the rail geometry, structure or surface. The equipment can also be time-consuming to set up, which can cause train delays. Other methods (magnetic and x-ray diffraction) need expensive instrumentation and also require frequent equipment calibration. Additionally, DIC methods, which are close to the method used in this dissertation, also need some kind of speckle paint on the rail which is not practical in the field. The rail goes through lots of climate conditions and weathering, causing the speckle paint to wear off; creating issues with finding the same reference rail features to correlate for displacement measurement.

This dissertation tries to address the deficiencies mentioned above in a practical way by using permanent feature tagging markings on the rail surface, with completely non-contact methodology to measure surface displacement. Furthermore, since the tagging is permanent, the features can be used over very long periods of time to keep monitoring the rail stress until it is time to remove the rail. This not only gives opportunity for long term displacement tracking but also represents a completely new paradigm for continuous long-term monitoring of rail stress and rail neutral temperature. More details will be discussed in the sections of this dissertation that follow.

1.4 Objectives

There are a very few non-contact methods available for measurement of rail stress to evaluate in-track departures from the rail neutral stress condition. One of the objectives of this dissertation is to address the deficiencies in the methods mentioned in literature review and make a fresh attempt to address them via already available field-hardened non-contact strain measurement technology. Goals necessary to achieve success of this project include accurate sensor development, testbed testing, sensor calibration, identification of temperature measurement procedure, extraction of the thermal stain, and finally estimate equivalent RNT within $\pm 5^{\circ}\text{F}$. Non-contact methods of accurately assessing strain have been developed for related applications involving diagnostic testing of prestressed concrete railroad ties. The accurate assessment of mechanical strain requires accurate displacement measurements from an initial (baseline) condition. Historically, this has been accomplished by measuring the relative displacement between two reference points on an object's surface. This technique has been successfully applied to the measurement of strain on the surface of prestressed concrete railroad ties [1-9]. Considerable

progress has been made in Digital Image Correlation (DIC)⁵ techniques and various devices incorporating specialized software algorithms have been developed to perform displacement and strain measurements on prestressed concrete. Current examples of non-contact displacement measurement devices include the Automated Laser Speckle Imaging Systems [1-4,9], Multi-Camera Non-Contact Transfer Length Measurement Systems [5,6,8], and Non-Contact Continuous Scanning/Traversing (CST) Transfer Length Measurement Systems [7-8].

Most of the available methods discussed in the literature review section have lots of restrictions, including need for expensive instrumentation, reliability, accuracy, ease of usage, business disruption, etc.[20]. The objectives of this dissertation are to introduce and demonstrate a new approach to the assessment of the state of stress in steel rail by overcoming deficiencies mentioned in currently available methodologies for strain measurement in the following steps:

Proof of Concept and Large-Scale Sensor Design:

- Utilize existing (proven) strain sensor technology (patented LSI system, and an existing multi-camera system) to demonstrate assessment of strain on a short rail section with varying gauge lengths by pairing off adjacent cameras.
- Modify existing multi-camera set-up (for example, lighting) to assess different design conditions needed for accurate displacement and strain measurement on rail.
- Demonstrate use of applied “markings” to tag displacement (strain).

⁵ Digital Image Correlation (DIC) is a common technique for assessing the relative shift of surface features in before and after captured images [10-12] .

- Design and fabricate full-scale prototype sensor with extended gage length, and a portable support system to mount the sensor safely for use on full-scale steel rail (work completed by John Bloomfield and his team at TDI).

Large-Scale Steel Test Facility and Large-Scale Sensor:

- Design and construction of a special steel frame facility to test full-scale sections of steel rail (completed by Dr Robert Peterman and Civil Engineering team and TDI).
- Incorporate the ability to provide controlled thermal loading (thermal strain) in addition to mechanical loading.
- Construct large-scale sensor system (based on new design) with extended gauge length and a portable magnetic support system for the large-scale sensor(work completed by John Bloomfield and his team at TDI).
- Create new LabVIEW program to perform pattern matching to assess resulting strain from large-scale sensor(basic program creation and testing done as part of this dissertation, with final program designed by John Bloomfield at TDI).
- Incorporate input from remote IR temperature sensor for assessment of thermal strain component.

Verification of Large-Scale State of Rail Stress:

- Test new large-scale sensor under conditions of pure mechanical and mechanical & thermal strain.
- Conduct full-scale rail tests using steel test facility.
- Measure baseline displacement conditions at known baseline (“rail neutral”) temperature.
- Subject steel rail section to controlled thermal conditions and imposed mechanical strain.
- Evaluate state of thermal stress from non-contact IR sensor temperature measurements.

- Extract state of mechanical stress and assess deviation from rail “neutral temperature” condition.

To achieve the objective of measuring state of stress and RNT of the rail, correct assessment of the rail strain was vital. Laboratory tests confirmed the process of measuring rail strain using manual tag marked with controlled application of mechanical and thermal loading in the testbed. The testbed was used to perform multiple displacement measurements on the same side of the rail. Future plans will include measurements on the opposite side of the rail to help eliminate horizontal bending effects. Following steps mentioned above, the end goal is to be able to accurately report state of stress in the rail and calculate equivalent RNT. After conducting laboratory tests, field testing will be arranged. The test results presented in this dissertation represent the first steps toward the goal of demonstrating this new technology in track.

Forces and Moments Acting on Rail:

Installed in track, railway rail has multiple force components and moments acting on it. These include forces in the x, y, and z directions and moments about the associated three rotational axes, as shown in [Figure 1.8](#). All these forces and moments generate stress in the rail and must be considered in order to achieve accurate deflection measurements and accurate assessment of the Rail Neutral Temperature (RNT).

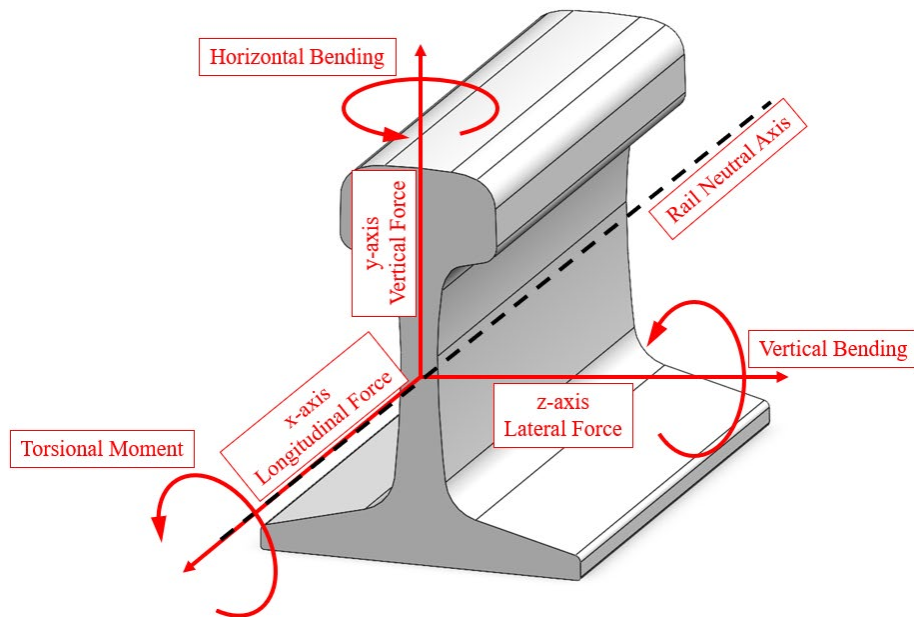


Figure 1.8 Forces and Moments Acting on an Installed Rail Section

The force in the x-direction will be captured by longitudinal strain measurement while the force in the y-direction will be neglected because lab testing will be performed when the rail is not connected to a tie. During field testing, the rail will be disconnected from ties to minimize vertical forces. The rail does not have any directly applied force in the z-direction; therefore, forces in this direction will be ignored during testing. To remove vertical bending effects, rail deflection will be measured on the rail neutral axis, as shown in [Figure 1.8](#). To capture and assess the presence of any horizontal bending effects, the deflection/strain will eventually need to be measured on both sides of the rail along the neutral axis. This will allow for averaging any of these lateral effects. The torsional moment in the rail will be neglected in the analysis of rail strain measurement.

1.5 Organization of Dissertation

[Chapter 2](#) – Measurement of strain/stress. This chapter includes a review of contact and non-contact strain measurement methods. It provides basic ideas on current technologies to measure strain, methods for tagging surface motions, and the new proposed dot-peen tagging method. It also covers methods for displacement measurement using Digital Image Correlation (DIC).

[Chapter 3](#) – Proposed non-contact strain sensor. This chapter reviews the basic dual-camera measurement principles, the proposed new sensor design (hardware and software) and the experimental set-up for calibration and sensitivity measurement.

[Chapter 4](#) – Full-scale facility for testing steel rail. This chapter discusses the new testbed that was designed and developed with the capabilities of tensioning the rail up to 300,000lbs. The chapter also covers the rail test section dimensions and the different lengths of rail sections (short rail-77” and long rail-147.25”) created for mechanical and thermal testing.

[Chapter 5](#) – Full-scale mechanical testing of steel rail. This chapter discusses testing of the sensor for mechanical loading only. It covers repeatability tests for the new strain sensor, theoretical analysis for strain measurement, and mechanical testing of short and long rail section.

[Chapter 6](#) – Thermal effects on steel rail section-laboratory verification. This chapter discusses the preliminary thermal analysis in the laboratory. This chapter was intended for the purpose of designing the set up for the thermal heating and thermal loading aspect of the project. It is very important because thermal strain must be removed from total strain to extract mechanical strain.

[Chapter 7](#) – Non-contact rail temperature measurement. This chapter describes different methods for temperature measurement. It provides comparison and check for reasonableness to use either of the methods of temperature measurement as per availability and convenience.

[Chapter 8](#) – Combined mechanical and thermal testing. This chapter provides information on the rail set up for combined mechanical and thermal loading on the testbed. It addresses the measurement of overall stress in the rail and removal of the thermal stress component to yield the pure mechanical portion for calculating RNT and state of stress. This is the main objective to be achieved for successful completion of the project.

[Chapter 9](#) – Summary and Conclusions. This chapter covers the key takeaways, measurement of the state of stress and RNT including current issues being looked into for removal of observed bias effects. It discusses the onset of the proposed new paradigm by using the new strain sensor for successful state of stress and RNT measurement.

[Appendix A](#) – Uncertainty analysis. This chapter covers important relationships used in the project and their use in uncertainty calculations.

[Appendix B](#) - Dual deflection measurements on the non-heater side of the rail. This chapter gives more information regarding ongoing work. The chapters briefly discusses box averaging and line scan analysis for temperature measurements for thermal strain extraction using IR imaging.

[Appendix C](#) – Testbed bending. This chapter provides some information on the testbed bending that was noticed while tensioning the rails. It also provides information on some attempts made to measure the bending.

[Appendix D](#) – Equipment used. This chapter provides information on all the equipment used in the project with their range, uncertainty and accuracies.

[Appendix E](#) – Measurement of coefficient of thermal expansion. This chapter discusses the assessment of pure thermal strain on the steel rail and its characteristics during and after heating. It gives an indication of the behavior of the Coefficient of Thermal Expansion (CTE) for steel rail

and its importance and impact on accurate thermal strain assessment. It is an important quantity used in calculating RNT.

[Appendix F](#) – Sensitivity comparison with the mechanical Whittemore gage. This chapter includes sensitivity comparisons made for the new strain sensor and the Whittemore gage. The comparison shows the uncertainty in measurement of strain using an established contact method vs. the non-contact method (new strain sensor).

[Appendix G](#) – IR heater dispersion effects. This chapter describes the effects of IR heater radiation dispersion by employing imaging of radiation absorbed on a brick wall. These tests included dispersion (diverging) and converging effects of the IR radiation. They were performed to check the requirements and set-up of the IR heaters used to heat up the rail on the large-scale testbed.

Chapter 2 - Measurement of Strain/Stress

Strain is defined as the change in length divided by an original length. Accurate strain measurement is very important because it is used to calculate stress on different materials. Strain can be measured by various methods including measuring displacement between two points before and after the stress is induced, or by measuring a change in current due to varying resistance associated with the deformation of the material.

2.1 Contact Strain Measurement Technology

Perhaps the most common method for measuring surface strain on solid surfaces is with a resistance strain gage. In this method, the strain gage is bonded to the surface with adhesive and the change in resistance is used to infer the strain on the surface. However, the issues with this technique are that it is highly sensitive to changes in temperature, the bonding between the surface and the gage, and the material properties. Whenever the bonded strain gage is used in the field, there are other unknown factors that can affect the readings including weathering. The gage must be adhered to the surface accurately in proper direction or the readings will be off, and the bonding surface must be smooth for proper surface to gage connection. Also, since the gage is bonded onto the surface, it cannot be relied on for long periods of time since either the bond or the gage itself can be affected by people touching it or by having the surface material change its characteristics[21]. Additionally, the gage is very sensitive, so it cannot be used in a harsh environment or in locations where a ruggedly constructed device is needed. Strain gages are used on railway tracks for a multitude of reasons, including longitudinal strain measurements [38,73].

Another strain measurement method that is commonly used on pre-stressed concrete is a mechanical device called a Whittemore gage, as shown in [Figure 2.1](#), which is basically a manual handheld gage used to measure displacement. As mentioned, since the gage has to be used by a

person, the accuracy is operator-dependent and there are obvious human factors for errors involved. Some other issues with the Whittemore gage is that it is bulky in size, the resolution is dependent on the gage length (precise length between two measurement points), surface preparation prior to testing and has low repeatability since it is user dependent. Furthermore, a large number of measurement points need to be formed on a surface to measure strain distribution, which can be time consuming labor-intensive work. Also, since it is highly user-dependent, the repeatability is a very big concern, and the accuracy will depend on how comfortable and experienced the user is. The accuracy of the experienced user with a mechanical handheld “Whittemore” gage is nominally about ± 0.0002 in. (± 0.005 mm) corresponding to a strain of about $\pm 25 \mu\epsilon$ for a standard 8.000 in. (203.2 mm) gauge length. This has been demonstrated on a concrete surface with machined brass points attached for measurement[1,3].

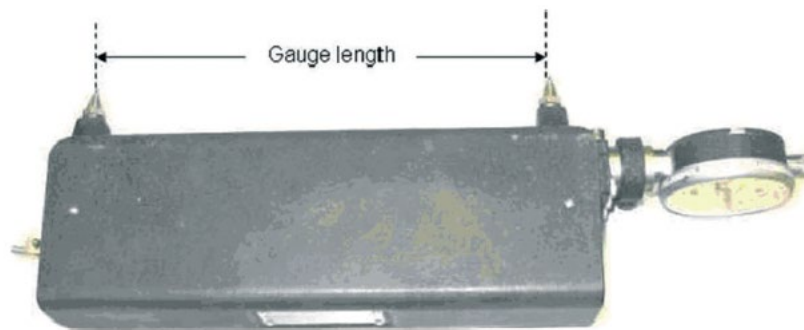


Figure 2.1 Whittemore Gage[1]

2.2 Non-Contact Strain Measurement Technology

Contact methods for strain measurement are acceptable, however, they may not be the most accurate and feasible method under harsh field measurement conditions. Non-contact (typically optical) methods for strain measurements are an alternative to contact methods. They not only save preparation time, but are less labor intensive, highly repeatability, less expensive because of lower maintenance costs and less prone to human error. Some of the existing non-contact strain

measurement sensors are discussed in the next section, as they relate to the current rail measurement problem.

2.2.1 Laser Speckle Device

One of the available optical methods makes use of the phenomena of laser speckle. Laser speckle is an image pattern caused by the constructive and destructive optical interference of light diffusely scattered from a roughened surface, as shown in [Figure 2.2](#). Measurement techniques employ the method of cross-correlation of the optical images of speckle captured by CCD (charged couple device) sensors (cameras). Optical speckle images are captured before and after the object displacement. The images are then cross-correlated, and the resulting peak position indicates the displacement [\[1\]](#).

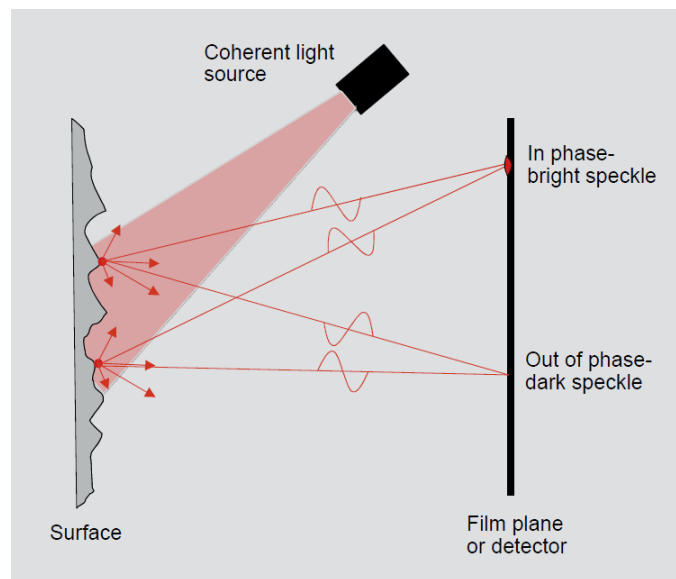


Figure 2.2 Generation of Laser Speckle [\[2\]](#)

The laser speckle method is highly susceptible to weathering and contamination around the measurement surface. In simple words, the speckle features change, there is no longer a correlation, so they can no longer be a tag for the displacement measurement.

2.2.2 Automated Dual-Camera and Multi-Camera Systems

Another system using digital image correlation, the automated transfer length⁶ or dual-camera strain measurement system, is comprised of two cameras mounted on a movable track. It was developed to a Technology Readiness Level (TRL) of 6[3,8]. [Figure 2.3](#) shows a CAD pictorial representation of an automated dual-camera surface strain measurement system using non-contact optical technology.

This system has been shown to be very robust and has successfully measured hundreds of transfer lengths even in the harsh environment of prestressed concrete tie plants. The transfer length represents the distance from each end of a concrete tie (or prestressed beam) required to fully transfer the force from prestressed wired/strands into the concrete tie [7]. This particular system can measure up to 60 points in 1 minutes with 0.01” repeatable sensor positioning accuracy. The system also has either “jog” mode or “continuous” traversing mode. It can assess surface displacement to an accuracy of better than ± 0.003 mm using any of several displacement-tracking “tag” characteristics, including laser speckle, reflective particle paint, and even concrete roughness (features). This translates into a strain measurement accuracy of better than $\pm 20\mu\epsilon$ for the nominal 6-in gauge length device[3]. However, the dual-camera system needs to be supported over the surface of the concrete tie to measure the strain profile from which the transfer length can be calculated. The transfer length can range nominally between 5” to 25”. The total scan length of the automated dual-camera system is 24” which provides sufficient measurement distance to well-define the transfer length on most concrete railroad ties.

⁶ The transfer length is defined as the distance required to transfer the fully effective prestress force in the prestressing strand to the concrete[2].



Figure 2.3 Automated Dual-Camera System[\[8\]](#)

The system still needs to be mounted on a rail because it has to traverse to measure the strain profile, so the creators of the system came up with the idea of manufacturing a new multi-camera system with 6 cameras spanning a 30” of distance to cover the full transfer length region of the concrete railroad tie. The idea behind the design of the 6-camera system was to provide a measurement of the entire strain profile (by pairing off adjacent cameras as 5 independent 6-in gage length sensors) in the transfer length region at the same time (one simultaneous flash and capture by all 6 cameras); yielding a small number of discrete strain measurements. The capability for transfer length measurement has been demonstrated in-plant using the 6-camera strain measurement system shown in [Figure 2.4](#) [\[5,6\]](#).

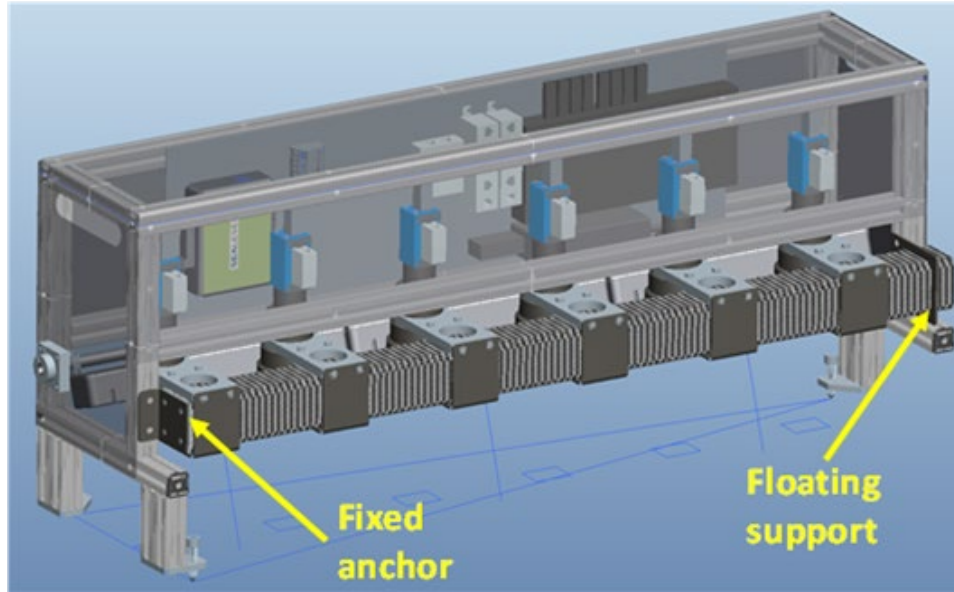


Figure 2.4 Multi-Camera System (6-Camera System)[8]

This multi-camera system provides multiple discrete measurements of strain at the same time over an extended length. With a camera spacing of nominally 6 in., there are 5 separate measurements of strain, beginning at approximately 3 in. from the end of the tie being measured. This spans a total measurement range of about 27 in. (690 mm), which is of sufficient span to capture typical transfer lengths as shown in [Figure 2.5\[8\]](#).

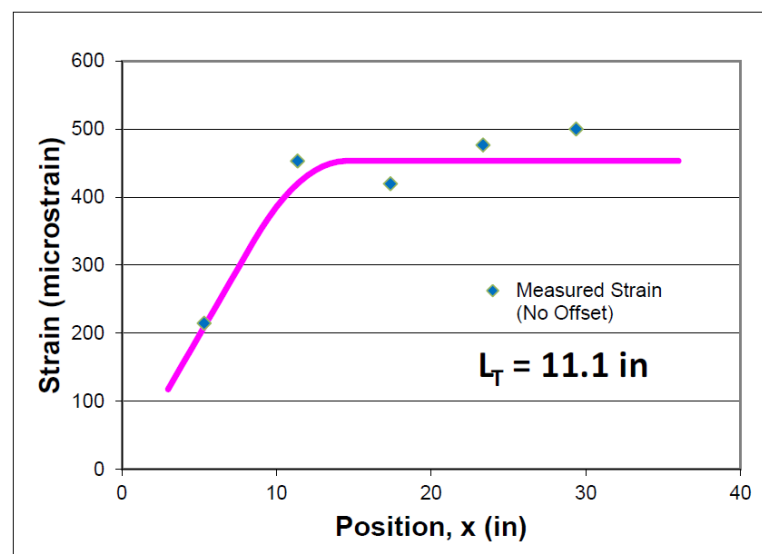


Figure 2.5 Single 5-Point Strain Profile with Transfer Length [8]

The system is capable of measuring the strain profile and calculating the transfer length right at the time of taking the images, utilizing a normalized cross-correlation image processing algorithm within a LabVIEW interface. The nominal strain measurement accuracy is $\pm 25\text{-}50\mu\epsilon$, which is comparable to strain measurements using the manual Whittemore gage[8].

While other stress assessment methods exist, the above-mentioned non-contact methods have been tested and are field hardened to estimate strain with a very high accuracy. This justifies selection of the proposed method of in-track assessment of the state of stress as a variation of the patented modular strain sensor system that has been previously used in FRA-funded research involving prestressed concrete rail-road ties[6,8].

2.3 Methods of Tagging Surface Motion (Displacement) for Non-Contact Strain Measurement

All the above-mentioned non-contact displacement measurement systems require some type of surface tagging to track surface movement, to facilitate assessment of surface strain. This tagging is typically comprised of some kind of natural surface feature or imposed marking that can be identified and tracked for the assessment of displacement. For example, the early version of the Laser Speckle Imaging (LSI) devices achieved displacement measurement by tracking movement of laser speckle patterns formed due to inherent surface irregularities under coherent laser light illumination. The Multi-Camera System and the Continuous Scanning/Traversing (CST) System track motion by physically marking the surface with “speckle paint” containing reflective particles. Alternatively, these systems have utilized inherent surface topological features as fingerprint “tags” for motion capture. Furthermore, the latter two types of tagging have been successfully employed in the harsh commercial tie plant environment [1-8].

2.3.1 Laser Speckle Imaging

A speckle image is typically generated by illuminating a rough surface with a coherent light source; for example, laser light. The diffusely reflected waves interfere with each other (constructively or destructively), resulting in a grainy image caused by optical interference on the camera sensor[2]. For example, when laser light is pointed at a ceiling tile, the observed grainy structure is actually generated by interference of the reflected waves at the sensor (a human eye or camera) and not at the ceiling surface.

The laser speckle imaging method can be used to measure displacement (strain) on virtually any rough surface with very high resolution (nominally about 1 micron, corresponding to a nominal strain of about ± 10 microstrain)[2]. However, it has been tested and verified that if the surface gets covered with water or absorbs moisture it can swell, and the surface features can change drastically, causing the displaced image to not correlate with a reference image. Additionally, the surroundings and the working area to be free from high intensity lighting so as not to interfere with the imaging for accurate displacement measurement. [Figure 2.6](#) shows the basic concept of Laser Speckle Imaging[2].

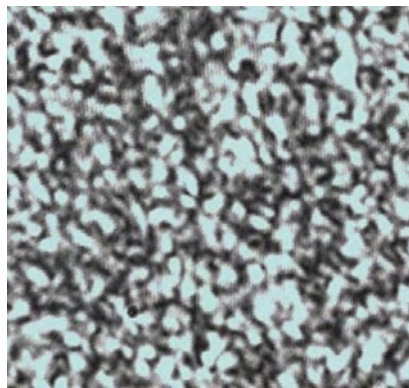


Figure 2.6 Laser Speckle Image[8]

2.3.2 Reflective Paint (Sparkle)

The speckle method suffers from a lack of robustness. A more rugged high resolution motion tag has been developed based on surface features created by a speckle paint, which has proved to be a very effective method in the laboratory and in the field with low dust environments[9]. The paint contains macroscopic reflective particles that diffusely reflect light creating a unique pattern of features for motion tracking. While it is not quite as high a resolution tag for displacement as the optical speckle pattern, it is much more resistant to being eroded or rubbed off during mild cleaning or short-term weathering (or the water-cooled cutting operation commonly used during concrete tie manufacturing). An object exposed to a harsh environment can have rust, dust or debris covering it and while cleaning the surface to expose the desired particle paint features, the paint can get rubbed off losing its displacement tagging (and optical image correlation) capabilities. Previous experience with field testing has indicated that the paint features will last for approximately 3 months on a steel surface in the field under relatively extreme weather conditions. While possibly useful for measurements under controlled laboratory conditions, or short-term field measurements, it is not robust enough to rely upon for accurate metal surface displacement measurement associated with long-term structures. A rail surface with reflective paint is shown in [Figure 2.7](#) [9].

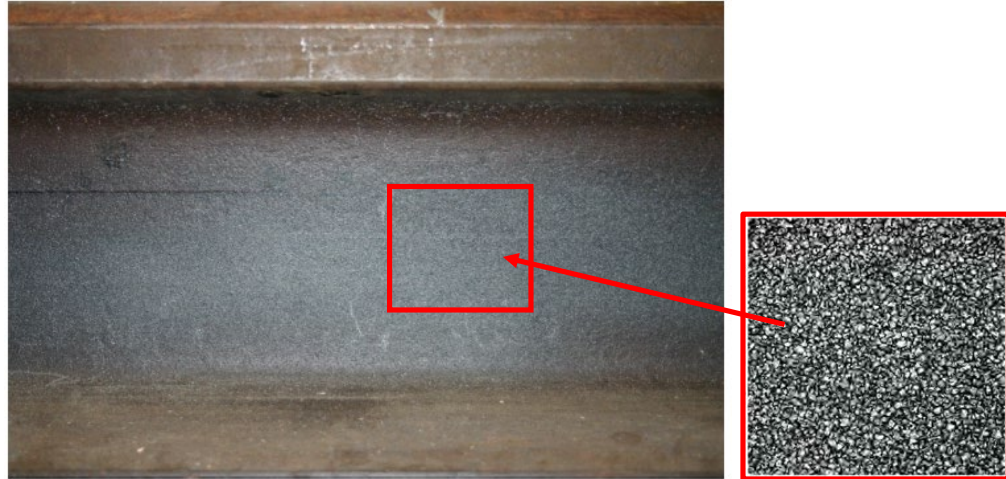


Figure 2.7 Rail with Speckle (or Sparkle) Reflective Paint[2]

2.3.3 Surface Roughness Imaging

Another method of feature tracking is to use surface roughness itself as a tag[5-8]. This method depends on the unique features related to the surface roughness (inherent topological features) rather than spraying the surface with speckle paint as detailed in the previous sub-section ([Section 2.3.2](#)). The dual camera and multi-camera systems were originally created for use on a concrete surface where the surface has unique features generated after the concrete settles and cures[5-8]. The feature-based tagging works well on a concrete surface with a nominal strain uncertainty between ± 25 -50 microstrain[6] but as soon as the surface is exposed to weathering or mechanical abrasion, the features tend to change causing the displaced images to lose image correlation. [Figure 2.8](#) shows examples of actual surface features used for testing and measuring surface displacement on a concrete railroad tie.

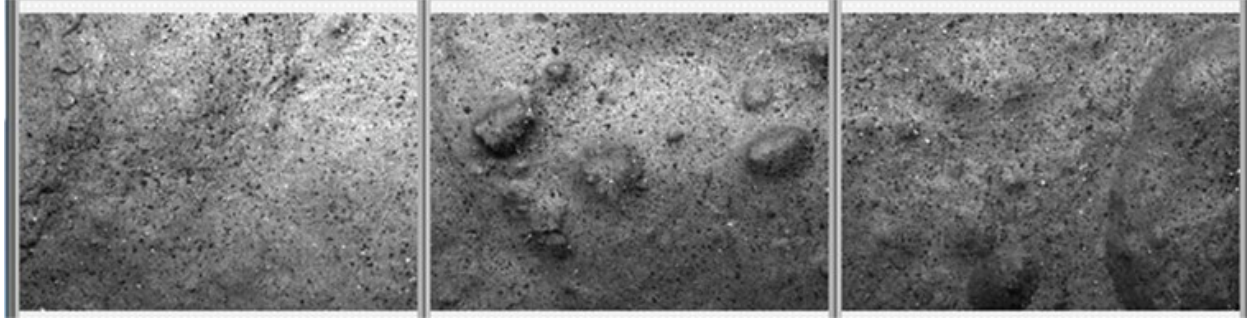


Figure 2.8 Surface Roughness Imaging

The tagging methods discussed above can have serious limitations when measurements are to be made under harsh environmental conditions, due to degradation of the features. Some of the challenges with the above-mentioned methods are: (1) If the surface features can be changed by unknown outside sources; consequently, the surface tag between initial and final images used to assess displacement can be lost. For example, with the use of laser speckle from interference of coherent diffuse laser light, the surface features can change causing degradation of feature tracking and image correlation [1,2]; (2) For the speckle (or sparkle) paint method, the paint can get covered or become less reflective with dust or debris, which will change the surface speckle features from those in the baseline measurements [9]; (3) The same issue is true when using naturally occurring surface features as fingerprints for displacement tagging, because the surface features can degrade over time and lose their unique and important identifying features [5-8].

To overcome the above-mentioned limitations, in conjunction with the measurement of displacement and strain on a metal surface (such as a railroad rail), a dot-peen pattern is proposed which can be used to generate nearly permanent and unassailable markings on a metal surface; providing robust and long-lasting displacement measurement capability.

2.4 Proposed Dot-Peen Tagging

For measurement of steel rail displacement and strain, associated with the assessment of the Rail Neutral Temperature (RNT) condition, a very effective and permanent tagging method is needed that is capable of withstanding harsh environmental conditions for extended periods of time. A dot-peen machine is one of the many permanent tagging methods that can be used to generate robust and virtually permanent markings on a metal surface to provide for long-lasting displacement measurement. The goal of the current research is to develop and demonstrate a method to measure strain on a railroad steel rail and assess (monitor) the important parameter RNT over a long period of time. To achieve this endeavor a permanent tag on the rail is the key to successful long-term strain and RNT measurement.

A dot-peen pattern is comprised of permanent deep impressions/indents marked on an object (metal surface) with a stylus usually made from tungsten carbide or diamond. The stylus strikes the surface rapidly generating a series of individual dots/indents to create a text, barcode or logo as designed by the user. [Figure 2.9](#) shows a commercially available dot-peen machine⁷, whereas [Figure 2.10](#) shows a schematic drawing of dot-peen machine marking a dotted cross pattern on a metal surface. Furthermore, the dot-peen machine can not only mark on flat surfaces, but it also works on contoured surfaces because of its versatility and the stylus's ability to follow the curves of the surface.



Figure 2.9 Commercially Available Dot-Peen Machine (E-Mark™)⁷

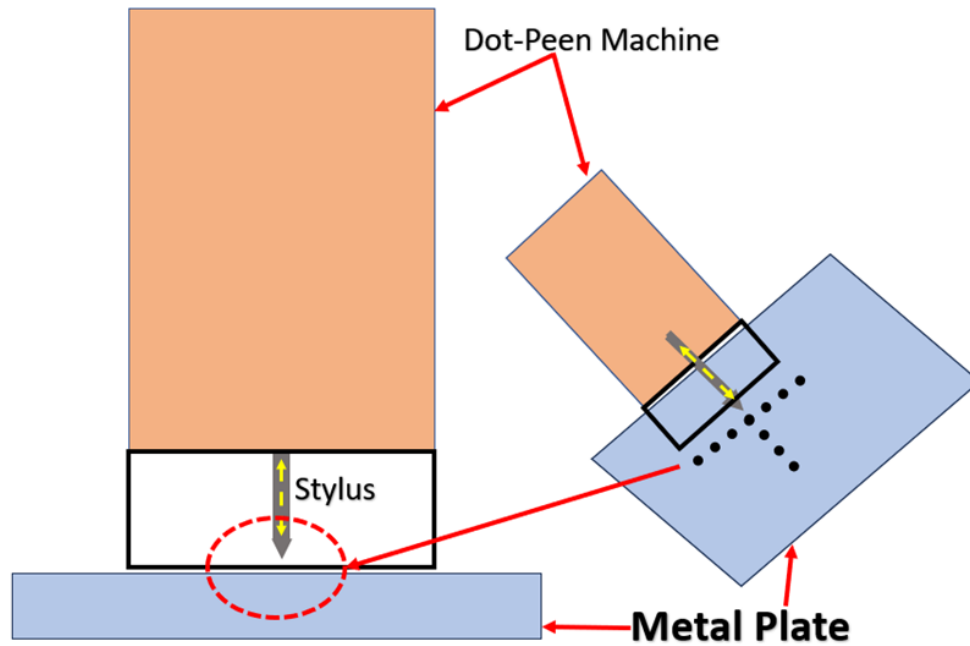


Figure 2.10 Schematic Image of Dot-Peen Marking Technology

⁷ E-Mark is a dot-peen machine manufactured by SIC Marking. <https://www.sic-marking.com/product/handheld-dot-peen-marking-device-e-mark/>

Since the surface of the metal is compressed with a stylus to create an indent, the pattern/tag will likely be long-lasting and easily re-conditioned when needed by cleaning (brushing) of the surface to remove any residue buildup that might have partially filled the indents over time. Additionally, the dot-peen machine has a capability to encode information within the pattern in a data matrix format. So, if the user wants to put some identification information on the object for future reference, this can easily be embedded within the dot-peen pattern.

Pattern Design:

The dot-peen pattern an obvious choice here for tagging steel rail displacement because not only is it permanent, but it also is durable, easily reproducible, and does not add stress to the material being marked with the indent pattern. To use a dot-peen pattern as a permanent displacement tag for rail strain measurement, it is important to identify a pattern design among other pattern variables. Some of the important pattern variables that need to be specified are the diameter of the dots (indents), depth of the dots, number of dots in the pattern, and the spacing between dots. It is very important that the indent pattern be a relatively simple and easily repeatable pattern with non-overlapping dots/indents to avoid feature tracking problems. The commercially available dot-peen machine has the capability of creating a user-defined shape/pattern in addition to providing a number of built-in patterns. Also, as mentioned earlier in the text, since the metal surface is punched, the indents will not generate additional stresses; rather, it will relieve stresses by pushing the material out above the metal surface being indented.

Some examples of the dot-peen pattern, text and data matrix are shown in [Figure 2.11](#).

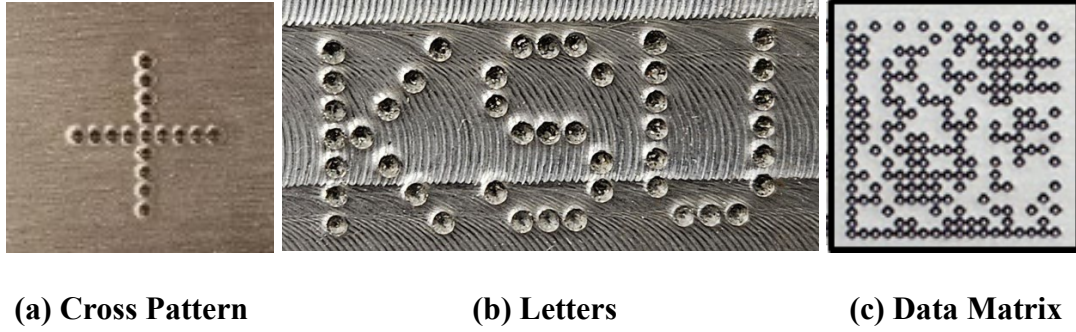


Figure 2.11 Examples of Dot-Peen Tagging

2.5 Displacement Measurement by Digital Image Correlation (DIC) Methods

2.5.1 DIC Method used by Dual-Camera and Multi-Camera Systems

The previously developed dual-camera and multi-camera strain measurement systems were primarily designed to measure transfer length from strain profiles on railroad ties[8]. Both systems utilize similar image processing algorithms, and the processing is performed on a devoted laptop under a LabVIEW interfacing software.

In both the systems, the strain is measured using adjacent cameras. Each camera measures the local displacement field and from these discrete displacement measurements as shown in [Figure 2.12](#), the local measured strain is calculated by subtracting adjacent displacements and dividing by the camera spacing, which is the gage length, L . [6]

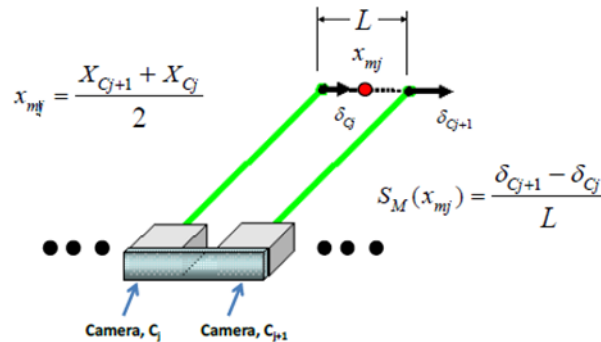


Figure 2.12 Strain from Separate Adjacent Camera Image Displacements [6]

2.5.2 Description of Common DIC Algorithms

There are numerous algorithms available for digital image correlation to determine surface displacement. One of the common methods is direct pixel correlation, which can include different pattern matching algorithms. The typical pattern matching process has two stages: learning and matching. While learning, the algorithm extracts the required information from a “template” and stores it at in temporary memory location. During matching, this pattern is systematically compared to sub-sections of the overall image to find the location of the template that best matches the displaced image.

To reduce the computing time, various algorithms were investigated for processing speed and correlation accuracy before selecting the fastest and most accurate one for displacement measurement. The multi-camera system uses two different processes, Pyramid Matching and Low Discrepancy Sampling. Both algorithms use the NCC (Normalized Cross-Correlation) technique as a base/core to identify the similarity between the two images being compared [22,23]. Other methods include a stereo DIC method to capture full-field measurements of shape, curvature, deformation and strain for displacement measurement [20]. A brief summary of key concepts associated with some common processing algorithms are provided below.

Pyramid Matching:

The image and the template are spatially sampled to lower resolutions using so-called Gaussian pyramids[74]. With this method, every other pixel is sampled, and the image is systematically reduced to one-fourth of its original size for every successive pyramid level as shown in [Figure 2.13](#) [22,23].

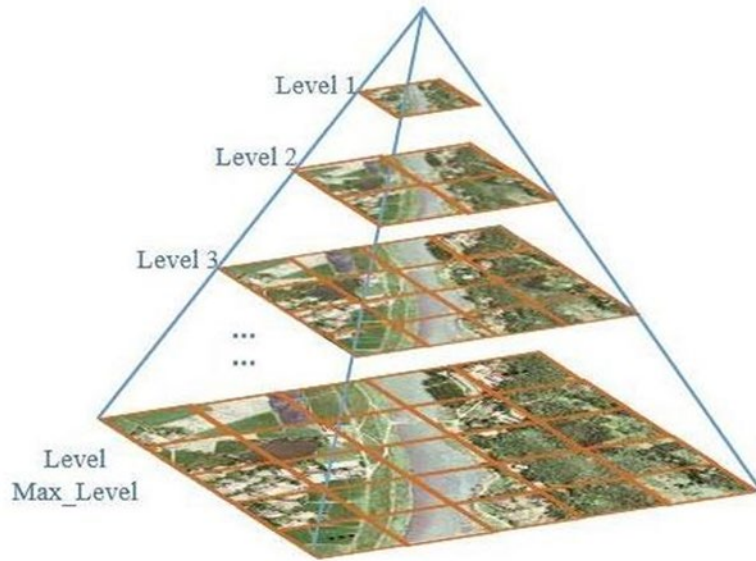


Figure 2.13 Visual Representation of a 5-Level Image Pyramid[22]

The algorithm attempts to find an optimal pyramid level (based on an analysis of template data) which would give the fastest and most accurate match. The correlation of template and image begins with the lowest resolution (so going from less information to more information)[22]. The pyramid matching model is divided into gray value (based on pixel intensities) and gradients (based on select edge information).

Gray Value Method:

This method uses normalized pixel gray values as features to perform correlation for pattern matching. The advantage of this method is that it compares all the pixels so that no information is left out while performing image correlation. However, the disadvantage of this method is it suffers when faced with occlusion (the object is partially or fully obstructed by another object) and non-uniform illumination [22,23].

Gradient Method:

This method uses filtered edge pixels as features. An edge image from a grayscale image is computed and a gradient intensity threshold is set automatically by the program based on the

analysis of the template image as shown in [Figure 2.14](#). The method is based on vector correlation and all the edge vectors higher than a prescribed threshold are kept for pattern matching [\[22,23\]](#).

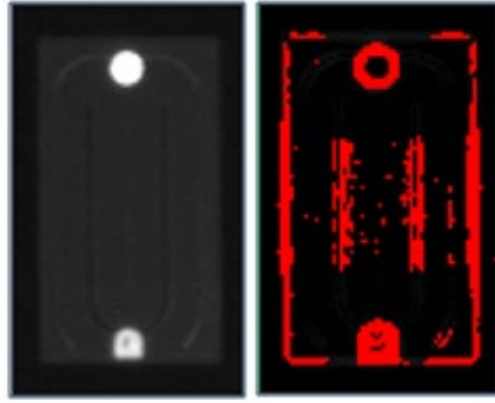


Figure 2.14 Pyramid Matching - Gradient Method[\[23\]](#)

Low Discrepancy Sampling:

Most images contain redundant information that can be neglected or removed to save processing time. This method is based on selecting high value points according to how accurately they represent their neighborhood. It is a smart sampling technique that includes edge pixels and region pixels and removes the image's excess information. [Figure 2.15](#) shows purple squares that are some edge/region pixels sampled by the algorithm for image correlation processing neglecting other redundant information from the image. However, templates containing similar grayscale large regions and minimal templates may cause image analysis problems due to the small number of sample points. Also, small templates can be an issue since they may contain insufficient information to be extracted [\[22,23\]](#).

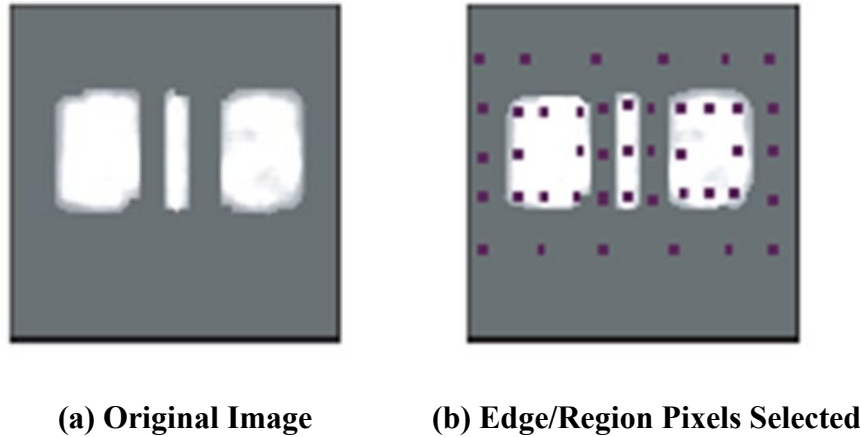


Figure 2.15 Low Discrepancy Sampling[\[22,23\]](#)

Image Processing Software:

A software called VIC-3D[\[19\]](#) can be used for image correlation and for measuring and visualizing full-field displacement and strain using 3D DIC. The DIC algorithm itself is based on python programming and can be customized as needed. One of the new features in new VIC software is that it can be used to directly compare the results with FEA analysis [\[19\]](#).

For reference, the VIC-3D software was used in research associated with rail neutral temperature and stress measurement analysis[\[20\]](#).

The correlation and displacement measurement algorithm associated with rail stress analysis must be capable of accepting minor pixel intensity changes and also the location of the same pixels may be moved a little. The algorithm should be able to overcome these pixel fluctuations and still calculate the required displacement with high accuracy. All of the above-mentioned methods have demonstrated desirable outcomes with high accuracy and repeatability for their intended application. However, looking at it from a practical standpoint, an external DIC software must be capable of adapting with the hardware and possibly it can cause issues at times when there is an update or hardware upgrade necessary. It was very convenient to develop a program in LabVIEW with in-built pattern matching codes (VI's) which then are fully compatible

with the hardware it was designed for. For the purpose of this project, a program was developed in LabVIEW for pattern matching, with some pre-processing algorithms used to analyze some of the image processing procedures which will be explained in later chapters.

Chapter 3 – Proposed Non-Contact Strain Sensor Design

The proven non-contact measurement of railroad tie strain measurement technology utilized in the dual-camera [3,7-8] and multi-camera systems [5,6] was the inspiration for the measurement of rail strain associated with the current dissertation research. The physical basis for the proposed method of in-track strain assessment is the dual-camera system that has been successfully used in previously funded FRA research involving prestressed concrete railroad ties. The most recent version of this dual-camera system, which was developed to a Technology Readiness Level (TRL) of 6, is shown in [Figure 3.1](#). It provides displacement accuracy of better than ± 0.003 mm and has been employed using a variety of different displacement-tracking “tags”, including laser speckle, reflective particle paint, and concrete roughness (feature). This level of displacement accuracy corresponds to a strain measurement accuracy of better than $\pm 20\mu\epsilon$ for the nominal 6-in gauge length device[3,7-8].



Figure 3.1 Automated Dual-Camera System[\[8\]](#)

The above strain measurement systems have been extensively used and field-tested under extreme conditions for the measurement of transfer length on concrete railroad ties. These systems have also been upgraded multiple times to accommodate new technologies and to increase efficiency, speed and accuracy. The multi-camera system, in particular, was used for investigation

of gage length selection since it can provide a variable gauge length by selectively pairing off adjacent cameras. Shown in [Figure 3.3](#), the multi-camera system has six vertically oriented equally spaced CMOS cameras mounted on a low thermal expansion coefficient carbon fiber tube. A high-intensity LED array linear strobe light-bar was used for illumination. The system can capture direct surface images, or the surface can be spray/speckle painted, and all the image capturing is processed through a LabVIEW interface. The cameras currently installed on the system can capture an image of the size 2592x1944 pixels [\[5,6\]](#). Each camera on the multi-camera system is approximately 6 inches apart but there is a capability where certain cameras can be turned off/disconnected to use only specific pairing of cameras. As an example, it is possible to turn off cameras 2, 3, 4, 5 and use only cameras 1 and 6 giving the longest gage length of 30 inches between the two cameras. This feature was exploited in the varying gage length preliminary testing.

3.1 Experimental Setup for Displacement and Strain Measurement

Displacement and strain are to be measured using adjacent cameras in the proposed rail strain measurement system. As shown in [Figure 3.2](#), each camera measures the local displacement field. From these discrete displacement measurements, the local measured strain is calculated by subtracting the net displacements on each end of the gage length and dividing by the camera spacing (the gage length, L). The nominal strain measurement accuracy for the multi-camera system with a 6-inch gage length camera spacing is about $\pm 25\text{-}50\mu\epsilon$ [\[5,6\]](#).

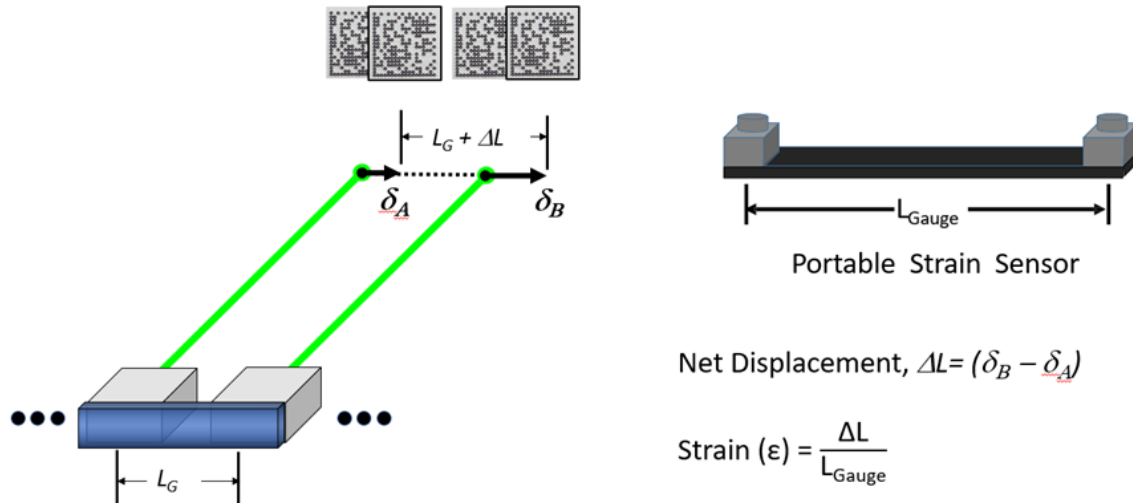


Figure 3.2 Strain Measurement Technique[5]

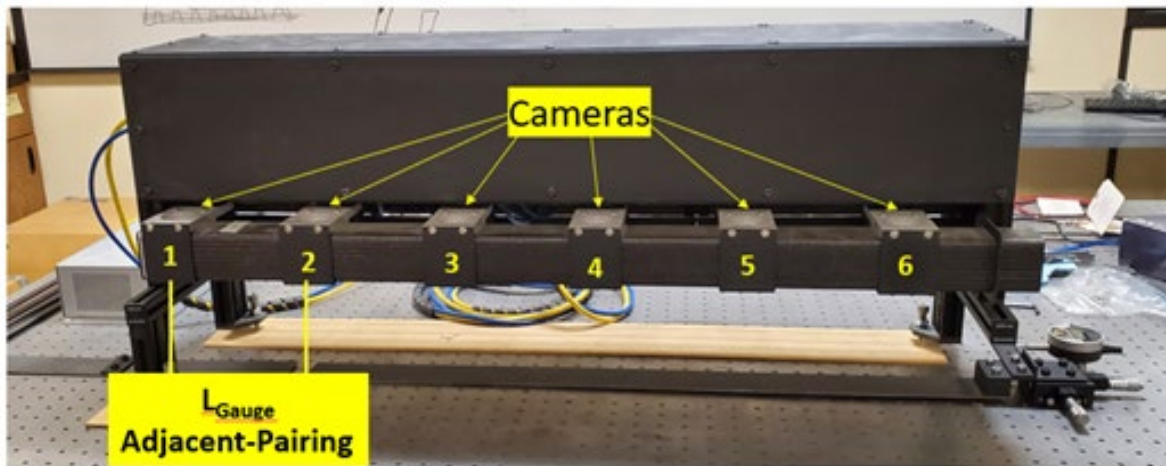


Figure 3.3 Multi-Camera System

For strain measurement and sensitivity validation purposes, a metal test plate, with the cross dot-peen pattern as shown in [Figure 3.4](#), was used to provide calibrated displacements that were measured using only one of the six cameras.



Figure 3.4 Cross Pattern

As mentioned above, the multi-camera system was designed to measure displacement on a rough concrete surface. But now that this technology is going to be used on a metal surface, that may be exposed to harsh environmental changes happening over an extended period of time, it is imperative to evaluate/upgrade the lighting for the new system. A modified type of ring set-up will be used to provide the necessary exposure of the dot peened surface instead of the built-in LED light bar used for illumination of the surface from only one side. This new ring-light idea was suggested by John Bloomfield (from TDI), and significant detailed testing to validate its performance was conducted as part of the work associated with this dissertation. The ring light illuminates the surface radially inward from all directions. Furthermore, because the angle of lighting is so shallow, the dot peen indents appear as distinct and well-defined shadows with almost white (highly exposed) background. The new ring light system is externally attached to the existing system with a 3D printed adjustable ring light holder, as shown in [Figure 3.5](#).

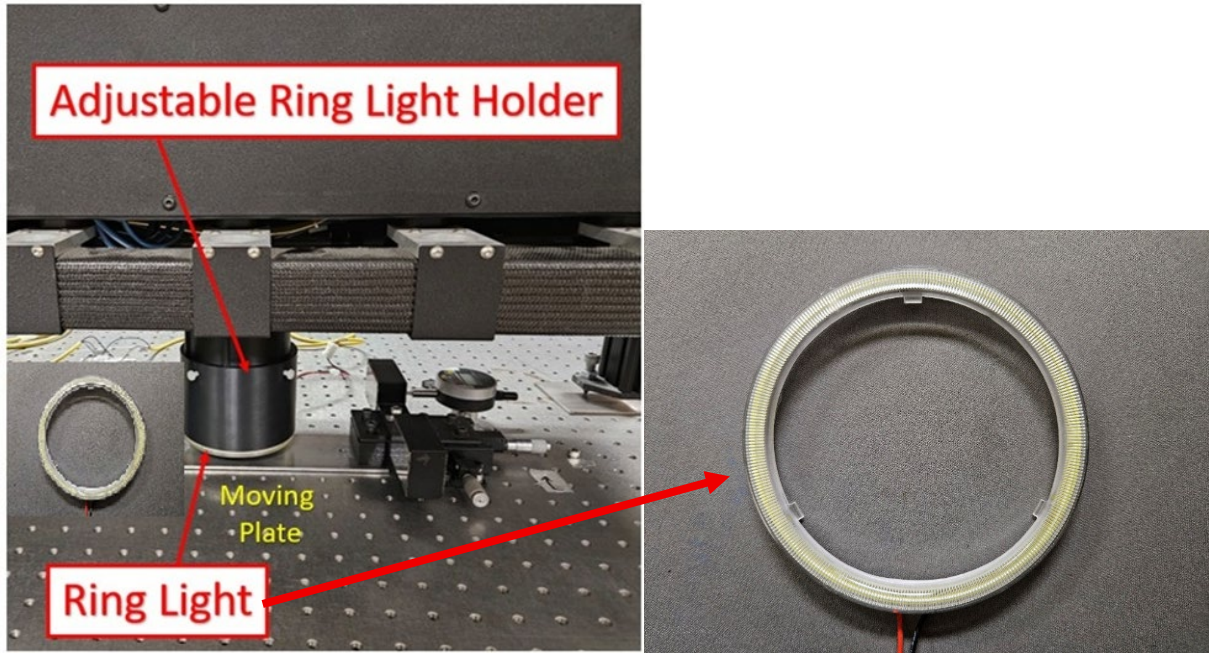
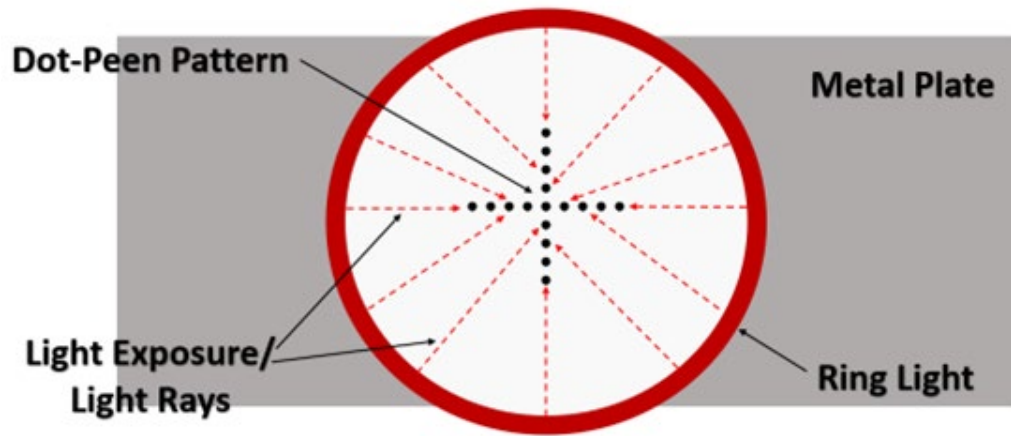
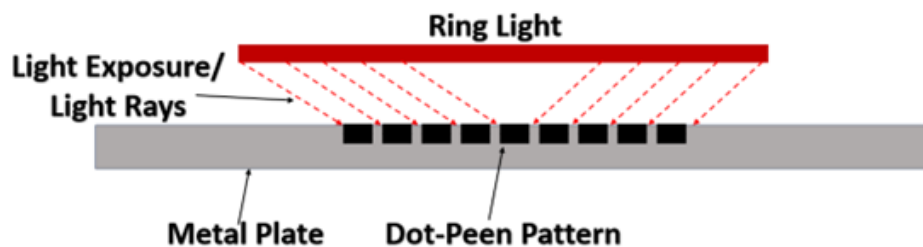


Figure 3.5 Ring Light Set-up

A schematic diagram of the ring light illumination of a dot peen pattern on a metal surface is shown in [Figure 3.6](#) (a) and (b). The ring light illuminates the surface radially inward from all directions as shown. Furthermore, because the angle of lighting is so shallow, the dot peen pattern indents appear as distinct and well-defined shadows with almost white (highly exposed) background.



(a) Ring Light Over a Metal Plate-Top View



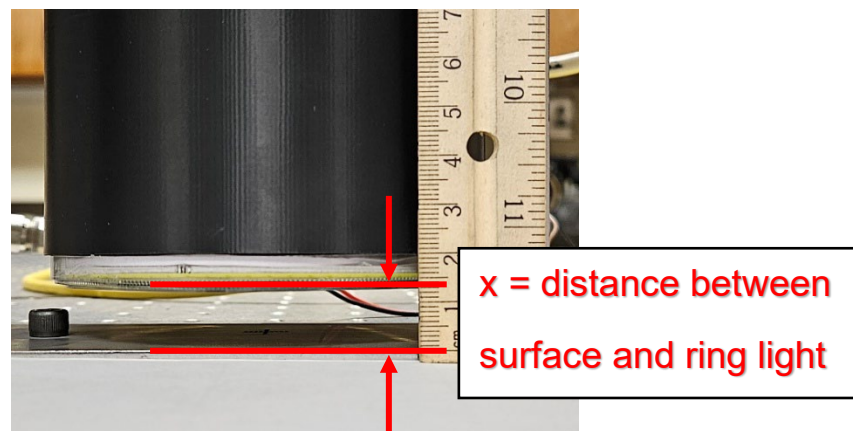
(b) Ring Light Over a Metal Plate-Side View

Figure 3.6 Schematic Diagram of Ring Light Illumination

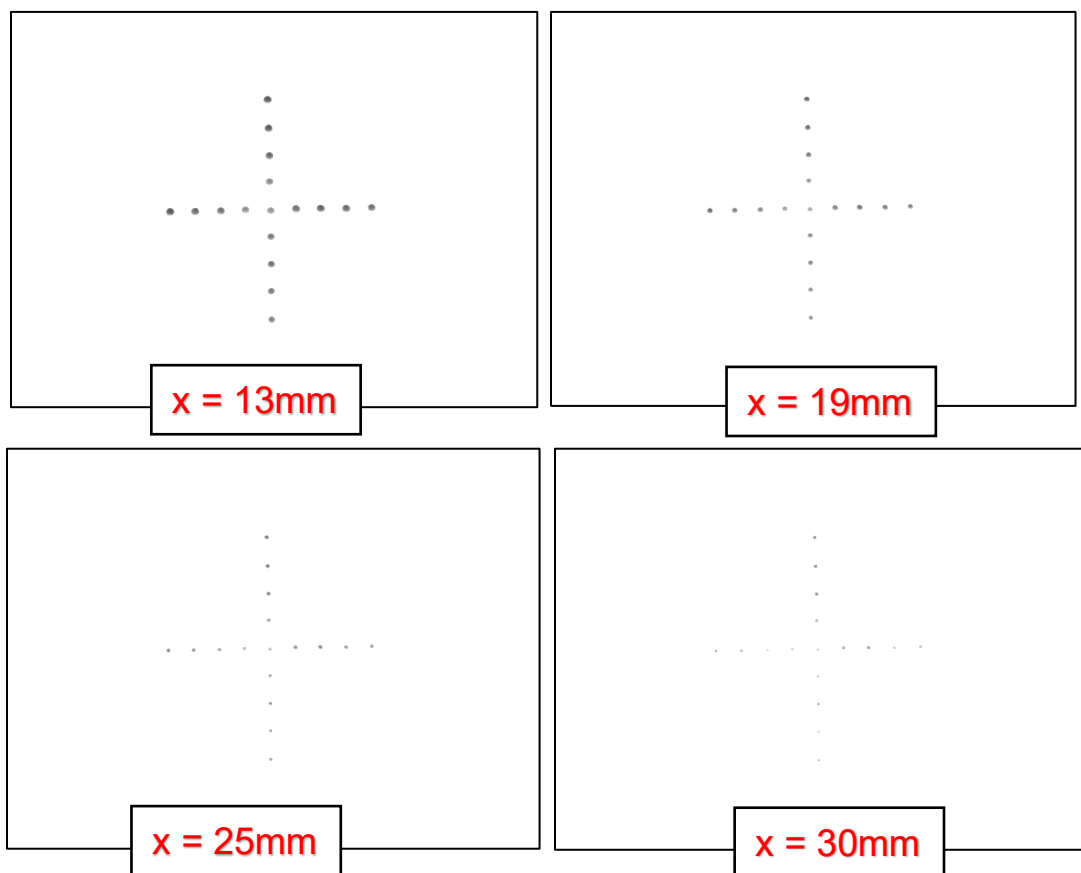
Variables which influence the quality of the dot-peen shadow images include spacing above the target (metal surface), angle of illumination and exposure duration. The physical characteristics of the dot-peen indents, including depth and diameter, will also influence shadow image quality. Various ring light distances from the surface were tested to get the best quality image with nearly pure white background and properly exposed dots (indents).

If the light source is too far from the surface, the shadowing is affected and images of the dots (indents) start getting smaller, become fainter with less contrast, and eventually fade out. This is because at larger distances and steeper illumination angles the light will enter and reflect from the interior walls of the holes making the dots indistinguishable from the plain metal surface. This can seriously affect the quality of the dot shadow images. The image pixels associated with the

indent shadows will then not be dark enough or have sufficient contrast from the plain metal surface background to allow accurate pixel (image) correlation.



(a) Distance From Surface to Ring Light Illumination



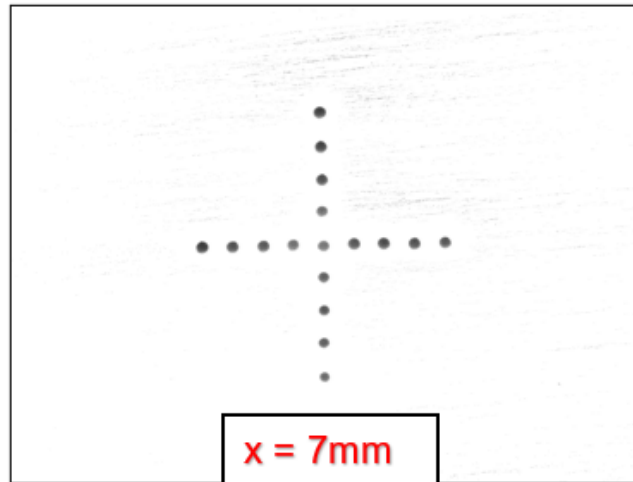
(b) Effect of Ring Light Distance from the Surface on Image Contrast

Figure 3.7 Effect of Ring Light Distance from Surface

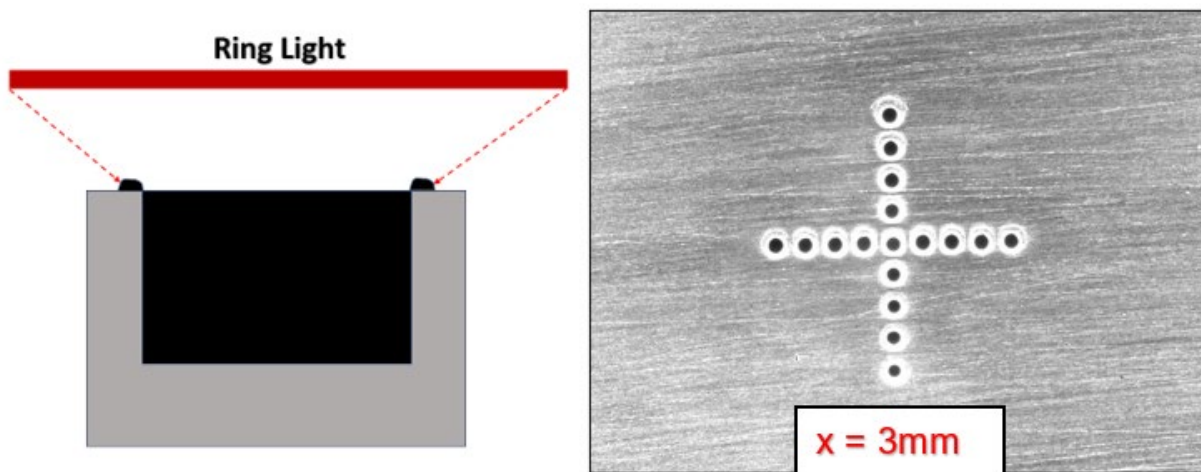
[Figures 3.7](#) (a) and (b) show the ring light for illumination distances of 13mm, 19mm, 25mm and 30mm above the metal surface, and the corresponding changes in contrast for a dot-peen cross pattern, respectively.

Incidentally, this shadowing may also be affected by rust particles hanging over the dot-peen indents. Hence, if the ring light is too close to the surface, the grain structure, cracks, and any unevenness of the metal surface will be exposed in addition to the indents, and the image then will not have a predominantly white background with only the important dot peen indents highlighted.

[Figures 3.8](#) (a) and (b) show the changes in the ring light illuminated dot shadow images, for distances of 7mm and 3mm above the metal surface, respectively.



(a) Cross-Pattern at 7mm Distance



(b) Cross-Pattern at 3mm Distance

Figure 3.8 Cross Pattern Images for Ring Light Distances Closer to Metal Surface

As the ring light gets closer to the metal surface, a bright “halo” light pattern appears, like that shown in [Figure 3.8](#) (b), where the light ring is 3mm from the surface. The halo results from illumination and reflection from the sides of the metal “lip” that is pushed out during the formation of the dot-peen indents. This halo effect tends to overpower the dark shadow images of the dot peen indents.

3.1.1 Strain Measurement Testing with Multi-Camera System

To test the use of the ring-light illuminated dot peen pattern in resolving surface displacement, one camera (camera #4) from the 6-camera system was used to capture images of an indented metal surface. Surface illumination consisted of a bright duration-controlled flash of the ring light. The image displacement was measured using the built-in 6-camera LabVIEW image displacement algorithms and compared against a calibrated micrometer setup, as shown in [Figure 3.9](#). The micrometer setup was comprised of a digital indicator with 0.001mm resolution, also shown in [Figure 3.9](#). To complete the displacement measurement, the LabVIEW interface performed image correlation between a reference image and the micrometer displaced dot-peen image on a 1018 cold-rolled steel metal flat plate [\[5,6\]](#). For each displacement, the indented plate was moved a known distance using the micrometer, and the (calibrated) displacement was recorded from the digital indicator. A total of 10 readings spread out over the span of the overall displacement were taken during the test. This allowed determination of the measurement sensitivity and an estimate of the measurement uncertainty. Image correlation was performed using the first reference image compared with the subsequent images captured after calibrated displacement. A reference (baseline) image was first taken, and the micrometer stage was then subsequently displaced in increments of approximately 0.01mm, over a displacement range of about 0.100mm. All the images taken for each displacement were then compared (correlated) with the reference (baseline) image taken when the dial gauge was at 0.000mm to yield a net displacement from the reference position.

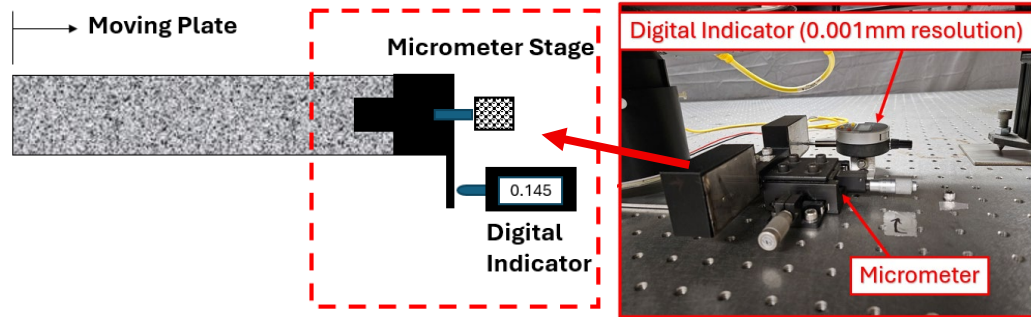


Figure 3.9 Micrometer Displacement Calibration Set-Up

[Figure 3.10](#) shows the plate with the indented cross dot-peen pattern, along with the exposure area enclosed within the red square.

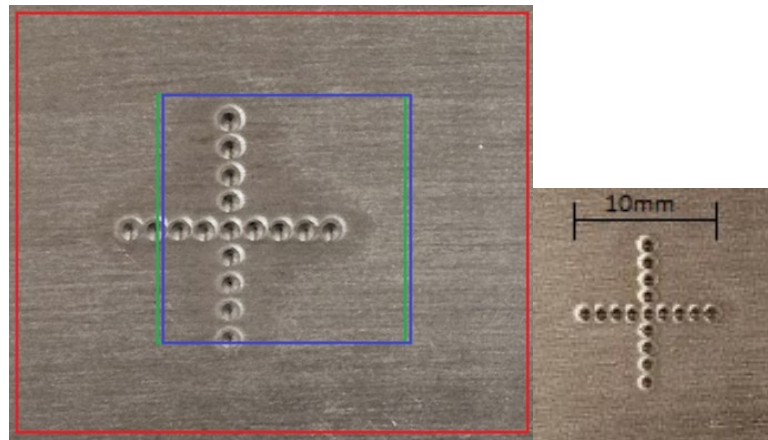


Figure 3.10 Cross Pattern with Camera Field of View

The ring light was kept at a distance of 13mm from the surface and the exposure time was set to 11000 microseconds for this test. The exposure time must be kept higher than what was used for the plain scratched surface because everything except the dot peen indent images must be “washed out” to produce shadows for the dot-peen indents. [Figure 3.11](#) shows an example of an image with 11000 microseconds ring light exposure.

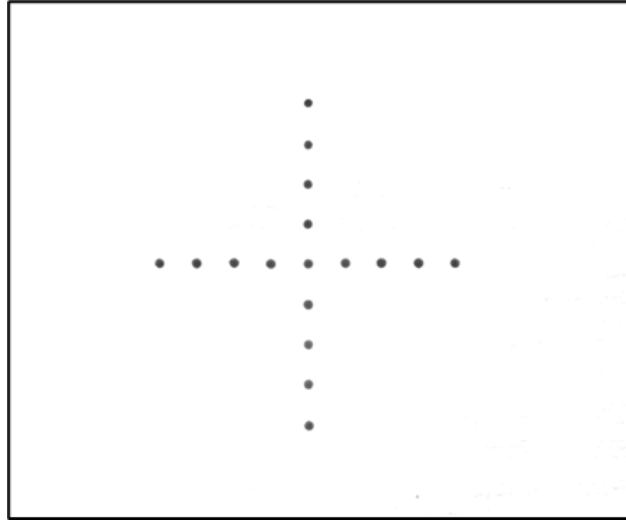


Figure 3.11 Cross Pattern with 11000 microseconds Flash

[Figure 3.12](#) shows the approximate field of view of the camera (red square). The green and blue boxes represent the before and after displacement measurements performed using pixel correlation, respectively.

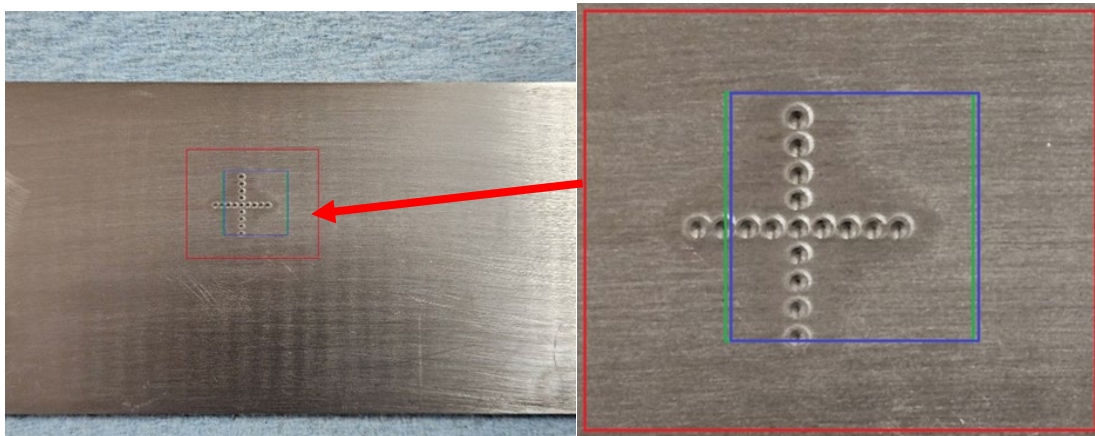


Figure 3.12 Cross Pattern Location on Metal Plate

[Figure 3.13](#) shows the measured displacement of the dot-peened metal plate in pixels vs. the actual displacement as measured by the digital micrometer. The slope (99.125 pixels/mm) of the trendline shown corresponds to the displacement measurement sensitivity.

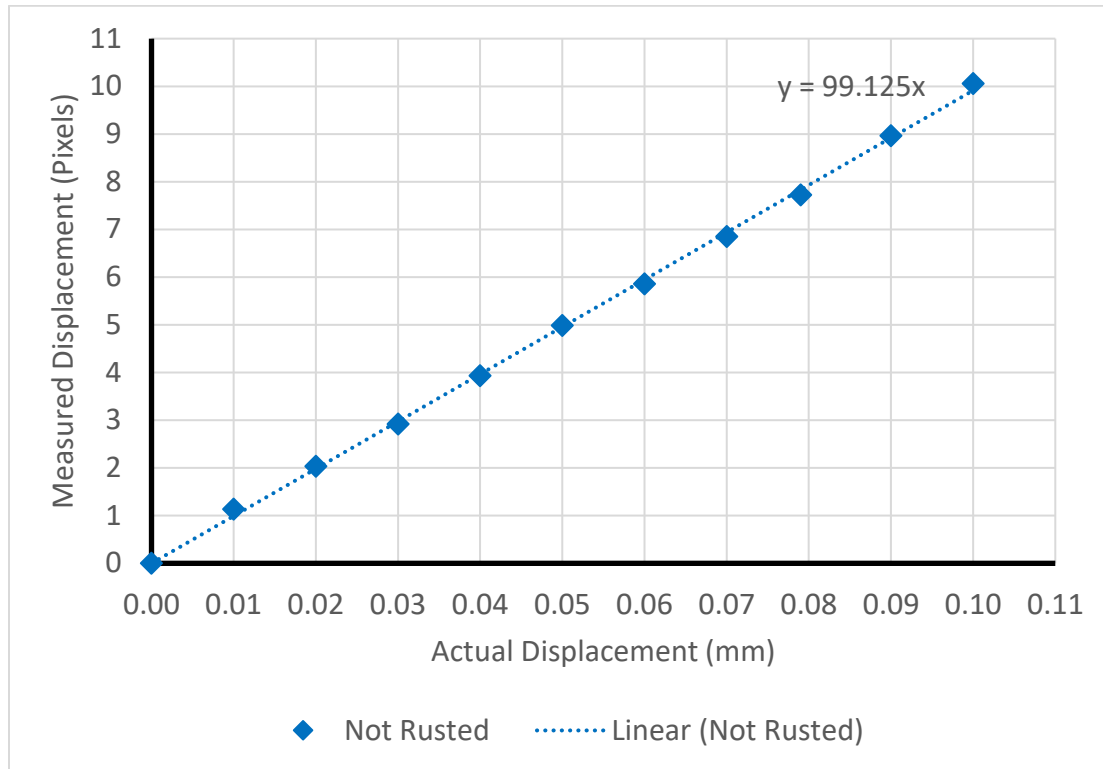


Figure 3.13 Non-Rusted Displacement Measurement for Dot Peened Plate

The trendline is highly linear, and all the measurement points are within a small deviation from this line. This is displayed in the deviation plot shown in [Figure 3.14](#).

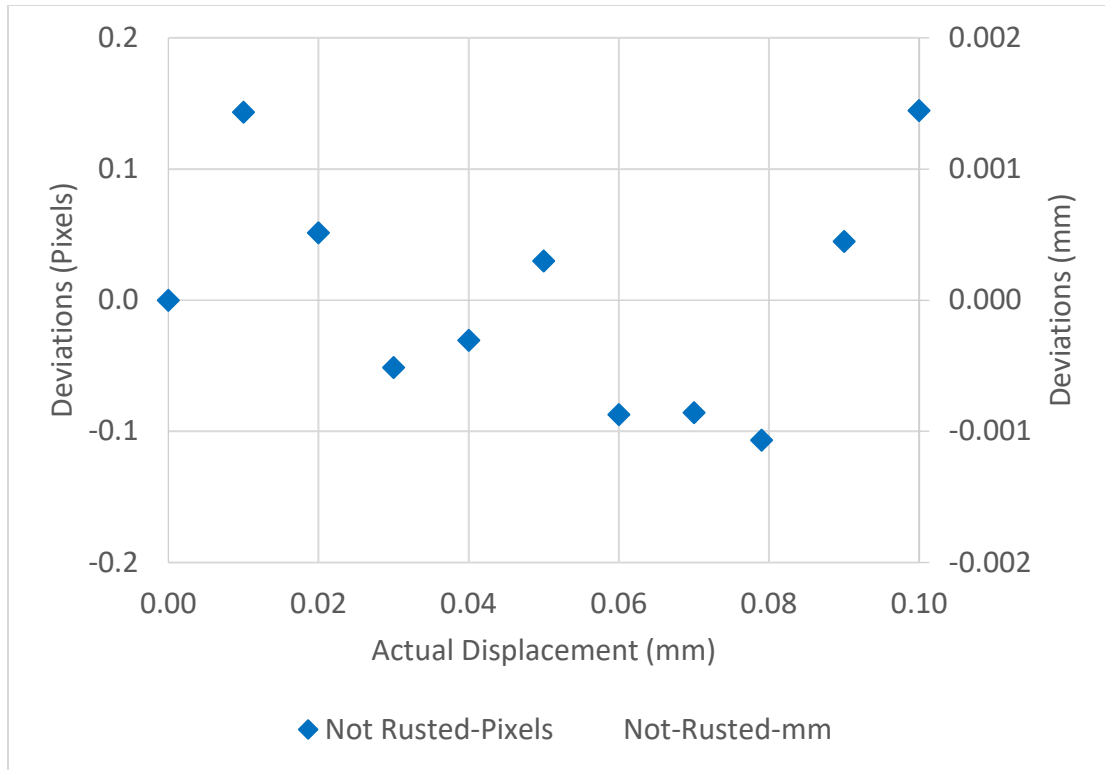


Figure 3.14 Deviation Plot for Non-Rusted Displacement Measurement for Dot Peened Plate

The maximum and minimum deviations fall within $\pm 0.002\text{mm}$ of the trendline, which corresponds to a strain deviation of approximately $\pm 13\mu\epsilon$ for a 6.00 inch. (152 mm) gauge length⁸.

3.1.2 Estimation of Required Gage-Length

Based on the displacement measurement capability shown above, using the dot-peen indent pattern as a tag for displacement measurement, and the image processing algorithms within the

⁸ The cross pattern is not fully contained within the interrogation window (correlation window), as shown in [Figure 3.12](#). This is due to the alignment limitations between 6-camera strain measurement system placement and the micrometer stage. To exclude pixel noise from the captured image borders, the correlation window was kept at 1200x1200pixels. This caused the cross mark to slightly shift outside of the interrogation box. Looking at the calibration results presented here, it is clear that the measurements are still very accurate with minimal scatter (random uncertainty).

previously developed strain measurement system (6-camera LabVIEW interface), seems like a viable option for the design of a new dual camera system for rail surface strain measurement. However, the gage length will need to be longer to reduce strain uncertainty to less than $\pm 6.5\mu\epsilon$ for the new sensor system. The idea here is to increase the resolution to get better accuracy, while keeping in mind that the system must also be portable to provide measurements in the field on railroad tracks. If the gage length is too short, it won't cover enough length of the rail to accurately indicate relative deflections (strain) and stress. If the gage length is too long, then it won't be feasible to carry the system around by one person for field measurements. The system will not only be heavy, but it may be fragile and quite sensitive to bumps and hits because displacement measurements are dependent on accurate image capture and correlation.

[Figure 3.15](#) shows graphically how the strain resolution is affected by an increase in sensor gage-length.

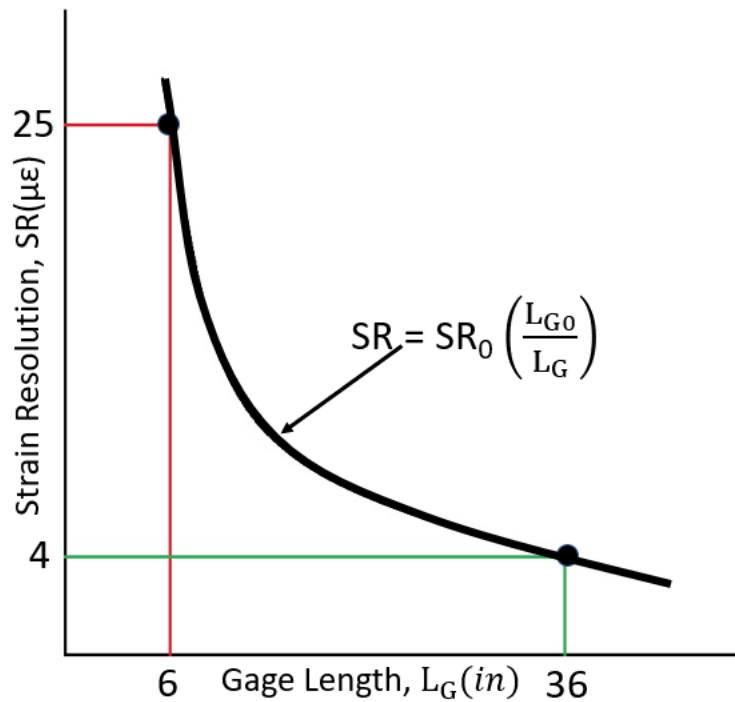


Figure 3.15 Strain Resolution vs Sensor Gage-Length

Table 3.1 Gage Length vs Strain Resolution and Equivalent RNT Temperature Resolution

Gage Length	Strain Resolution	Corresponding RNT Temperature Resolution
6"	$\pm 25\mu\epsilon$	$\pm 4^{\circ}\text{F}$
36"	$\pm 4\mu\epsilon$	$\pm 1^{\circ}\text{F}$

From [Figure 3.15](#) and [Table 3.1](#), a gage length of 36" seems to be a viable option, providing nominally about a $\pm 1^{\circ}\text{F}$ resolution for the equivalent RNT. This gage length was therefore selected for the new sensor system design.

3.2 The Proposed Strain Sensor

3.2.1 Hardware

As mentioned earlier, the design of the strain sensor was inspired by the dual camera system which has been successfully used for strain measurement diagnostics on concrete ties for many years. The purpose of fabricating the new strain sensor is to measure rail strain and rail neutral temperature. The new sensor developed for steel rail strain measurement has a dual camera set up to take baseline and after image sets for measurement of displacement (strain). A magnetic frame is used to position initial rail markings and to mount the camera sensor properly and repeatably aligned to the rail as shown in [Figure 3.16](#).

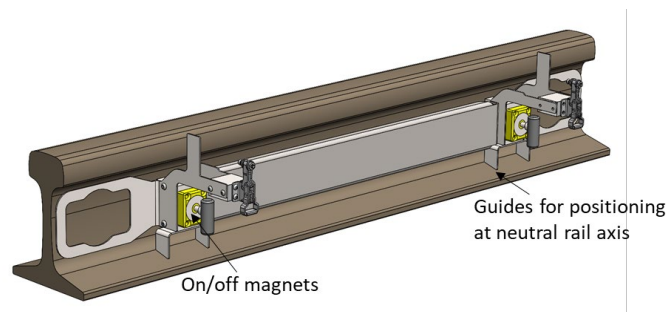


Figure 3.16 Magnetic Template for New Strain Measurement System

[Figure 3.17](#) shows a zoomed-in image of the magnetic template with the space to accommodate the dot-peen machine. This frame ensures the dot-peen machine alignment and that the pattern is in the center of the web.



Figure 3.17 Dot-Peen Marking Using Magnetic Template

The cameras are mounted on a carbon fiber tube having very low coefficient of thermal expansion (CTE) so as to maintain a fixed gage length, therefore reducing uncertainty in the displacement measurements. The low thermal expansion carbon fiber tube is shown in [Figure 3.18](#).

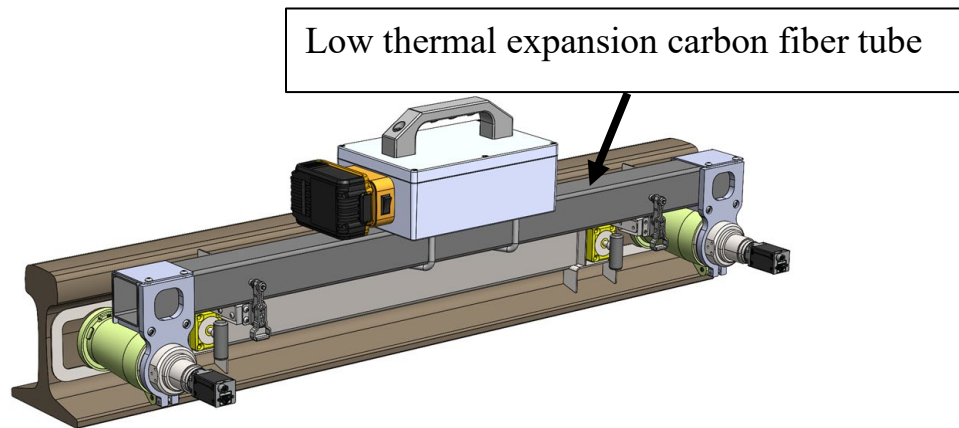


Figure 3.18 Strain Measurement System 3D Model

[Figure 3.19](#) shows the actual dual camera sensor system, which was designed and fabricated by the Technology Development Institute (TDI). The design team was comprised of John Bloomfield, along with a team of supporting TDI engineers.

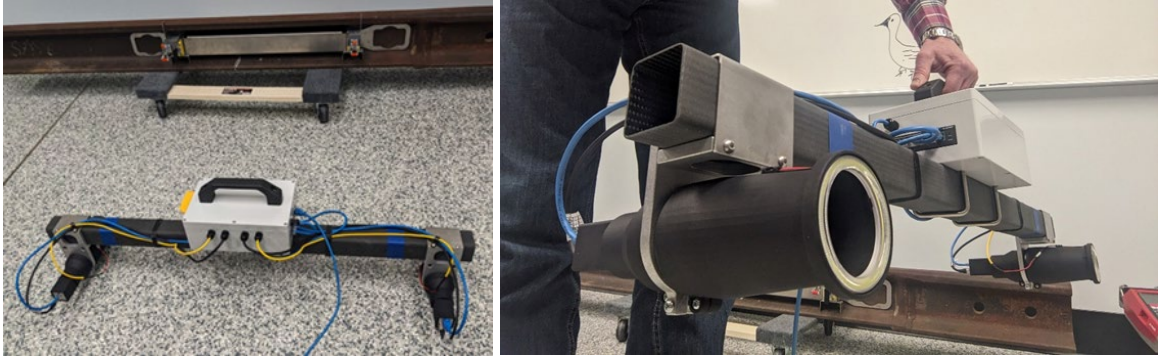


Figure 3.19 New Strain Sensor (Left) and Ease of Carrying the Sensor (Right)

Data collection and processing is performed using a devoted laptop connected via ethernet cable. The new sensor utilizes image processing algorithms similar to those used in earlier sensor designs for prestressed concrete surface strain measurement and incorporates a similar LabVIEW™ interface. The software first pre-processes captured images, and then calibration settings within the software accurately calculate the displacement between images relative to a given baseline.

3.2.2 Processing Algorithms

Simplified Algorithm Description:

- Image Capture
- Invert Image (Black to White, White to Black)
- Low-Pass Filtering of Image
- Thresholding of Image
- Correlate Images for Displacement Measurement using Centroid & Pattern Recognition Algorithm.

Mentioned above is a simplified algorithm description for processing the image captures to arrive at a measurement of displacement (strain). It is very important to understand the details of how each step is performed in the algorithm sequence.

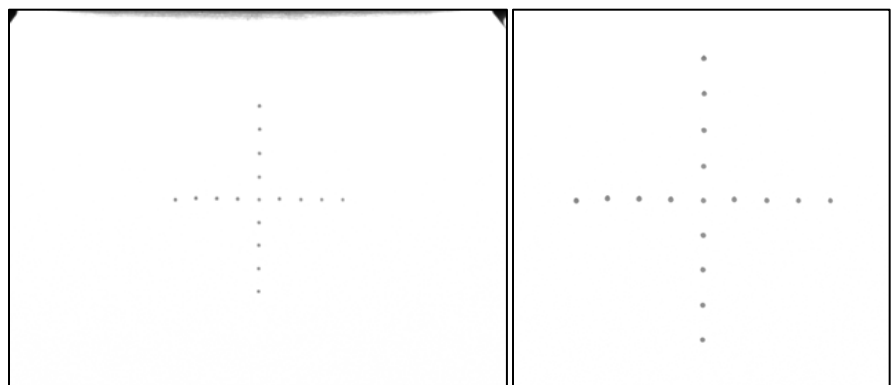
Image Capture:

This step basically captures the images (reference and after displacement images) with the new strain measurement system. Once the images are captured the software processes image calibration and then follows through the next steps of the algorithm to infer accurate displacement.

The camera hardware used in the system has the following features:

- Basler acA4024-29um 12.2 MP
- Lens: VST TCM017-110 Telecentric lens
- Field of View: 1.72 x 1.30 inches
- Spatial resolution: 91.9 pixels/mm

Each of the two cameras is capable of taking an image of size 4016 x 3036 pixels. Once the image is captured, the program uses pre-calibrated data for pixel vs dimension (mm/pixels) and assigns dimension to each pixel to create an image of a certain length and width. Moving forward, the next image, called the after image, is taken with a smaller resolution (for example 2000 x 2000) to avoid the image noise from around the actual dot-peen pattern and to focus on the dot-peen pattern only for easy pattern identification while performing correlation. [Figure 3.20](#) shows a reference image and an after image.



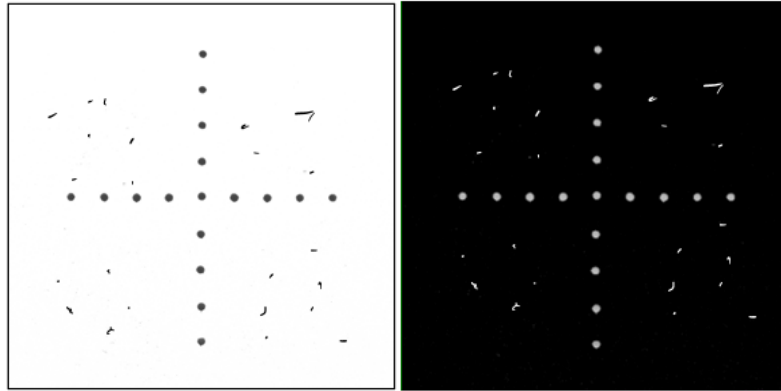
(a) Reference Image

(b) After Image

Figure 3.20 Images from New Strain Sensor

Invert Image Intensity:

This step basically converts a grayscale image to another grayscale image but as an inverted version of the main image. For example, the images taken by the cameras are 8-bit grayscale images, meaning the intensity of each pixel falls between 0 and 255 with 0 referring to a black pixel and 255 being a white pixel. While performing inversion, the system subtracts the pixel image intensity from 255 and assigns that new intensity value to that pixel. For example, if the intensity of a pixel is 0 (it is black) then after the inversion the new intensity of the same pixel will be $255 - 0 = 255$ (white pixel) which means the black pixel is now a white pixel. A similar process happens for all the pixels in the image prior to performing correlation. The actual reason to do this is that the cross dot-peen “shadow” pattern that is used as a tag to measure the displacement must be the only noticeable feature in the image. Currently the image taken is so bright that everything around the dot-peen indents is imaged as white while dot-peen indents are imaged black. The best way to perform correlation would be to allow the system to detect only dot-peen indents and find the displacement of that same pattern in the next image. LabVIEW considers white pixels as 255 and black as 0 making it harder to find displacement with dot-peen indents being black. This is because, without inversion, most of the image pixels will be white while the dot-peen pattern of useful displacement information will be contained in only a small number of black pixels embedded in an expanse of white pixels. An example of this inversion is shown in [Figure 3.21](#).



(a) Original Image

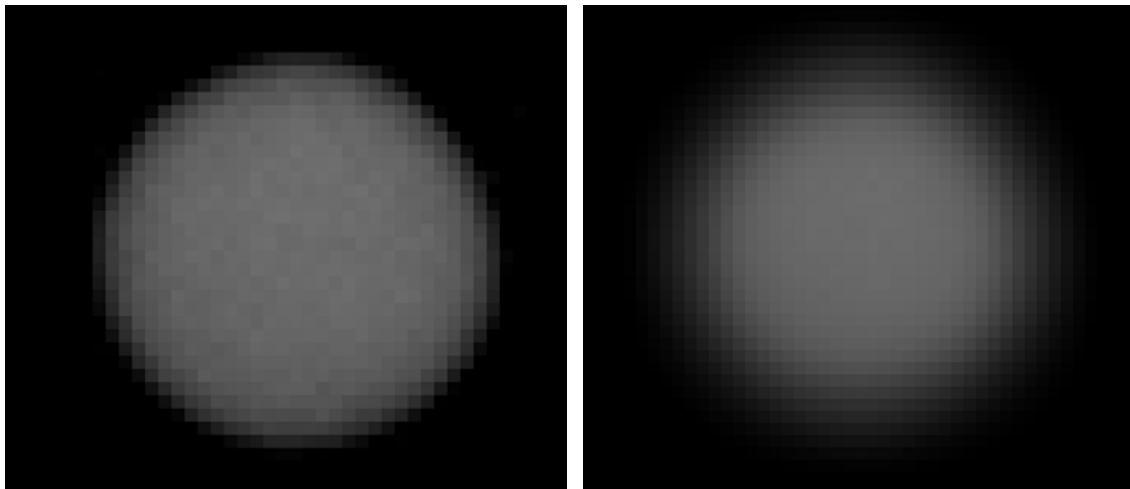
(b) Inverted Image

Figure 3.21 Intensity Inversion of an Image

The image (a) on the left in [Figure 3.21](#) is the original image from the new strain sensor and the image on the right (b) is after the 1st step of pre-processing which is inversion of the image.

Low-Pass Filtering of Image:

The associated LabVIEW VI calculates the inter-pixel variations between the pixel on hand versus the pixels surrounding it. If the pixel on hand is different from the set threshold from the average of the surrounding pixel intensities, the algorithm automatically replaces the pixel on hand with the average intensity of the surrounding pixels[24]. In other words, low-pass filtering reduces high frequency noise so as to generate a smoother image. For example, shown in [Figure 3.22](#) (a) is the image of one dot-peen indent from the cross mark made on a metal plate. This image is with no low pass filtering, which means that all the pixels holds their original intensity values.



(a) Before Low Pass Filtering

(b) After Low Pass Filtering

Figure 3.22 Low Pass Filtering

[Figure 3.22](#) (b) shows the same pixels after implementing the low pass filter algorithm, resulting in a very smooth pixel intensity distribution. Each pixel intensity was compared with the average intensity of its surrounding 9x9 matrix of pixels and when the difference in intensity was greater than 1% of the intensity of its surrounding pixels, the original pixel intensity was replaced with this average value.

It is very important to understand the processing time requirements for implementing algorithms such as this filtering algorithm. Increasing filter matrix size may result in a smoother image of the dot indent but as the system needs to process more calculations, it may be a more time-consuming process.

Thresholding of Image:

Image thresholding is a process to remove noise from an image with a fixed cut-off value (lower intensity pixels only) for pixel intensity. For example, the dot peen indents have high peak intensities and the small noise levels are with very low intensities and small peaks as shown in [Figure 3.23](#).

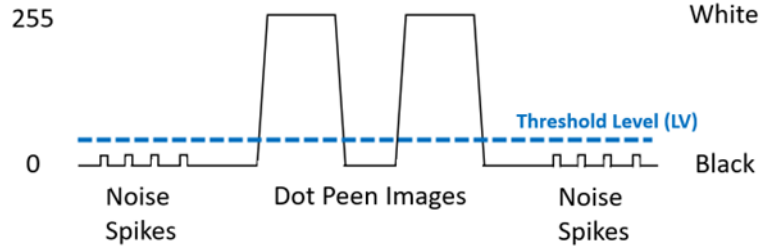


Figure 3.23 Image Thresholding (Low Pass Thresholding Only)

After the thresholding algorithm is processed, the new image has the image noise effects removed and only major dot peen indent image intensities remain, as shown in [Figure 3.24](#) (a) and (b) for comparison. [Figure 3.24](#) (a) shows the image without thresholding, and it can be seen that the edge of the circle has all the pixels going from low intensity to high intensity. On the contrary, [Figure 3.24](#) (b) shows the same circle image with the edge having all of the low intensity pixels removed and converted to black (crispier boundary of the circle).

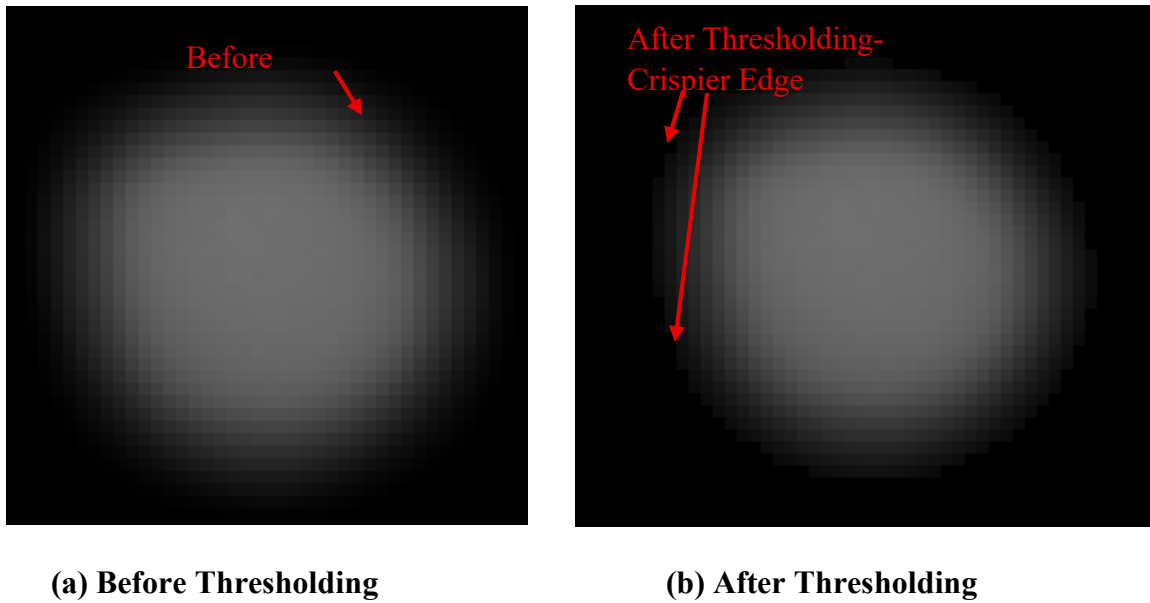


Figure 3.24 Image Thresholding

Image Correlation for Displacement Measurement using Centroid Algorithm:

In simple words, the centroid method calculates the center of energy (intensity) for the image. The centroid method is a really versatile and well-known method to calculate the actual

intensity center of the image. This is accomplished by multiplying the pixel intensities by their respective position within the image, and dividing by the total intensity integrated over the entire image. The centroid of an image has two coordinates: one for the x-centroid and the other for the y-centroid.

For example, [Figure 3.25](#) shows a manually created image having a 4 x 4 pixel arrangement with black pixels on top and bottom rows and white pixels in the middle two rows. [Table 3.2](#) shows the pixel intensities for each pixel in the image shown in [Figure 3.25](#).

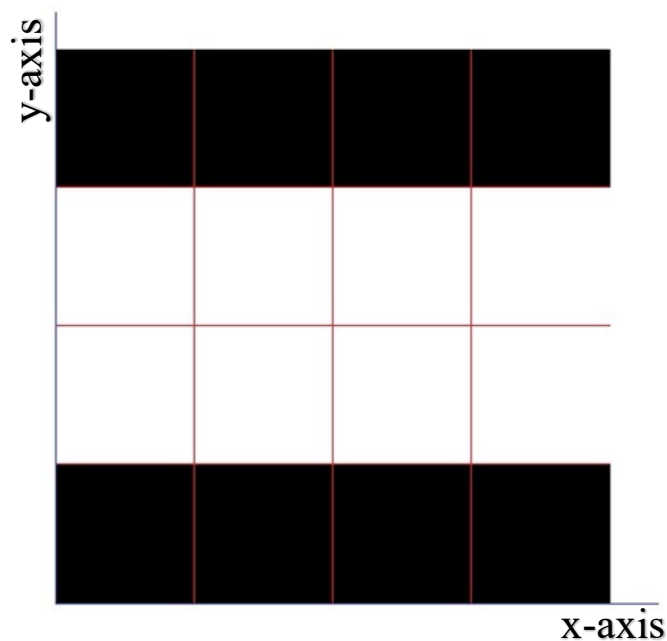


Figure 3.25 4 x 4 Pixel Manually Created Image

Table 3.2 Pixel Intensities for Image in [Figure 3.25](#)

Image Pixel Intensities			
0	0	0	0
255	255	255	255
255	255	255	255
0	0	0	0
Sum of all the pixel intensities			2040

Step 1 in calculating the centroid is to assign the pixel positions as shown in [Table 3.3](#).

Table 3.3 Default Matrix Table for Calculating Centroid

X-Coordinate					Y-Coordinate			
0	1	2	3		0	0	0	0
0	1	2	3		1	1	1	1
0	1	2	3		2	2	2	2
0	1	2	3		3	3	3	3

Step 2 is to multiply each pixel intensity with its respective position number and find a final sum of the values as shown in [Table 3.4](#).

Table 3.4 Table Indicating Final Values for Centroid Calculations

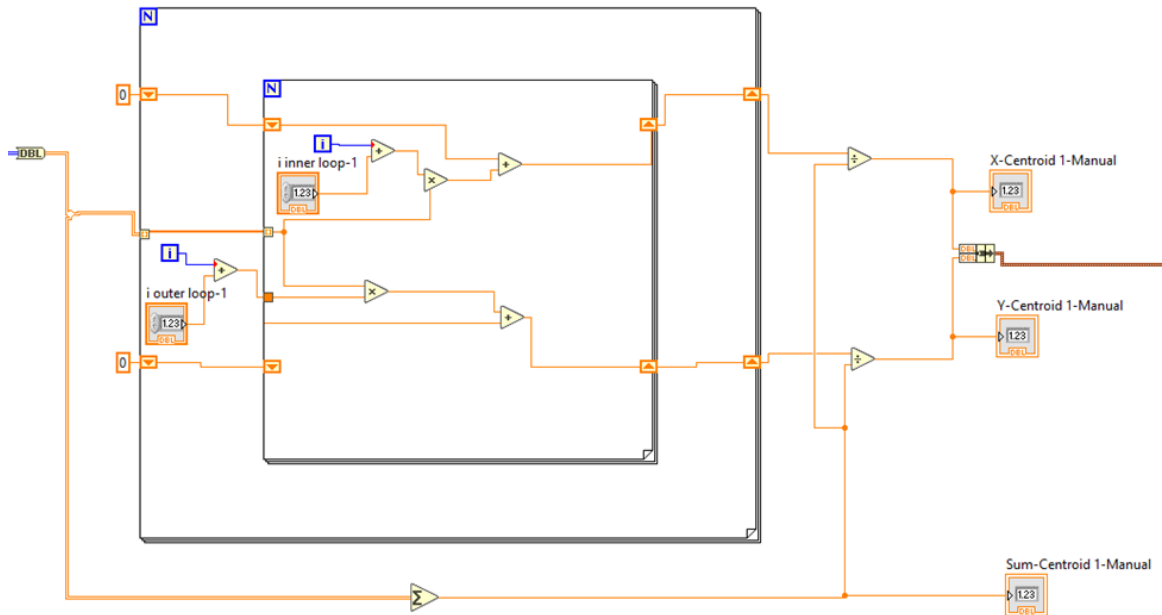
X-Coordinate * Image Pixel Intensity					Y-Coordinate * Image Pixel Intensity			
0	0	0	0		0	0	0	0
0	255	510	765		255	255	255	255
0	255	510	765		510	510	510	510
0	0	0	0		0	0	0	0
Sum (X-Coordinate * Image Pixel Intensity)			3060		Sum (Y-Coordinate * Image Pixel Intensity)			3060

Step 3 is to divide “Sum (X-Coordinate * Image Pixel Intensity)” by “Sum of all the pixel intensities” as shown in [Table 3.5](#).

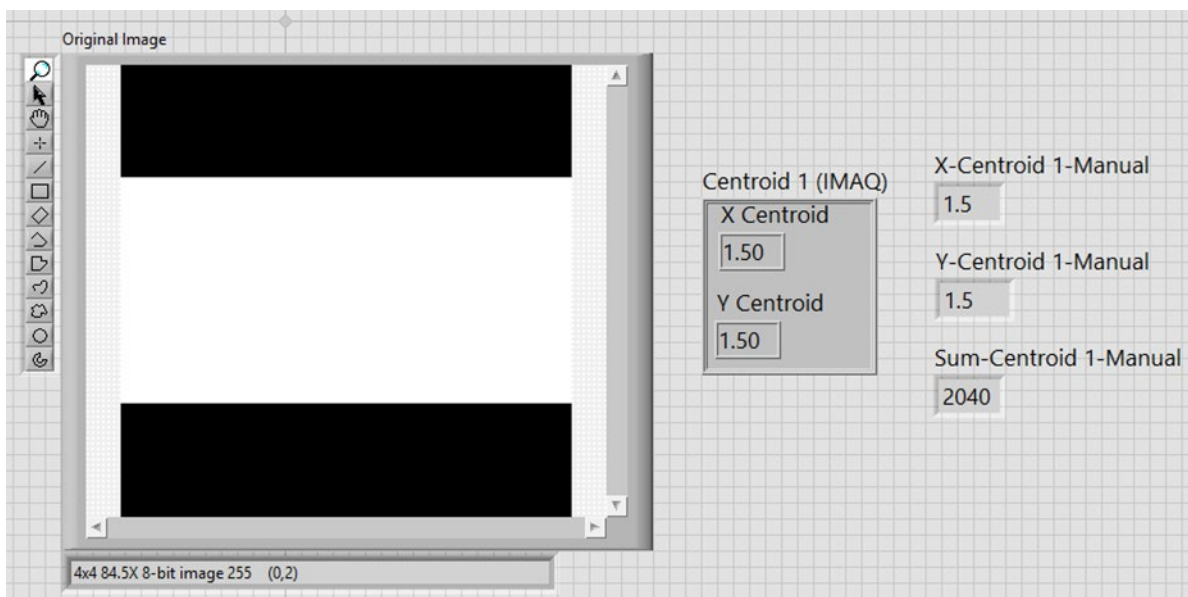
Table 3.5 X and Y Centroid Calculation

X-Centroid	Y-Centroid
$= \frac{\text{Sum (X-Coordinate * Image Pixel Intensity)}}{\text{Sum of all the pixel intensities}}$	$= \frac{\text{Sum (Y-Coordinate * Image Pixel Intensity)}}{\text{Sum of all the pixel intensities}}$
$= \frac{3060}{2040}$	$= \frac{3060}{2040}$
$= 1.5$	$= 1.5$

Running the same image in LabVIEW with the centroid algorithm (VI) shown in [Figure 3.26 \(a\)](#) gives the output shown in [Figure 3.26 \(b\)](#).



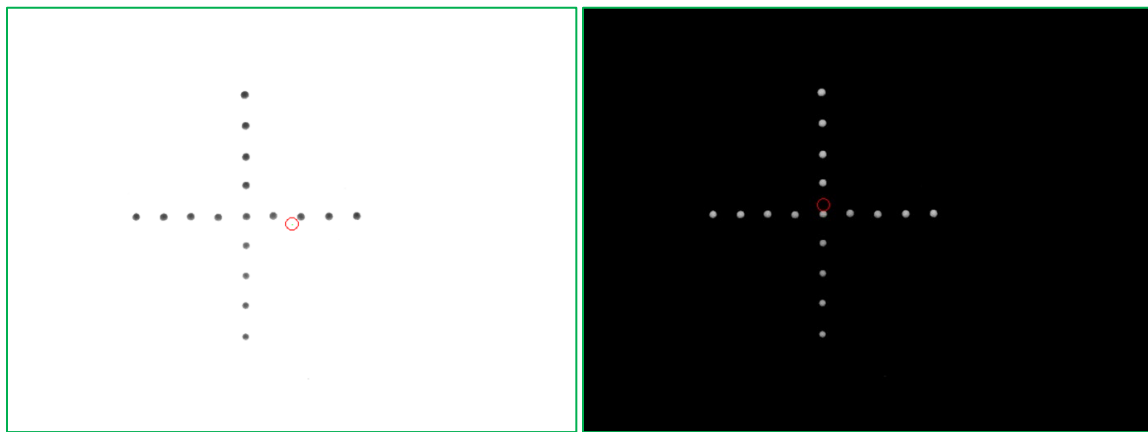
(a) Centroid Algorithm (VI)



(b) Centroid Algorithm Output

Figure 3.26 Centroid Calculation Results in LabVIEW

Since a dot-peen cross pattern is one of the viable tags for assessing displacement (strain) on steel railroad rail, it is very important to test the dot-peened cross pattern centroid algorithm and locate the centroid of the image for displacement measurement. [Figure 3.27](#) shows two examples illustrating the reason for inverting the images as one of the image processing steps. [Figure 3.27](#) (a) which shows a dot-peen cross image taken with white/flashed out background, and [Figure 3.27](#) (b) which shows black dot-peen indents, representing an inverted copy of the original image. [Figure 3.27](#) also shows the location of the centroid of the processed images, indicated by a red circle.



(a) Centroid on Original Image

(b) Centroid on Inverted Image

Figure 3.27 Centroid Calculations for Original Image and Inverted Image

As shown in [Figure 3.27](#) (a), the centroid of the image (red circle) is closer to the center of the image itself and not near the center of the cross pattern. The inverted image in [Figure 3.27](#) (b) is seen to have a centroid marker (red circle) very close to the center of the cross pattern. This shift in the centroid (red circle) of the image is due to the presence of high intensity pixels (noise) in the image. The centroid calculation on the original image gets affected by brighter pixels (shade of white) in abundance that are around the black dot-peen pattern indents; while in the inverted image, most of the bright pixels are in dot-peen pattern indents. The grayscale image in LabVIEW

has an intensity distribution going from darker to brighter pixels, meaning that the black pixels are considered 0 and white are 255. All pixels with shades in between black and white are assigned intensity between 0 and 255 as per their increasing brightness.

Centroid Algorithm Limitations:

After testing image correlation with the centroid algorithm, it was noticed that the strain readings are inconsistently fluctuating with a minor change in pre-processing of the images. This indicates that the centroid algorithm is very sensitive to the noise and changes in the camera flash/lighting. It is almost impossible to keep completely consistent lighting because the sensor is designed to work in the field. Also, the reference image has some noise around the borders because of the surface features of the rail and due to shadowing effects. The centroid algorithm gets affected with the changes in dot-peen indent size and design as well, which may be harder to control giving higher uncertainties in the strain measurements.

Image Correlation for Displacement Measurement using Pattern Recognition Algorithm:

The other algorithm used in the new strain measurement system LabVIEW interface is “Pattern Recognition.” With pattern recognition the algorithm first identifies a reference pattern and then locates the same/similar pattern in the displaced image. In other words, it locates the region of the grayscale image that matches with a selected reference pattern. A template of the “object” to be located is created and then the algorithm searches for this so called “object” in the acquired images. The LabVIEW algorithm generates a match score between 0 to 1000 with 1000 being a perfect match. This type of pattern matching algorithm finds template matches regardless of lighting variation, blur, noise, and geometric transformations such as shifting or rotation of the template [25].

Pattern Matching Limitations:

Pattern matching is a quick, general use algorithm to locate an object in an image. However, pattern matching is not well suited where the object to be detected has a different scale or if more than 10% of the image is occluded. Non-uniform lighting in the search images can also reduce the effectiveness of pattern matching.

3.3 Experimental Calibration of New Strain Sensor System

Calibration of the new sensor is a necessary step in verifying the repeatability and overall uncertainty of the new system. To perform this calibration, a simple but effective set-up was created in the laboratory as shown in the [Figure 3.28](#). The set-up included two metal plates with dot-peen patterns on them, the sensor's magnetic support bar to hold the sensor in fixed position during operation, the new strain sensor itself, the dedicated laptop for capturing and processing captured images, and a means of providing a calibrated known displacement.

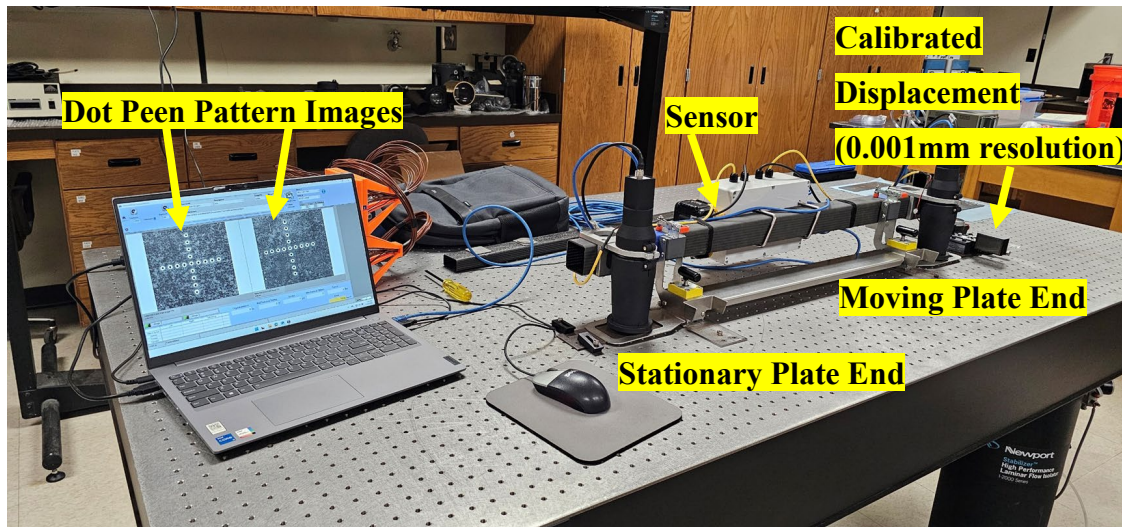


Figure 3.28 Calibration Set-Up for New Strain Measurement System

A digital indicator with 0.001mm resolution was used to record the actual displacement. To complete a given displacement measurement, an image correlation was performed between a reference image and a given displaced image. To achieve this, a reference image is taken and then

the plate is moved for a known distance using the micrometer stage shown in [Figure 3.28](#). The actual displacements were recorded from the digital indicator. A total of 10 readings of approximately uniform increments spread out over the span of the overall displacement of 0.1mm, were taken during the calibration. This allowed determination of the measurement sensitivity and the measurement uncertainty. Image correlation was performed using the reference (first) image and compared with the subsequent images captured after calibrated displacement. The measurement steps were as follows: (1) a reference (baseline) image was first taken, (2) the micrometer stage was then displaced in increments of approximately 0.01mm, (3) increments were repeated to span a displacement range of about 0.1mm. A set of images taken for each displacement was then compared (correlated) against the reference (baseline) image taken when the dial gauge was at 0.000mm to yield a net displacement from the reference position.

[Figure 3.29](#) shows the displacement of the dot-peened metal plate measured by the sensor vs. the actual displacement as measured by the digital indicator. The slope given in units of mm/mm corresponds to the overall uncertainty with very little bias in the measurements.

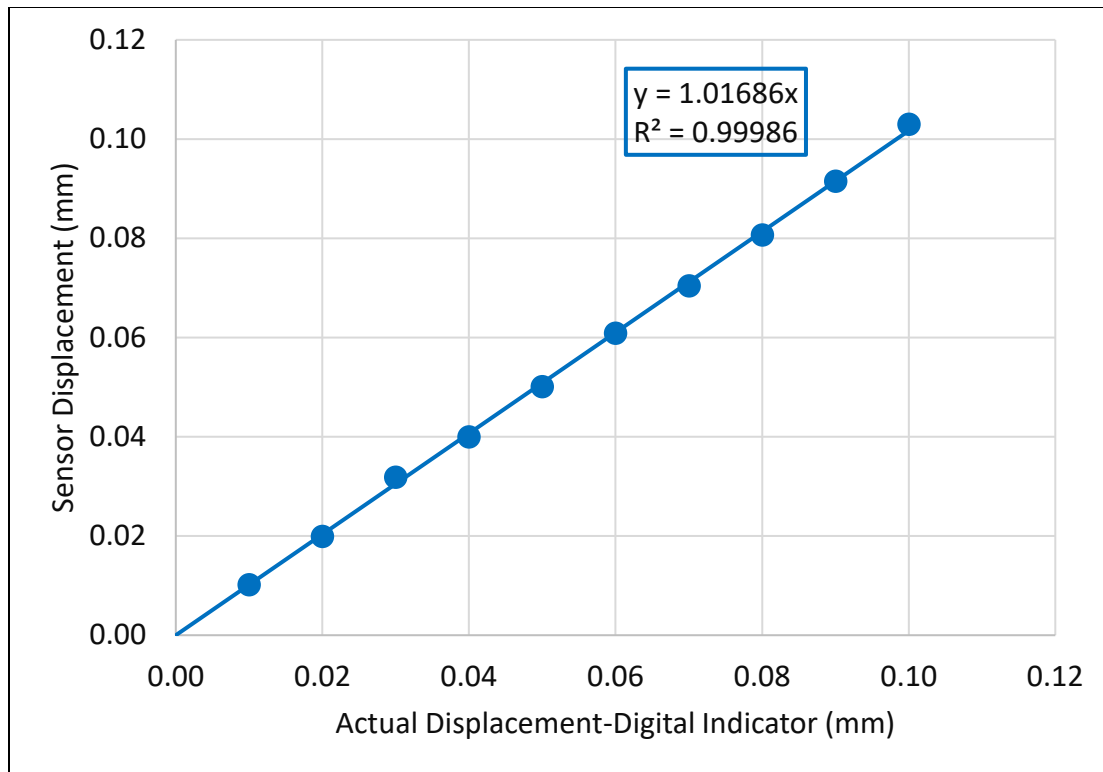


Figure 3.29 Non-Rusted Displacement Measurement for Dot-Peened Plate

The trendline is highly linear, and all the measurement points are within a small deviation from this line, which is displayed in the deviation plot shown in [Figure 3.30](#).

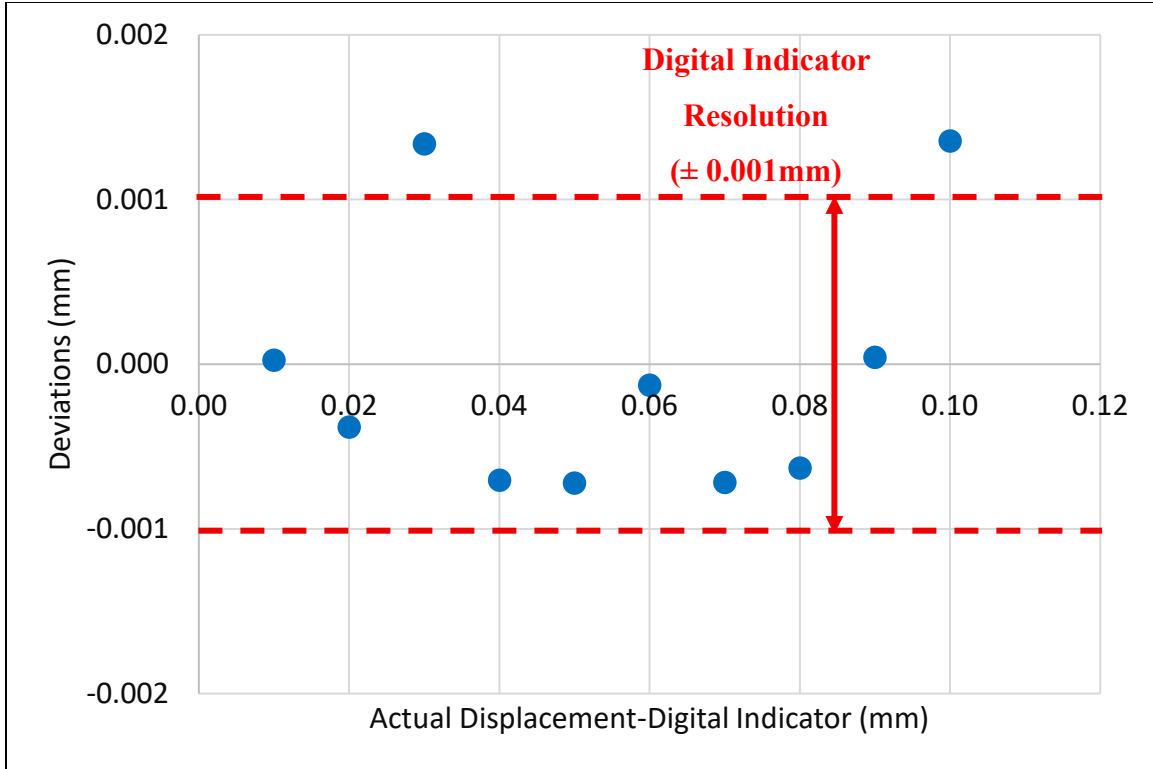


Figure 3.30 Deviation Plot for Non-Rusted Displacement Measurement for Dot-Peened Plate

Most of the deviations for overall uncertainty fall between $\pm 0.001\text{mm}$ which corresponds to approximately $\pm 1\mu\epsilon$ for the 36inch (152.4mm) gauge length sensor.

3.4 Thermal Stability Testing of the New Strain Sensor

The new strain sensor design is based on cameras used for displacement measurement mounted on carbon fiber tubing with low thermal expansion/contraction. This helps keep the system uncertainty very low with stable and consistent strain readings for all round weather/climate conditions. Saying that, it is necessary to investigate the thermal expansion/contraction of the sensor developed to verify the claim of low thermal expansion of carbon fiber tube. A heating test was performed at TDI by John Bloomfield on the new strain sensor, as shown in [Figures 3.31](#), and [3.32](#), and the results are plotted in [Figure 3.33](#).

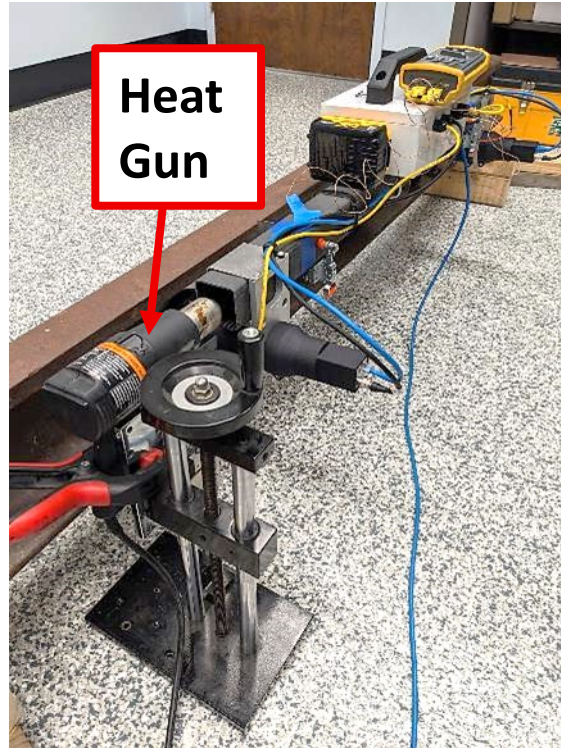


Figure 3.31 New Strain Sensor with Heat Gun to Check Carbon Fiber Expansion

The new strain sensor was mounted on a rail as shown in [Figure 3.31](#) with a dot-peen pattern on the rail being used for displacement measurements. The sensor mounted on the rail was left untouched to confirm the changes in the displacement readings just due to changes in sensor carbon fiber tube length. A heat gun was used to raise the temperature from ambient of the carbon fiber tubing for this test. Thermocouples were attached to the carbon fiber tubing, as shown in [Figure 3.32](#) , for accurate temperature measurement. Once the tubing temperature was raised about 40F higher than ambient, the heat gun was turned off, and the carbon fiber tubing was allowed to cool naturally while taking readings of displacement.

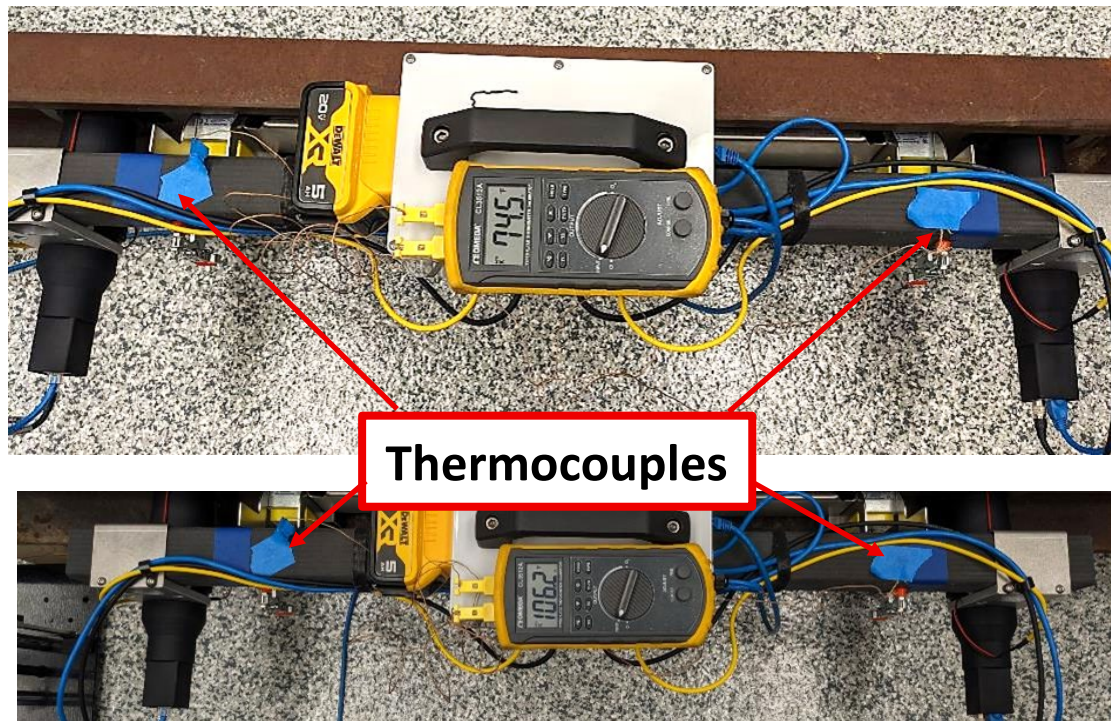


Figure 3.32 Thermocouples Attached to Sensor Tubing for Temperature Measurements

The displacement readings taken while the carbon fiber tube was cooling were plotted on displacement vs. temperature difference graph as shown in [Figure 3.33](#). Additionally, for comparison purposes, a plot was made for the same temperature differences with properties of a 36" steel rail section using an average CTE value of $6.5\text{E-}6\text{ }^{\circ}\text{F}^{-1}$. It can clearly be noted that the comparison plot shows a linear trend of carbon fiber tube change in length compared to change in displacement of the steel rail section. This indeed proves that the carbon fiber tube is a good choice for the new sensor design, and that it will not likely add large uncertainty in the displacement readings due to inclement weather conditions affecting the length of the sensor support tubing.

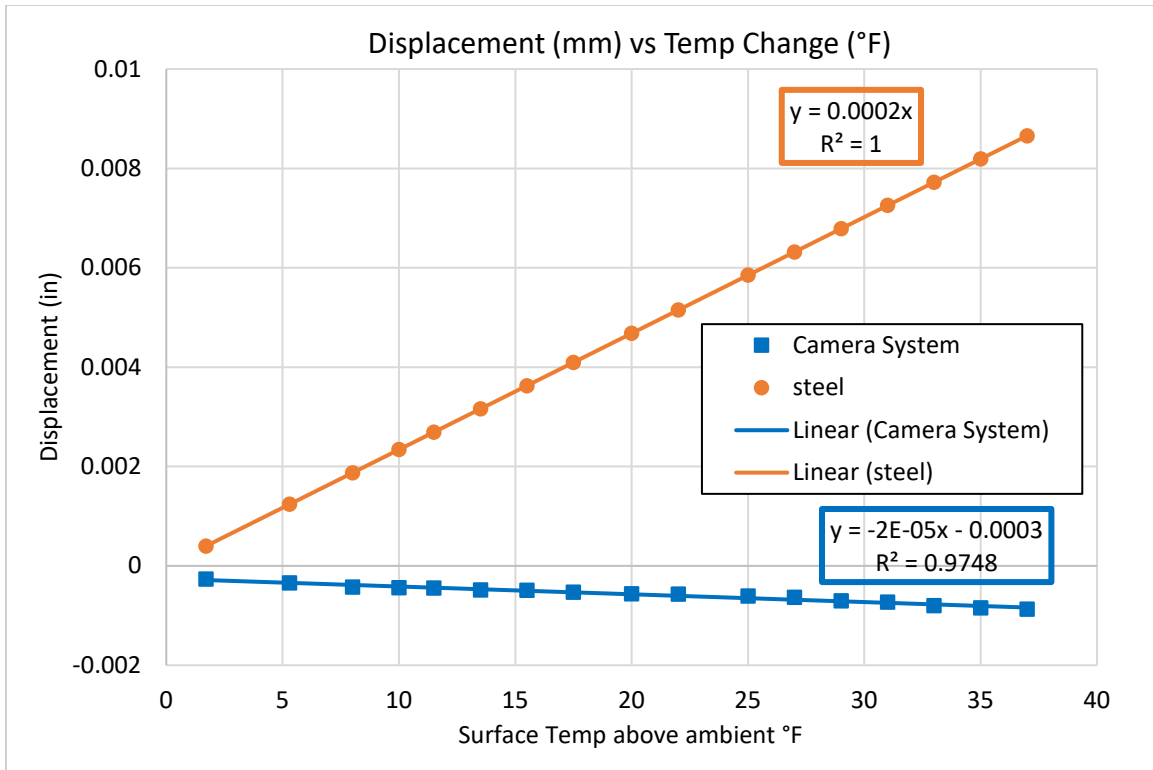


Figure 3.33 Displacement Comparison of Steel with Carbon Fiber

Chapter 4 – Full-Scale Facility for Testing Steel Rail

4.1 Testbed

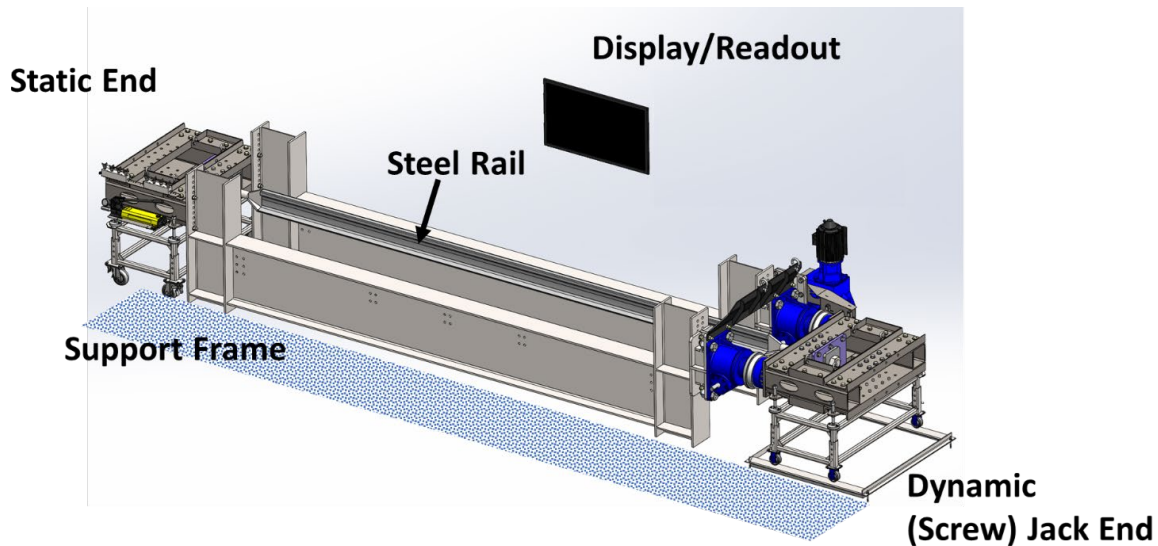
To conduct preliminary testing and to verify the new sensors operation, a laboratory set up was an absolute necessity. A full-scale laboratory test facility has been developed for conducting tests on sections of steel rail. A new testbed was designed and fabricated by the Technology Development Institute-TDI (John Bloomfield and his team) in the laboratory (074 Fiedler Hall). The testbed has a capacity of 300,000 lbs with load cells attached to the frame for accurate force/tension measurement.

There are two common types of control systems that can be utilized for generating mechanical displacement of a specimen (for example, a bar or rod) under test. These are (1) force-based, which means that a controlled (typically constant) force is applied to cause elongation (displacement), and (2) displacement-based, which means that the rate of specimen displacement is controlled by the rate of force application necessary to achieve the desired rate of displacement.

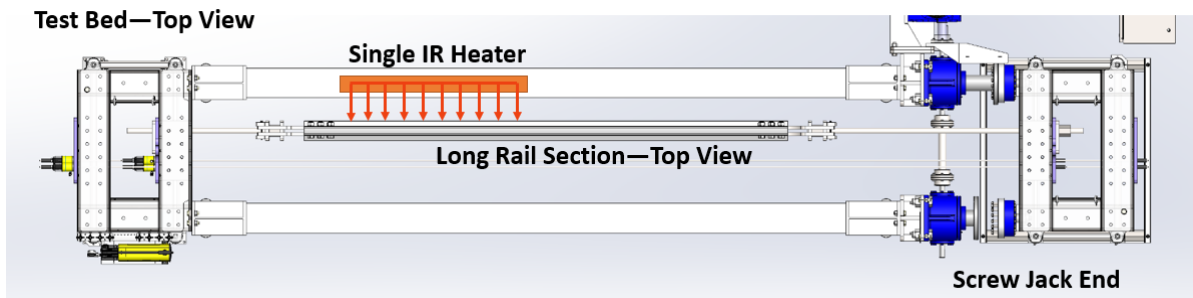
The testbed in this project is a displacement-controlled system, which generates tension in the rail by the application of manually controlled screw-jack displacements. Load cells simultaneously measure the amount of applied force (rail tension). It is desirable to use a displacement-controlled system in this case because a force-based system could have difficulty recognizing and compensating for an abrupt crack/fracture in the rail. Continued application of force, subsequent to a specimen failure, could cause damage to the testbed frame and the rail test section.

The rail test sections are connected on each end to the testbed by clevis supports comprised of three bolts/pins. The clevis is then connected to rods that then connect to the testbed frame to generate tension. [Figure 4.1](#) (a) shows the basic 3d CAD model of the testbed and [Figure 4.1](#) (b)

shows the top view schematic drawing of the testbed, also showing the mounting of a typical steel rail test section⁹.



(a) 3d CAD Model of a Testbed



(b) Top View of Testbed

Figure 4.1 Testbed

The testbed has a load generating capacity of 300kips of tension in the rails, with the help of two jacks mounted on the dynamic end. Each jack has 150kips capacity giving the testbed its

⁹ The testbed has a multifunctional purpose: rail tension/force application for the current FRA funded project (and this dissertation), and fabrication of prestressed concrete prisms for an unrelated project.

necessary tensioning capabilities. Additionally, each jack is connected to a precisely calibrated load cell with a capacity of 200kips to measure the tension levels accurately. Each load cell has a static uncertainty of about $\pm 0.07\%$ of 200,000 lbs., making them accurate in recording the tension created on the rail for a given applied load.

4.2 Steel Rail Test Sections

Rail test sections were required to conduct the laboratory testing. Two separate rail test sections were fabricated from available lengths of AREMA 136RE steel rail for the laboratory tests. The shorter rail section has an overall length of approximately 77 inches, including the space to connect the three clevis bolts on each end. The longer rail section is approximately 147 inches long, including the space to connect the three clevis bolts on each end. These rail test sections were provided by one of the project sponsors, BNSF railway, to help test the new sensor under controlled laboratory conditions. The cross-sectional view of a 136RE rail is shown in [Figure 4.2](#), with basic dimensions of the rail given, along with its nominal cross-sectional area.

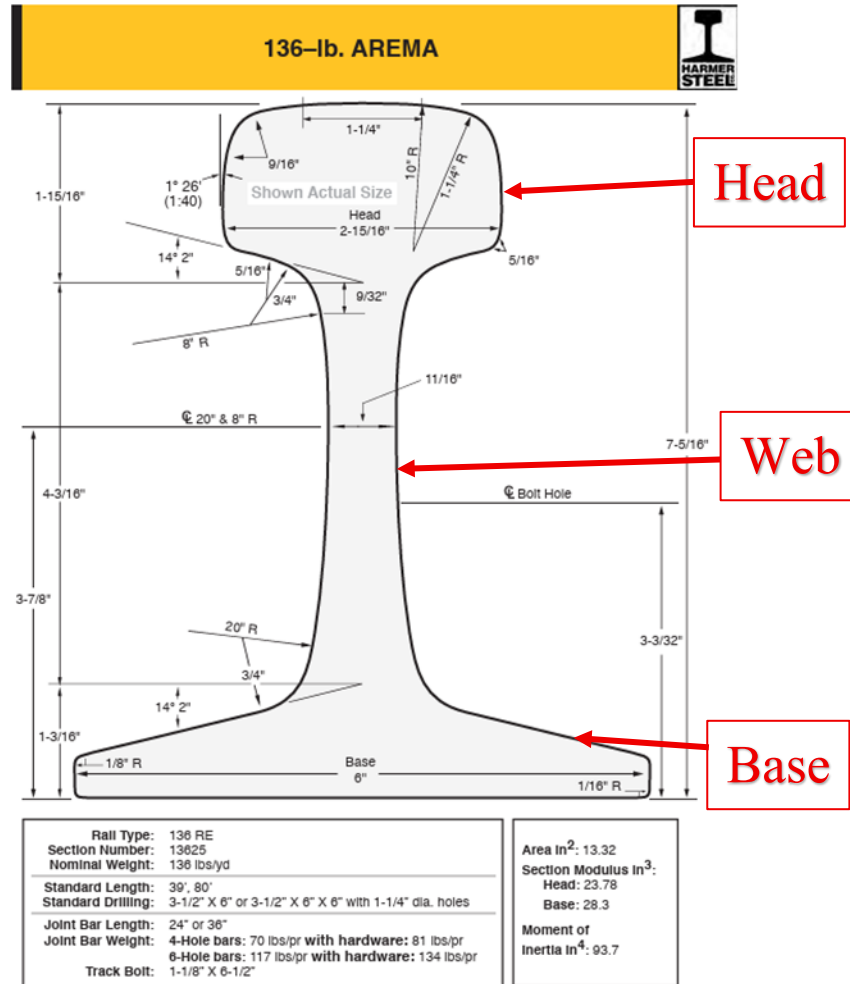


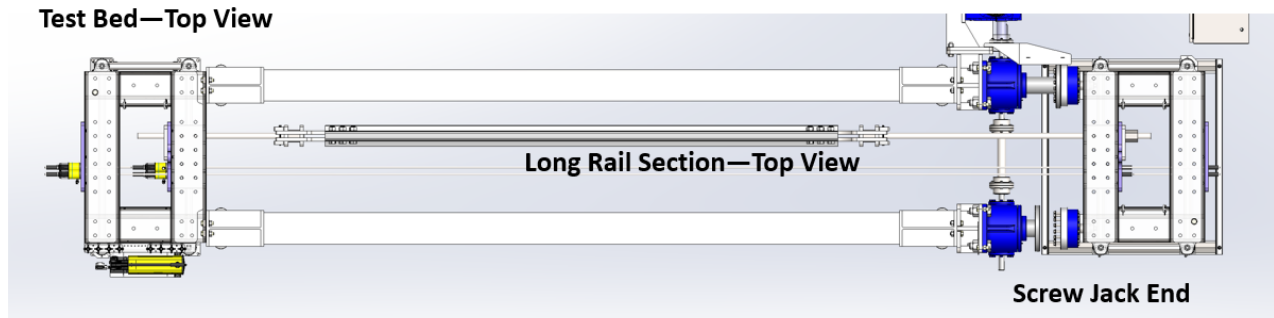
Figure 4.2 AREMA 136RE Rail Cross-Sectional View (Image Copied from [17] for Informational Purposes)

The 136RE rail is made of carbon steel having the following composition: Carbon - 0.70 to 0.82%, Manganese - 0.75 to 1.05%, Manganese and Phosphorus - 0.035%, Sulfur - 0.040%, and Silicon - 0.10 to 0.35% [16].

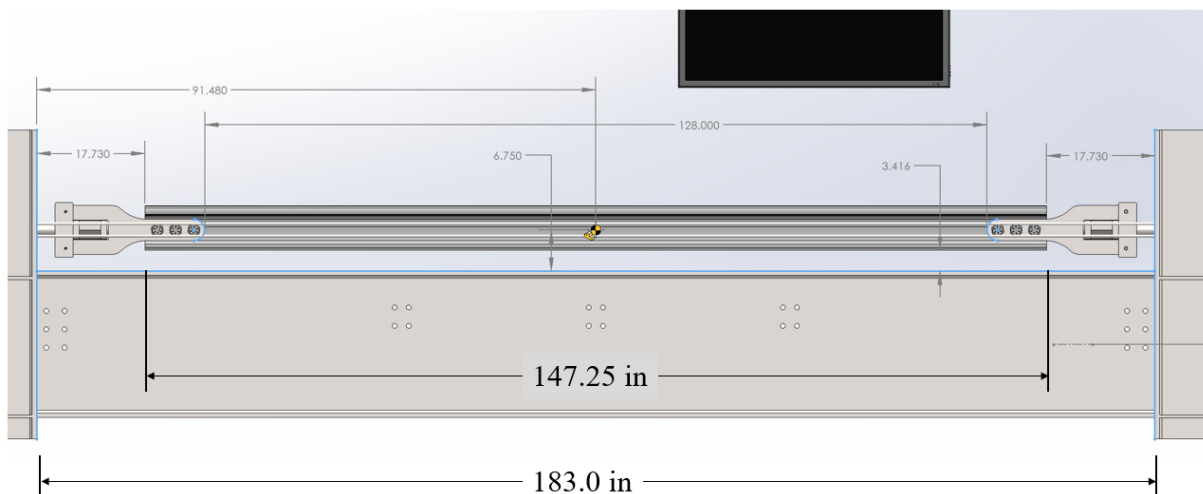
The Coefficient of Thermal Expansion (CTE) for the rail steel is about $6.5 \times 10^{-6} \text{ }^{\circ}\text{F}^{-1}$ [16]. Young's modulus, E_R , for the steel rail is about $29 \times 10^6 \text{ psi}$ [75].

Special consideration was made to select and fabricate these rail sections so as not to have rail manufacturer markings in the required locations where the dot-peen markings must be made.

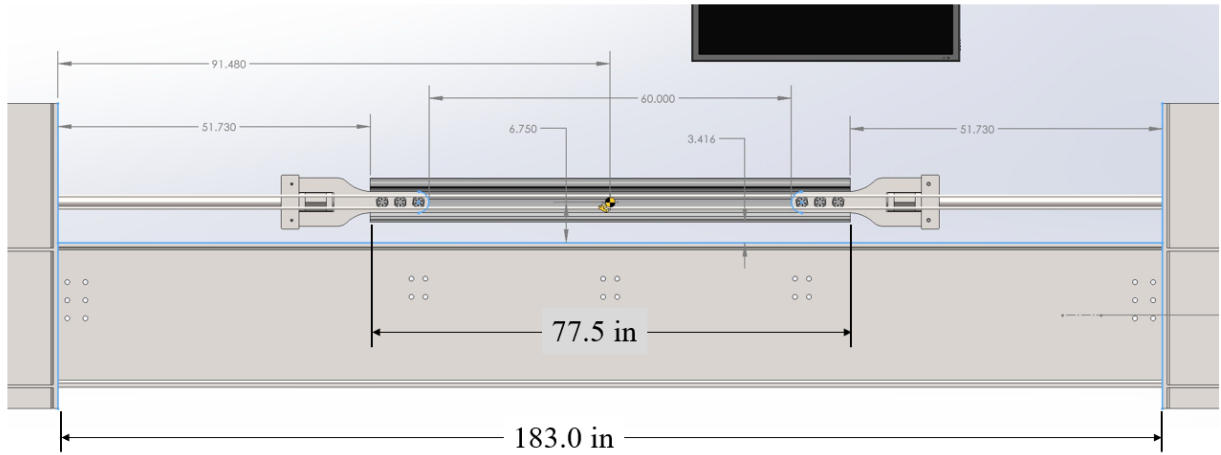
However, since the rails were not originally supplied as fabricated test sections, the longer rail section did have some manufacturer labeling markings in an inconvenient location. Therefore, the dot-peen patterns were shifted a little away from being centered on the rail.



(a) Top View of Testbed with Long Rail Section Installed



(b) Side View of the Long Rail Section on Testbed



(c) Side View of the Short Rail Section on Testbed

Figure 4.3 Rail Sections Installed on Testbed

[Figure 4.3](#) (a) shows the top-view of the testbed with the long rail test section installed and [Figure 4.3](#) (b) and (c) shows the side view of the testbed with the long rail test section and short rail test section installed, including some of the important dimensions of the rail and testbed.

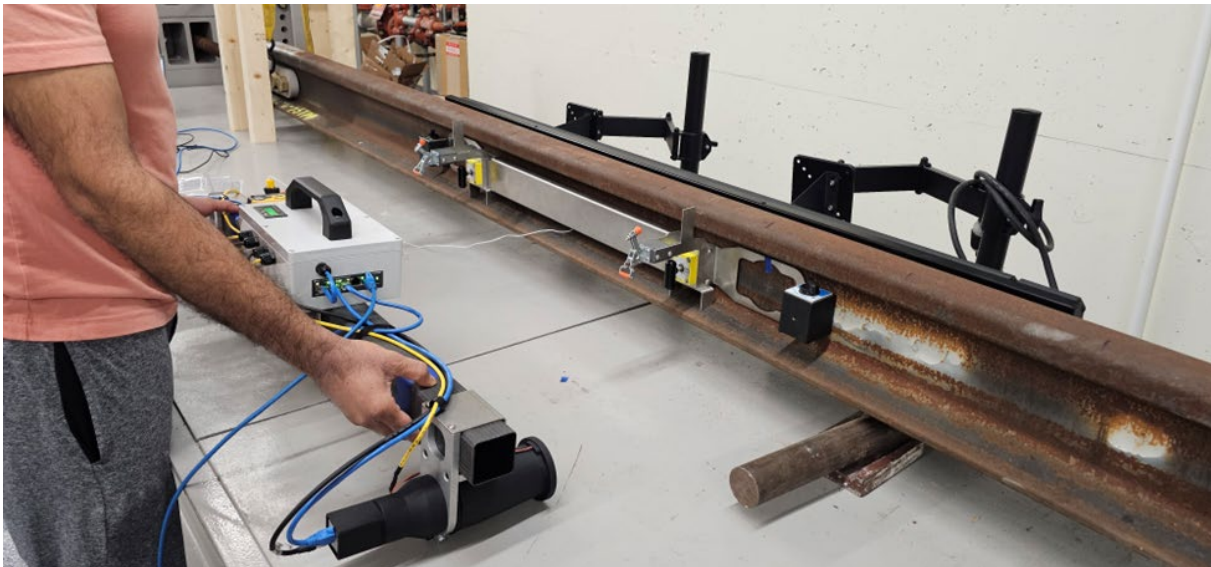
Chapter 5 – Full-Scale Mechanical Testing of Steel Rail

5.1 Repeatability Test for New Strain Sensor

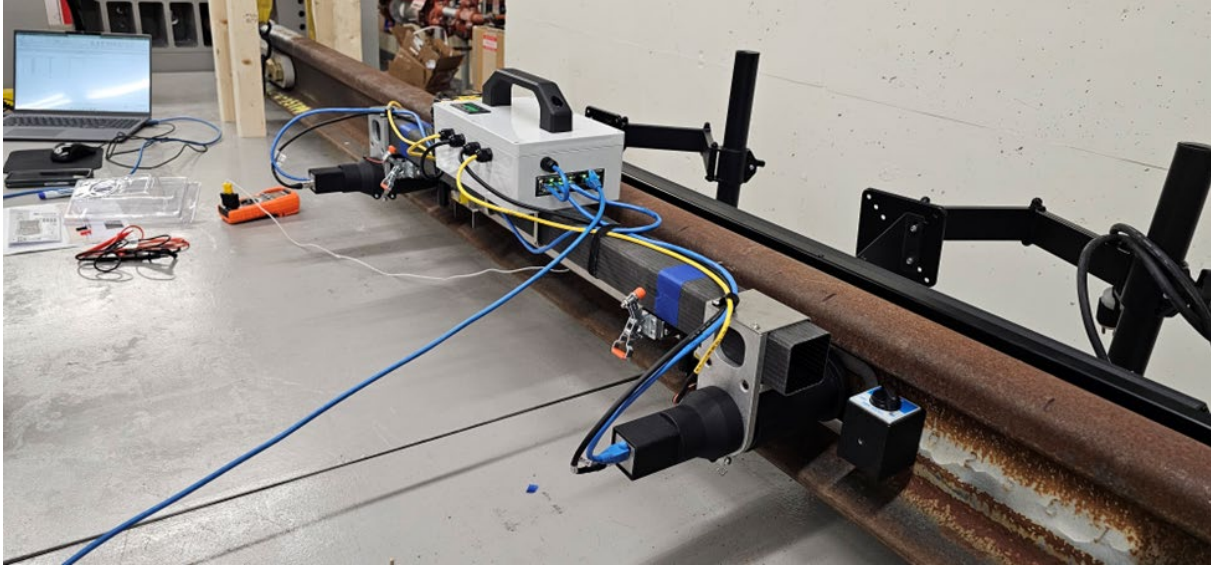
Prior to starting mechanical testing on the rail sections, some confirmation checks needed to be performed on the new strain sensor to identify the repeatability. Two separate tests were performed on the new strain sensor using the longer rail section to confirm the readings.

5.1.1 Static Repeatability

To perform a static repeatability test, the new strain sensor was mounted on the rail section with the magnetic bracket attached, to hold it statically in place, as shown in [Figure 5.1](#) (a). While the sensor on the rail was kept untouched, multiple readings (10 readings to be precise) were taken repeatedly within a time frame of about 8 minutes. [Figure 5.1](#) (b) shows the sensor mounted on the rail section.



(a) Magnetic Bracket to Mount the Sensor



(b) New Strain Sensor Mounted on the Rail for Static Repeatability Test

Figure 5.1 New Strain Sensor Magnetic Mounting Bracket and Rail Mounting

The data in [Figure 5.2](#) shows the displacement output of the new strain sensor. Looking at the plot, it can be confirmed that the static repeatability of the system is very consistent and within $\pm 0.001\text{mm}$. Each pixel is about 0.01mm so, in terms of pixels, the scatter is within ± 0.1 pixel or $1/10^{\text{th}}$ of a pixel.

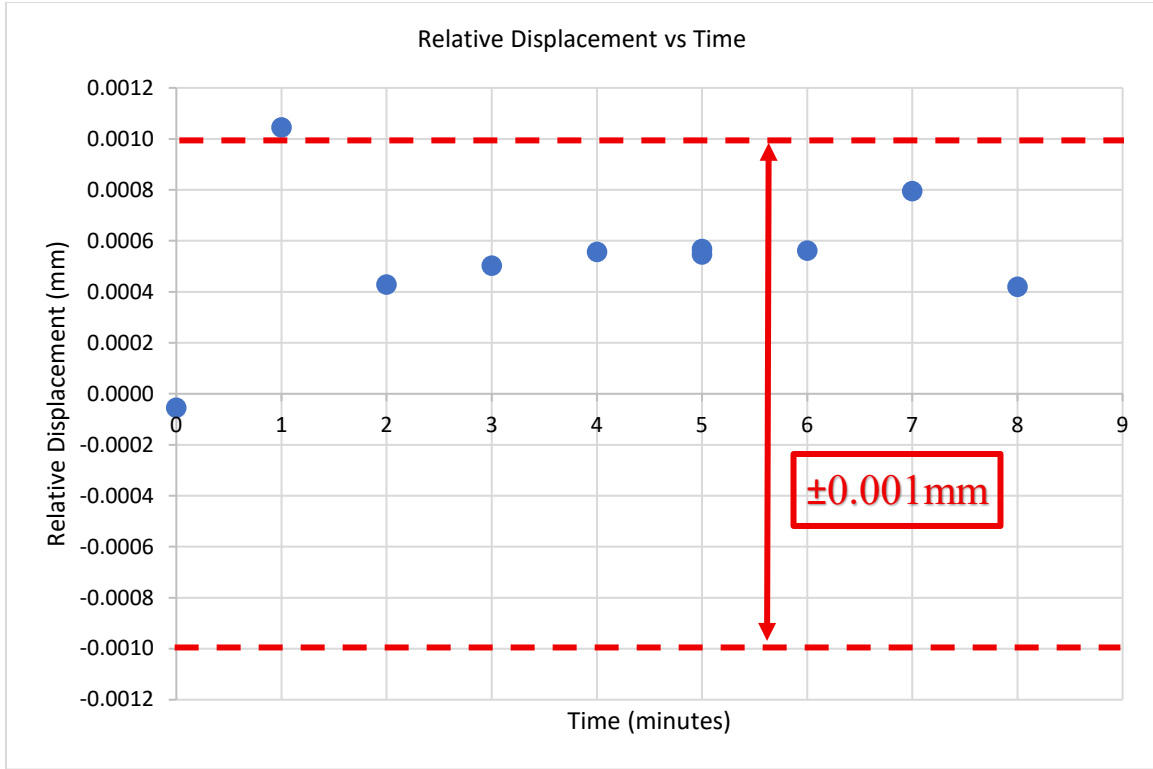


Figure 5.2 Displacement Output of New Strain Sensor for Static Repeatability

To further scrutinize this testing for verification and validation purposes, the static displacement for each individual camera was plotted separately with the relative displacement (sensor output) on the same plot. [Figure 5.3](#) shows the actual x-displacement of individual left and right cameras on the new strain sensor. Therefore, it can be confirmed that the displacement measured by each sensor system camera has very minor fluctuations. Comparing the x-displacement results for each camera (left hand scale) with relative displacement results (right hand scale) shows that the results are consistent within ± 0.001 mm.

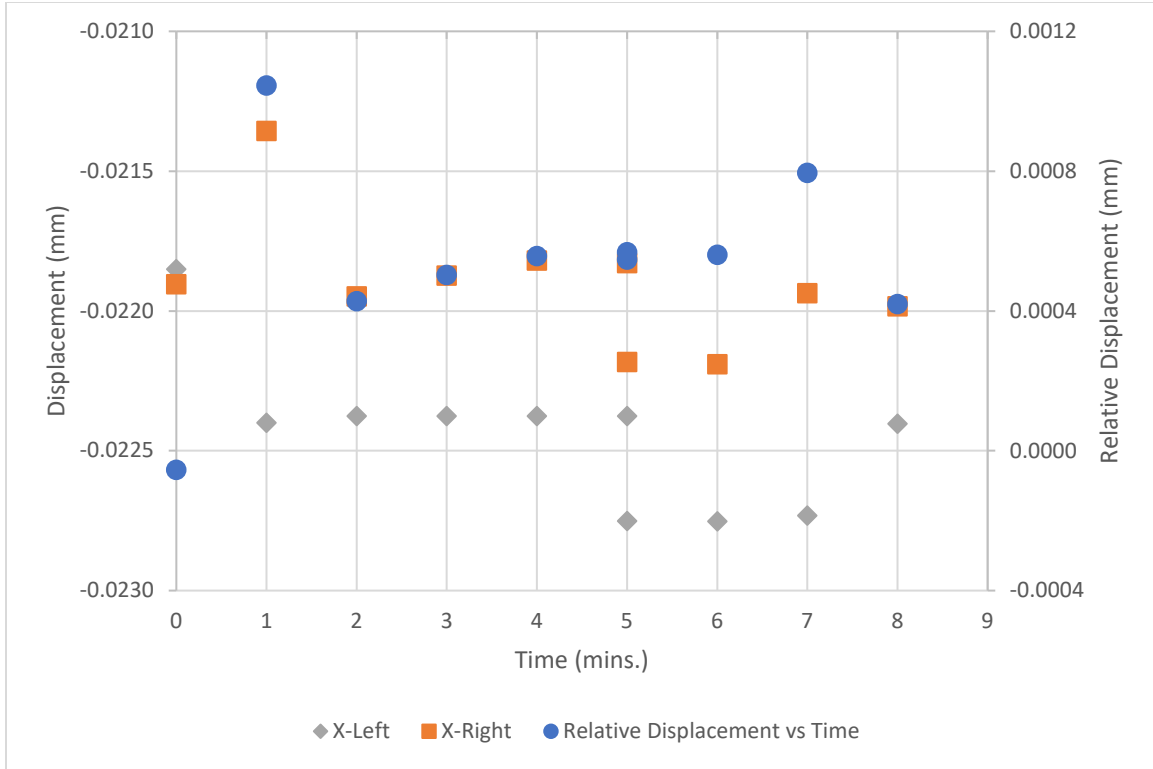


Figure 5.3 Left and Right Camera Displacement and Relative Displacement

5.1.2 Sensor Mounting Repeatability

To perform this test, the new strain sensor together with magnetic mounting bracket was mounted and de-mounted from the rail section each time a measurement was made. While the sensor was mounted on the rail, a single reading was taken. Then, for each subsequent reading, the sensor was first removed and then re-attached to the rail for the next reading. A total of 10 readings were taken within a time frame of about 30 minutes.

[Figure 5.4](#) shows the relative displacement (output of the sensor) between left and right strain sensor cameras. These results confirmed that the repeatability of the system is within $\pm 0.01\text{mm}$. With each pixel being about 0.01mm , the scatter is within about ± 1 pixel (omitting the one outlier point).

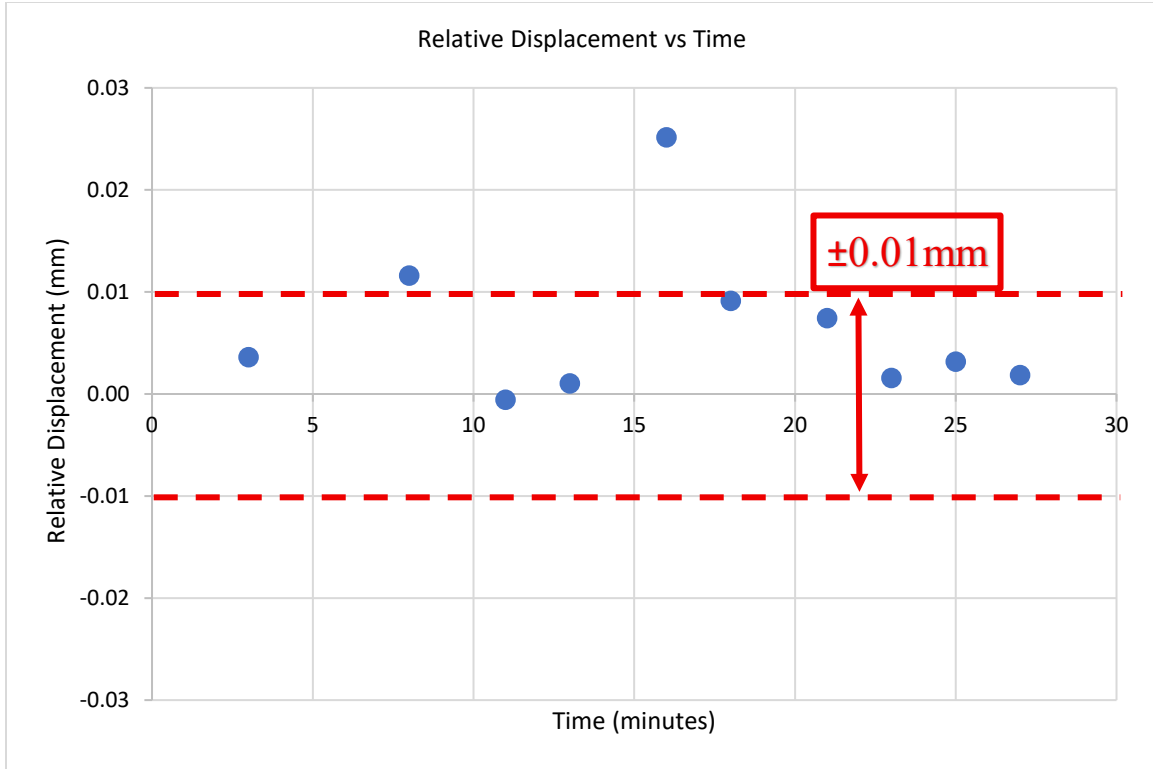


Figure 5.4 Relative Displacement – New Strain Sensor Repeatability Test

Inspecting further, [Figure 5.5](#) shows the displacement for each camera plotted separately, with the relative displacement on the same plot for verification and validation purposes. The data shows the actual x-displacement for the left and right cameras on the new strain sensor. These results confirmed that the displacement measured by each camera in the sensor system is similar and has very minor relative fluctuations. Comparing the x-displacement plots with the relative displacement (sensor output) plot shows that the results are consistent within about $\pm 0.02\text{mm}$.

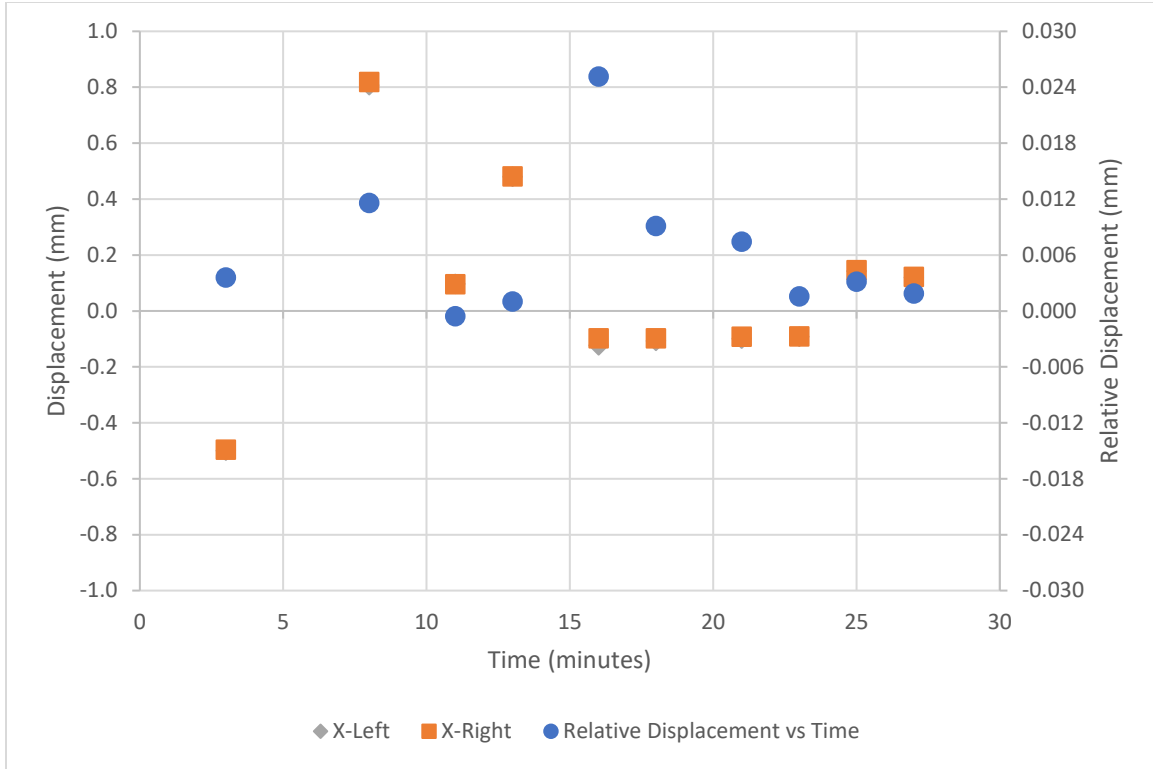


Figure 5.5 Left and Right Camera Displacement and Relative Displacement

5.2 Theoretical Analysis of Mechanical Testbed Testing

The basic idea of conducting the mechanical testing associated with this project was to connect the rail sections and perform tension tests using the testbed. By using the testbed, known and controlled tension can be induced in the rail, which can be used to verify the dual camera sensor results. Below is an example of a basic mathematical formulation for the purely mechanical testing of rail in the testbed, prior to combined thermal and mechanical testing.

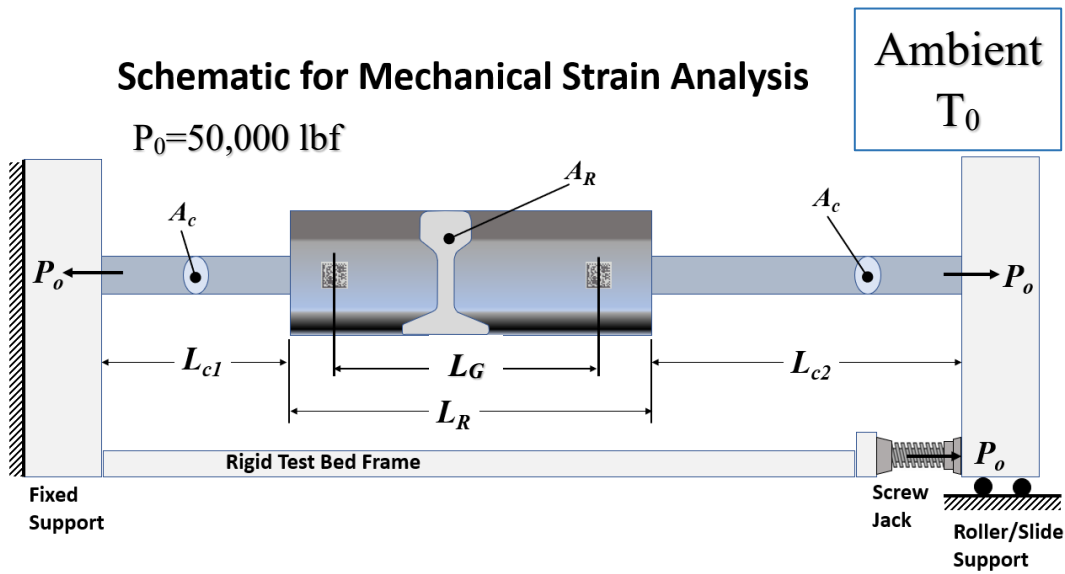


Figure 5.6 Theoretical Analysis of Mechanical Testing on Short Rail Section

[Figure 5.6](#) represents a basic setup of the rail on the testbed. It shows the initial loading condition that was put on the rail (P_0) of 50,000 lbs. at an ambient temperature. It shows rail with length (L_R) and cross-sectional area (A_R), along with the distance between two dot-peen patterns, the gage length (L_G). The tensioning rods that are used to connect the rail through the clevis are of lengths (L_{c1} and L_{c2}) with cross-sectional area (A_c). This example represents a basic tension phenomenon on the rail and shows how to extract strain and displacement.

Below are the formulas used for calculating mechanical strain and displacement, along with a numerical example. Mechanical strain is represented ϵ_m given by

$$\epsilon_m = \frac{\sigma_m}{E_R} \quad (5.1)$$

Here σ_m is the mechanical stress and E_R is Young's Modulus for the rail, where

$$\sigma_m = \frac{P_0}{A_R} \quad (5.2)$$

P_0 is the applied force and A_R is cross-sectional area of the rail.

Substituting equation (5.2) in equation (5.1) yields

$$\epsilon_m = \frac{\sigma_m}{E_R} = \frac{P_o}{E_R A_R} = \frac{50,000}{29 \times 10^6 \times 13.32} = 0.0001294 = 129.4 \mu\epsilon \quad (5.3)$$

Displacement is defined as ΔL and can be calculated using the mechanical strain formula,

$$\epsilon_m = \frac{\Delta L}{L_G} \quad (5.4)$$

Here L_G represents gage length. Rearranging equation (5.4) yields

$$\Delta L = L_G \epsilon_m = 36" \times 0.0001294 = 0.004660 \text{ in} = 0.1184 \text{ mm} \quad (5.5)$$

Mechanical testing was performed with the loads from 0 up to 150,000 lbf at increments of 10,000 lbs. The next sections present results to not only validate the accuracy of the new sensor, but also to address the uncertainty involved in the sensor readings for each set of tension tests.

5.3 Short Rail Section – Mechanical Testing

The short rail section of approximately 77" length was used to start the testing of the new dual camera sensor. The rail was drilled to accommodate the three bolts on each end with the clevis connecting to the end support rods and eventually to the testbed frame itself. As shown in [Figure 5.7](#), the rail was raised using straps on each end to avoid any bending effects from gravitational loading.

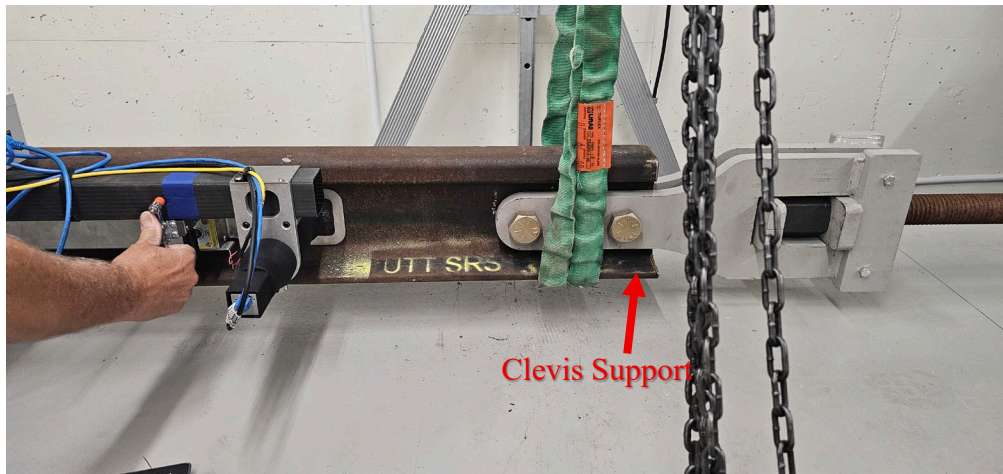


Figure 5.7 Straps and Clevis Support for Rail Section

[Figure 5.8](#) shows the comparison between actual measured results using the strain sensor and the theoretical analysis based on linearly elastic deformation theory.

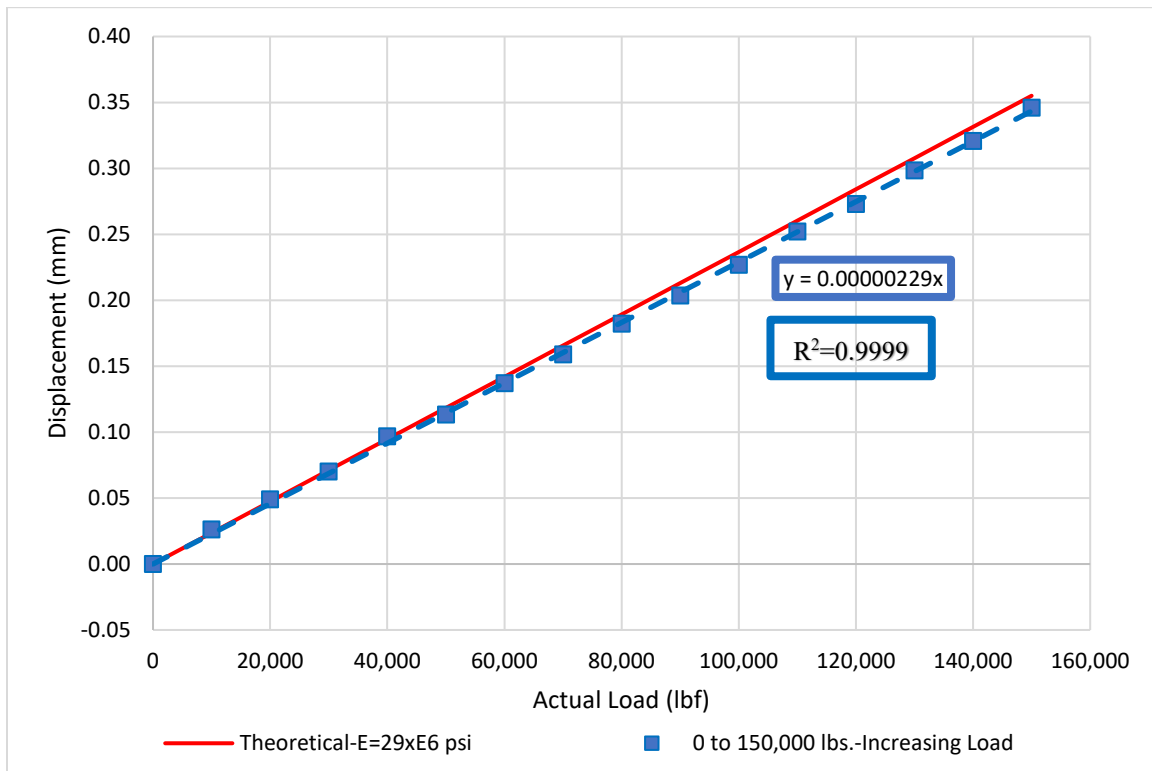


Figure 5.8 Displacement vs. Actual Load for Increasing Load - Short Rail Section

Additionally, [Figure 5.9](#) shows the theoretical calculations for each of the load setting in decreasing order from 150,000 lbf to 0 lbf, along with the respective strain sensor readings for comparison.

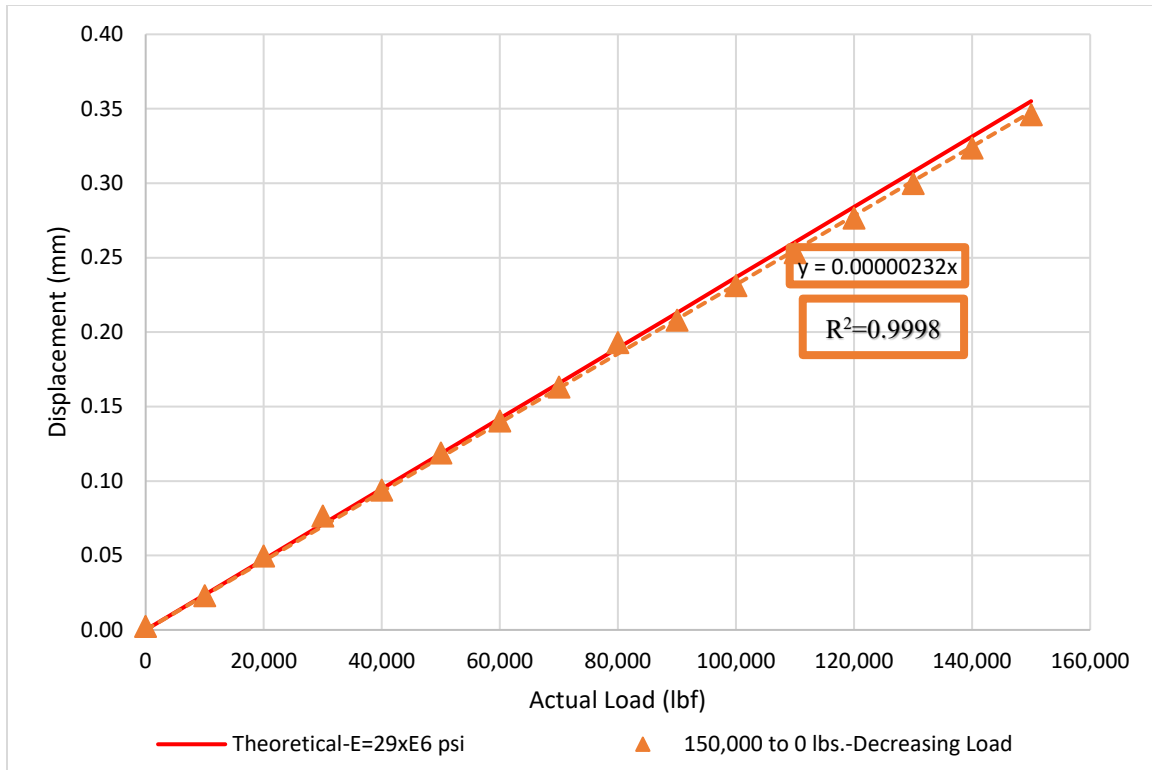


Figure 5.9 Displacement vs. Actual Load for Decreasing Load - Short Rail Section

Looking at the plots in [Figure 5.8](#) and [Figure 5.9](#), it can be confirmed that the dual camera sensor readings and the theoretical readings calculated from load cell measurements are very consistent and that the sensor measurements are highly accurate. The R^2 values of 0.9999/0.9998 mean that the data is nearly perfectly following a linear trendline. This also indicates that the value of 29M psi for Young's Modulus represents the tensioning results very well and hysteresis effects are small.

In addition to the above increasing and decreasing load capacity tests, it was determined to perform a special test where the researcher (Ph.D. candidate) would leave the laboratory and one of the observers would set the rail to a particular tension. Once the tension was set (tv screen was turned off to keep it a secret), the researcher was called back in the laboratory and given an opportunity to follow the strain and displacement procedure on the new strain sensor and determine that unknown tension. The tests were called blind tests and were performed to verify the system

accuracy with a random change in the load values instead of a known increasing load step-by-step.

[Figure 5.10](#) shows the theoretical displacement line vs. two blind test results, indicating close proximity to the theoretical line, based on the known rail mechanical parameters. Both the results were within 10% (actually, 4.83% and 7%) of this theoretical line.

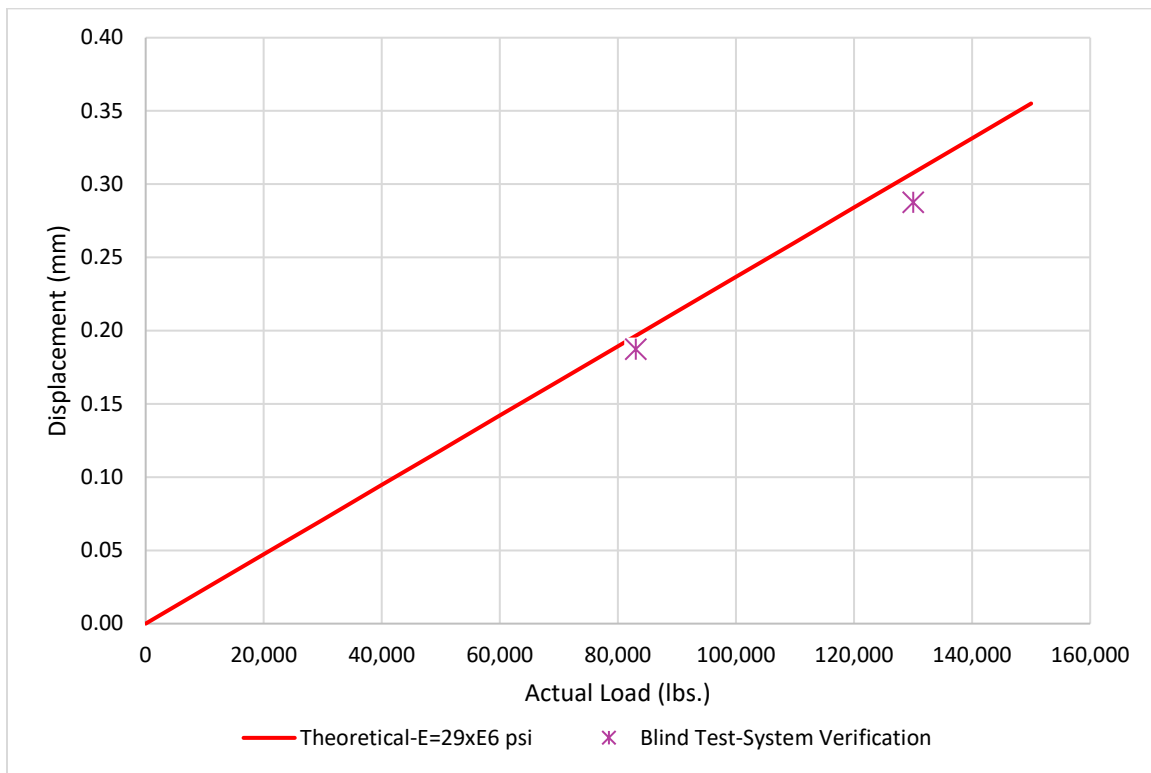


Figure 5.10 Blind Test-System Verification on Short Rail Section

As a side note, some hysteresis effect was noted while performing mechanical testing with decreasing load. This is thought to be because of the stress concentration “clevis” area very close to where the strain sensor was mounted on the rail. The end effects/stress concentration issue likely happens because the clevis was very close to the dot peen marks used by one end of the sensor.

According to Saint Venant’s principle [26], as shown in [Figure 5.11](#), the stresses and strains in a body at points that are sufficiently remote from points of application of load depends only on the static resultant of the loads and not on the distribution of loads.

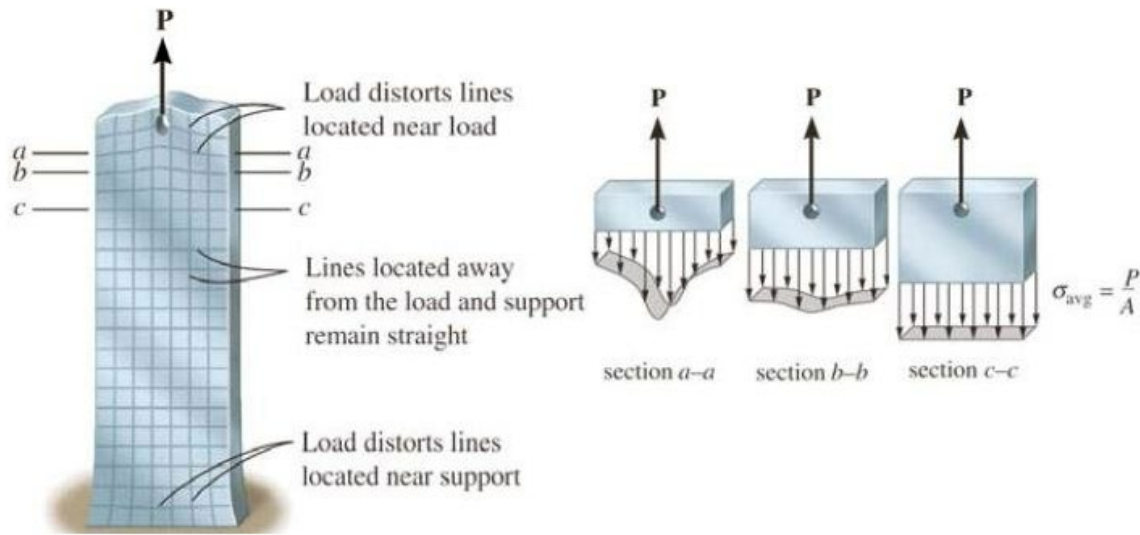


Figure 5.11 St Venant's Principle[\[26,64\]](#)

As shown in [Figure 5.11](#), it can be seen that the strain (and stress) is non-uniformly distributed near a hole [\[26\]](#). When a point load is applied, it generates a region of stress concentration at that local position. The increase in stress can be due to multiple reasons including discontinuity in material, changes in cross-sectional area of the material, or load application. Since stress and strain are proportional, lines can be drawn parallel to the normal plane to check if they remain parallel during the load application. As seen in [Figure 5.11](#), lines near a hole and load application spot are non-parallel while the lines are parallel as the position gets farther away from the loading point and hole[\[26\]](#).

5.4 Long Rail Section – Mechanical Testing

The long rail test section of approximately 147 inches length was also used for testing the new dual camera sensor and to investigate the end effects. The rail was drilled to accommodate the three bolts on each end to accommodate the clevis connecting to the rods, and eventually to the testbed frame.

For the results shown in [Figure 5.12](#), the rail was supported using a method similar to what was used with the shorter test section; that is, with a set of straps on each end to avoid any bending effects. [Figure 5.12](#) shows the comparison between theoretical analysis and the strain sensor measurements.

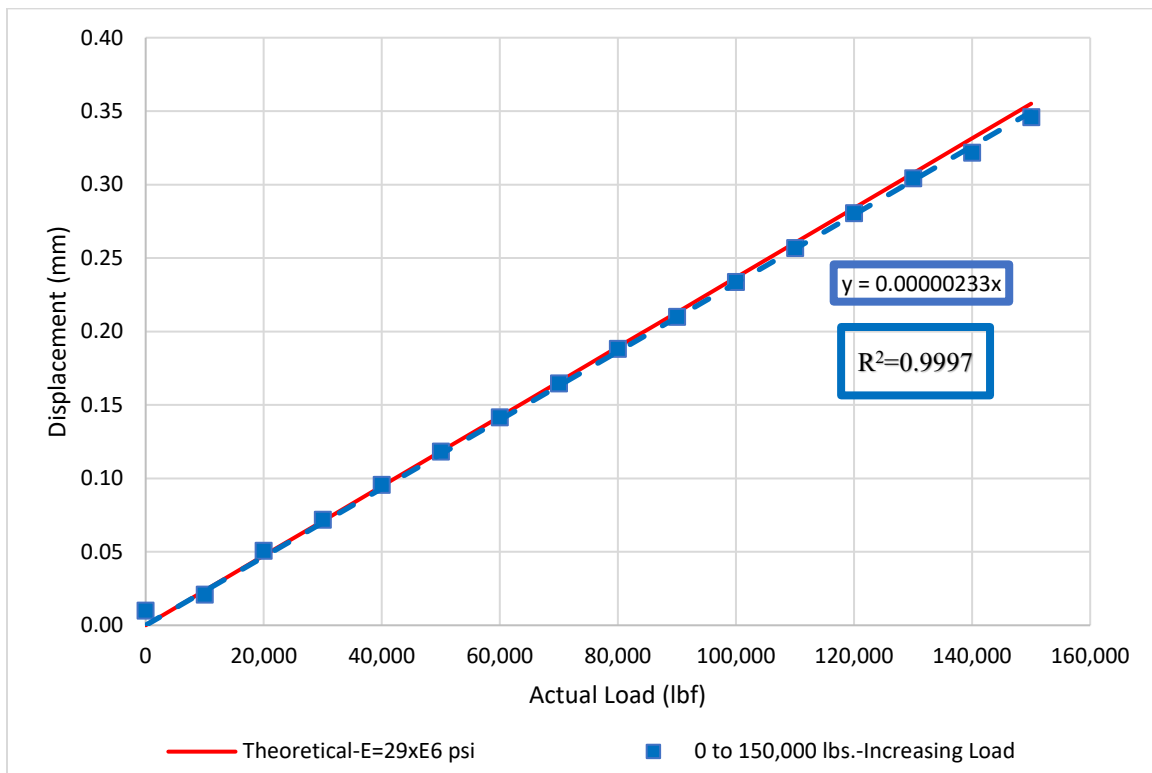


Figure 5.12 Displacement vs. Actual Load for Increasing Load - Long Rail Section

[Figure 5.13](#) shows the displacement measured by the sensor for each of the load settings in decreasing order from 150,000 lbs. to 0 lbs. The solid red line shows the theoretically predicted strain sensor reading for comparison.

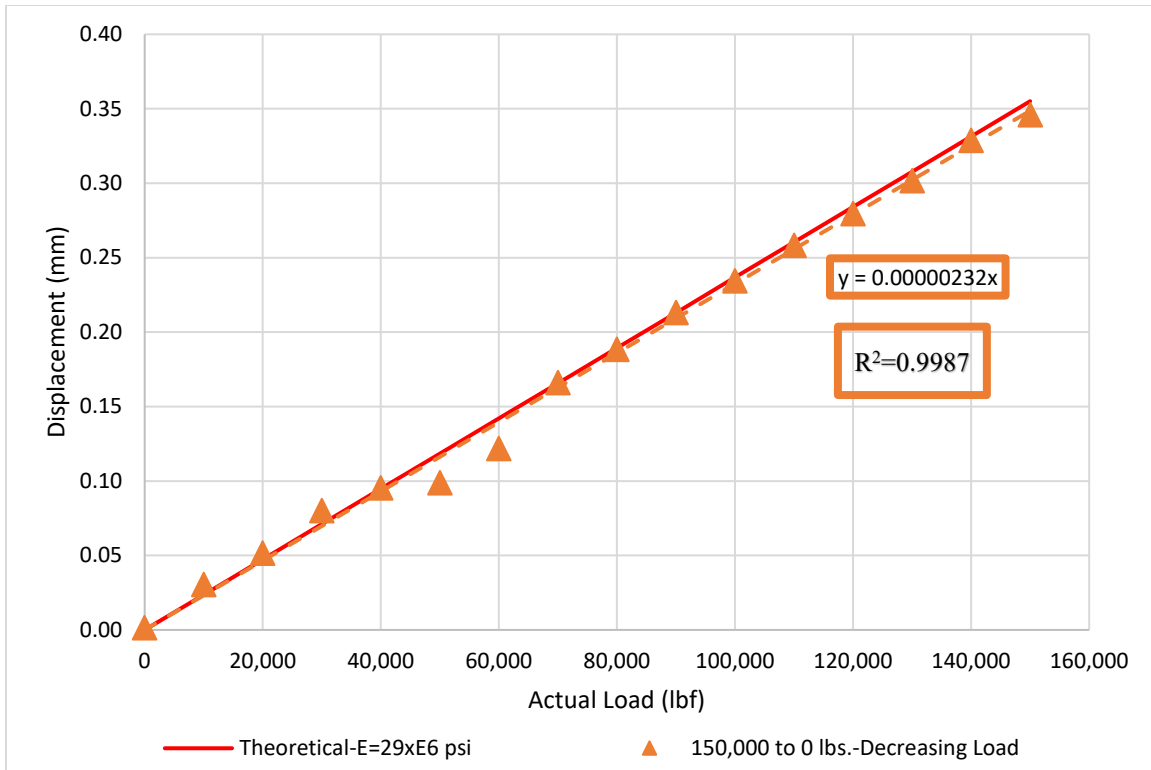


Figure 5.13 Displacement vs. Actual Load for Decreasing Load - Long Rail Section

Looking at the plots in [Figure 5.12](#) and [Figure 5.13](#), it can again be confirmed that the dual camera sensor readings and the theoretical predictions calculated from load cell measurements are in very good agreement. The R^2 values of 0.9997/0.9987 for the trendlines indicate that the data follows a very linear trendline with agreement similar to what was observed for the short rail section. However, a few outlier points do exist. The reason for these is still under investigation, but one reason could be due to bending of the testbed as mentioned in [Appendix C](#).

Once again blind system verification tests were conducted and compared with the above increasing and decreasing load capacity tests. Three blind tests were performed with random settings in the load values. [Figure 5.14](#) shows the theoretical line along with these three blind test results, indicating very good agreement with the test results all falling almost right on the line created by theoretical analysis based on linearly elastic deformation theory. All these results were well within 5% error (actually, 0.66%, 0.22% and 2.16%). This shows that the system is capable

of measuring mechanical tension/load very accurately with just two set of images for displacement measurement. It also suggests that St. Venant's principle[26] has some effects on the stress distribution on the rail structure when the sensor measurement location is close to the clevis pins.

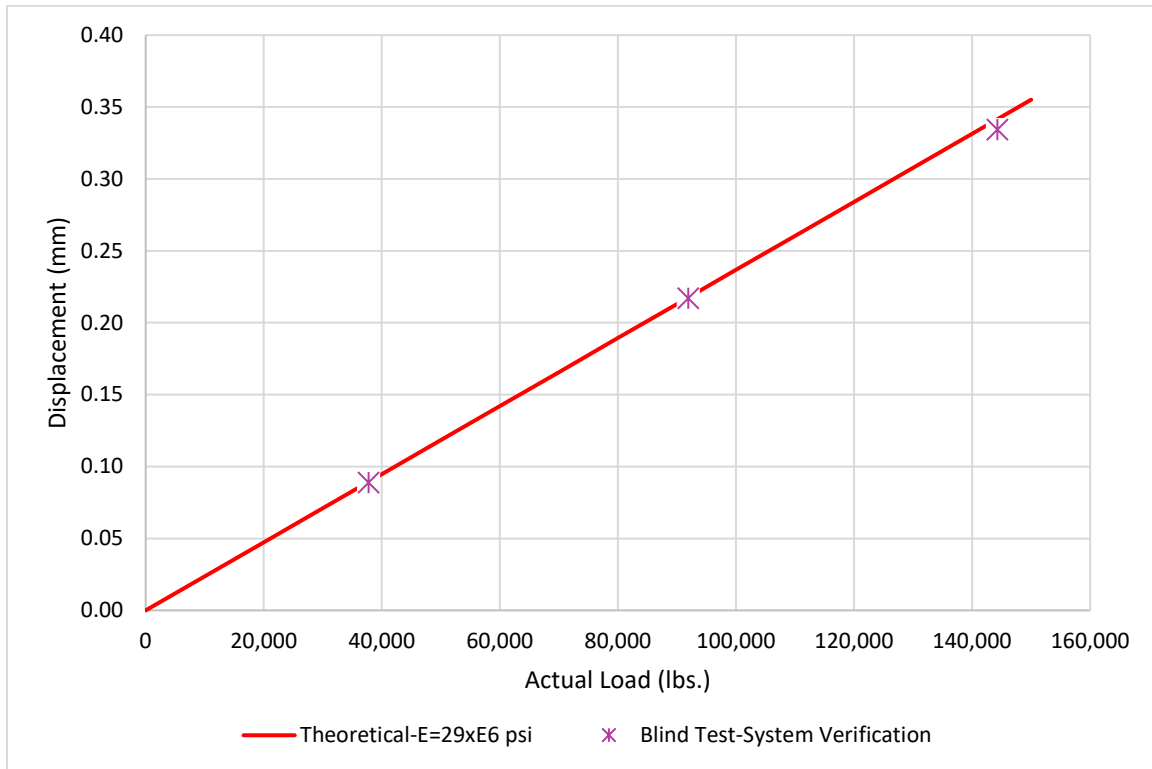


Figure 5.14 Blind Test-System Verification on Long Rail Section

Hence, for accurate measurement of rail strain, it will be important to keep the sensor (and the dot peen patterns) away from the ends of the rail test sections.

Chapter 6 – Thermal Effects on Steel Rail Section-Laboratory

Verification

The goal of the project is to measure RNT of the rail by measuring strain in the rail. To achieve this, preliminary thermal analysis in the laboratory is necessary for the purpose of designing the thermal heating setup for the testbed. The new strain sensor measures total strain in the rail system; that is, the combined mechanical and thermal strain. From this total strain, thermal strain must be removed to get mechanical strain which, in turn, can be converted into rail stress and then the RNT. Prior to getting into the details of the RNT measurement process using the testbed, it is necessary to perform some basic evaluation tests in a controlled manner. For this reason, a small rail section of 17.5” was cut from the 136RE rail section. Preliminary thermal tests/analysis and heat transfer tests were performed on this small rail section in the Non-Contact Precision Measurement (NCPM) lab. The heating of rail on the testbed is going to be achieved by placing an IR heater on one side of the rail web and allowing the rail temperature to equalize before taking strain readings. Some of the key things to establish before the testbed thermal testing can take place are the heat absorption characteristics of the rail, power requirements necessary for heating to achieve steel rail temperatures above ambient temperature, and temperature redistribution within the rail after shutting down the heater. It is desired to establish whether the rail can be treated as a lumped system, total rail heating power and flux requirements, and cooling response time to decide on the strain measurement process using the new strain sensor.

6.1 Biot Number Calculation for Rail

The Biot number (Bi) represents the ratio of conduction thermal resistance in the interior of a slab system to the convective thermal resistance between the surroundings and system surface[65]. This is illustrated in [Figure 6.1](#) for 1D conduction in a rectangular slab.

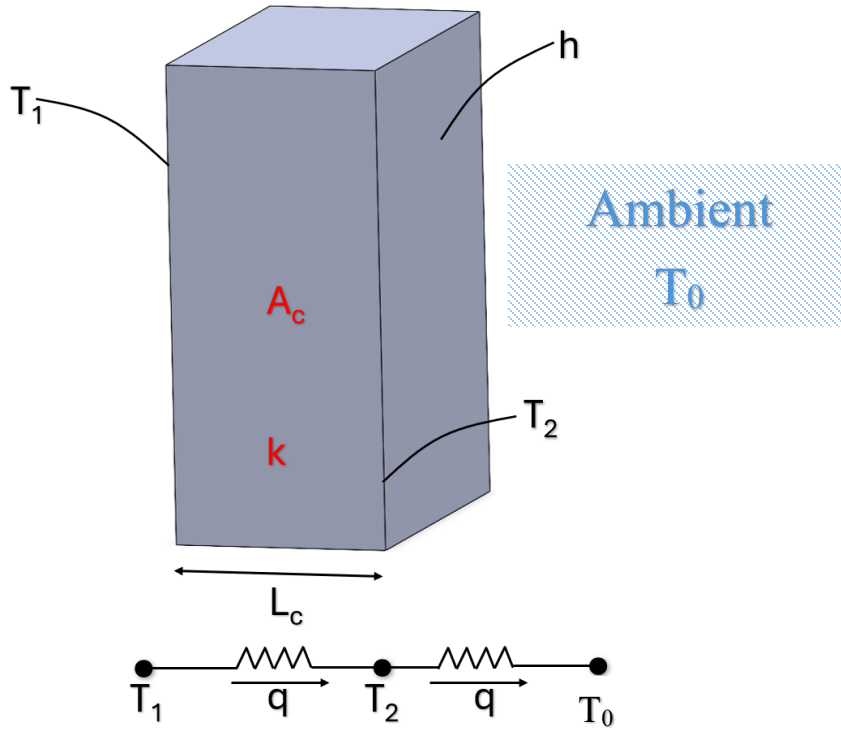


Figure 6.1 Resistance Model for Metal Slab

The rate of heat transfer through a material via conduction is expressed as

$$q \text{ (conduction)} = \frac{kA_c(T_1 - T_2)}{L_c} \quad (6.1)$$

where q is the rate of conduction heat transfer, k is thermal conductivity, A_c is cross-sectional area of the metal slab, $(T_1 - T_2)$ is the temperature difference across the material and L_c is a characteristic (or effective) length for the slab (steel rail).

The rate of convective heat transfer can be expressed as

$$q \text{ (convection)} = hA_c(T_2 - T_0) \quad (6.2)$$

Here q is rate of convection heat transfer, h is the convective heat transfer coefficient, A_c is the surface area from which the heat is transferred to the ambient, and $(T_2 - T_0)$ is the difference between the surface temperature and the ambient temperature.

Writing both the equations (6.1) and (6.2) in terms of temperature differences and dividing yields

$$\frac{(T_1 - T_2)}{(T_2 - T_0)} = \frac{\left(\frac{qL_c}{kA_c}\right)}{\left(\frac{q}{hA_c}\right)} = Bi \quad (6.3)$$

Where Bi is the Biot number defined by

$$Bi = \frac{hL_c}{K} \quad (6.4)$$

where h is the convective heat transfer coefficient, k is the thermal conductivity of the slab material and L_c is a characteristic length (thickness) of the slab.

A low Biot number (typically < 0.1) indicates that minor to negligible temperature gradients exist inside the solid, indicating that the solid behaves approximately like a “lumped system;” justifying the use of a simplified "lumped capacitance" model for the slab temperature response [66,72].

To calculate Biot number using equation (6.3), values for all the quantities including characteristic length of the slab L_c , convective heat transfer coefficient h, and thermal conductivity of the slab material k must be estimated .

The thermal conductivity of carbon steel (k_{steel}) is assumed to be around [67,68]

$$k_{\text{steel}} = 50 \left(\frac{W}{m \cdot K} \right) = 28.89 \left(\frac{BTU}{hr \cdot ft \cdot F} \right) \quad (6.5)$$

The characteristic length of the rail, L_c is expressed as

$$L_c = \frac{V_{\text{body}}}{A_{\text{surface}}} = \frac{A_c L}{P L} = \frac{A_c}{P} \quad (6.6)$$

Here A_c is cross-sectional area of the rail and can be taken from [Figure 4.2](#) , while P is the perimeter of the rail which was calculated from the 3D CAD drawing of the 136RE rail in SolidWorks™.

Substituting values of cross-sectional area and perimeter in equation (6.6),

$$L_c = \frac{13.32}{27.56} = 0.4833 \text{in} \quad (6.7)$$

An approximate value used for natural convection heat transfer coefficient (h) is,

$$h = 2 \left(\frac{BTU}{hr \cdot ft^2 \cdot F} \right) \quad (6.8)$$

Substituting all the values from equations (6.5), (6.7), and (6.8) in equation (6.4) yields

$$Bi = \frac{0.4833 \text{ in} \times 2}{28.89} = 0.00279 (\lll 0.1) \quad (6.9)$$

The Biot number is very small, and it should be reasonable to consider the rail section as a lumped system.

6.2 Rail Transient Temperature Response

Since the heating of the rail will be conducted on one side of the web as mentioned in the beginning of this chapter, and the measurements will be made on the other side of the web, it is necessary to know after what time the temperature distribution across the web will be stabilized.

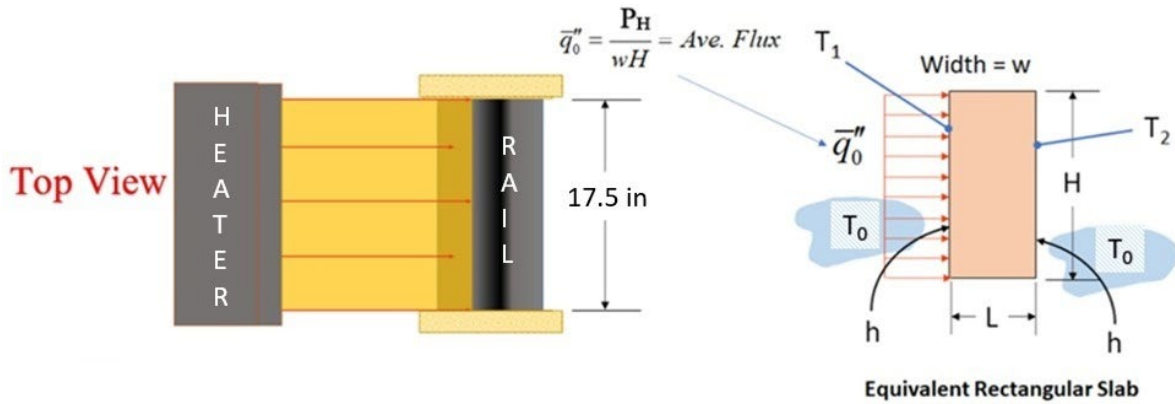


Figure 6.2 Rail Considered Equivalent to a Rectangular Slab-Lumped Response

[Figure 6.2](#) shows top view of a rail section with IR heater heat flux radiating on it. On the right side, the equivalent rectangular slab is shown to represent the rail section because it was determined by a low Biot number that the rail section can be assumed as lumped system.

The equation to calculate an approximate penetration time (t_L) for the conduction with a step change in applied heat flux using integral analysis is [\[70\]](#),

$$t_L = \left(\frac{L_{\text{eff}}^2}{6\alpha_T} \right) \quad (6.10)$$

Where L_{eff} is the effective length of the slab, or in other words the effective thickness of the steel rail under consideration as shown in [Figure 6.2](#), and α_T is the thermal diffusivity.

The specific heat capacity (C_p) for carbon steel is approximately[[69](#)],

$$C_p = 470 \left(\frac{\text{J}}{\text{Kg.K}} \right) = 0.112 \frac{\text{BTU}}{\text{lb.F}} \quad (6.11)$$

The density of steel (ρ) is assumed to be,

$$\rho = 7850 \left(\frac{\text{Kg}}{\text{m}^3} \right) = 0.284 \frac{\text{lb.}}{\text{in}^3} = 490.75 \frac{\text{lb.}}{\text{ft}^3} \quad (6.12)$$

Calculation of the thermal penetration time requires the thermal diffusivity (α_T) which is

$$\alpha_T = \left(\frac{k_{\text{steel}}}{\rho C_p} \right) \quad (6.13)$$

Substituting values from equations (6.5), (6.11) and (6.12) yields,

$$\alpha_T = \left(\frac{50}{7850 \times 470} \right) = 1.35 \times 10^{-5} \left(\frac{\text{m}^2}{\text{s}} \right) \quad (6.14)$$

Calculation of the effective length, L_{eff} , requires the cross-sectional area of the rail A_c and height of the slab H , which can be taken from [Figure 4.2](#) yielding

$$L_{\text{eff}} = \frac{A_c \text{ (cross-sectional area)}}{H \text{ (height of an equivalent slab)}} = \frac{13.32}{7.3125} = 1.82 \text{ inch} = 0.046 \text{ m} \quad (6.15)$$

Substituting values from equations (6.14) and (6.15) into (6.10) yields for the diffusion time

$$t_L = \left(\frac{0.046^2}{6 \times 1.35 \times 10^{-5}} \right) = 26.123 \text{ seconds or } 0.435 \text{ mins} \quad (6.16)$$

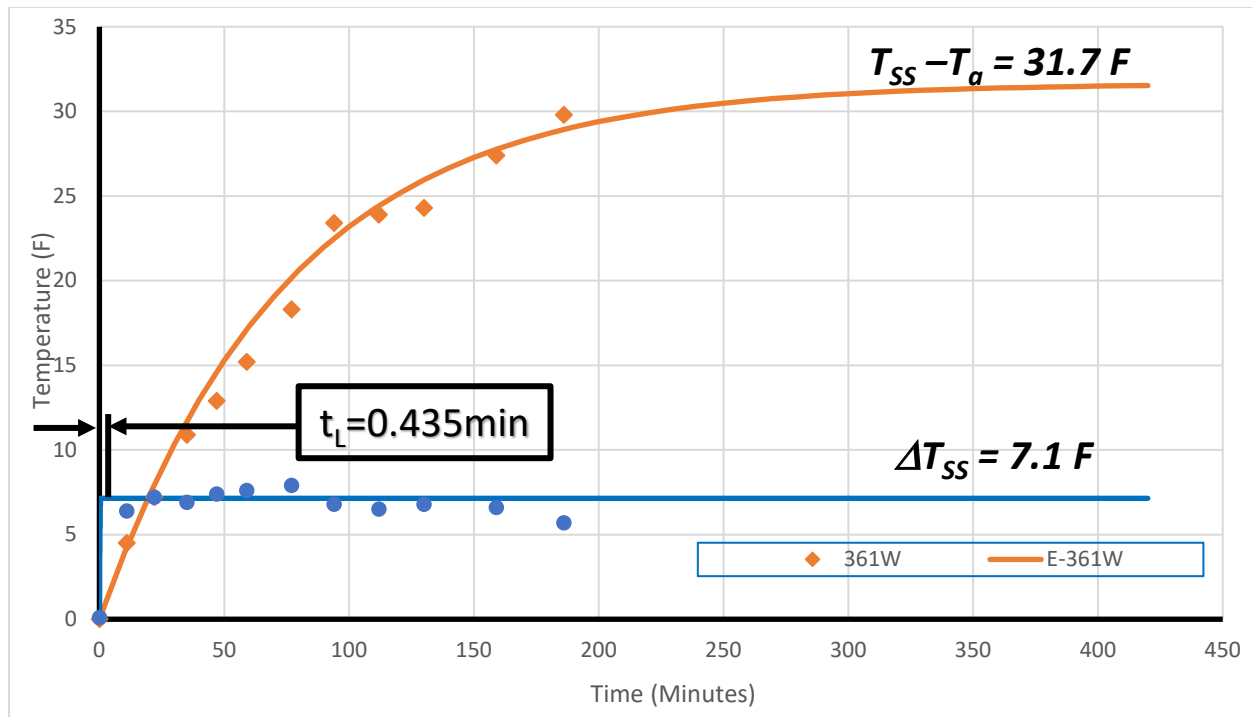


Figure 6.3 Temperature vs. Time Plot Showing Penetration Time and Average Delta

Across Surface

It was critical to calculate the penetration time to understand the nature of the rail temperature difference response. The effective penetration time (t_L) is approximately 0.435mins which indicates that the rail would not take very long to get a stable temperature difference across the web once the heating is turned on. This number also indicates that the rail has a very quick temperature redistribution response as is also shown graphically in [Figure 6.3](#).

In addition to the penetration time, it is necessary to know the steady state temperature difference between opposite sides of the web when the heater is only heating from one side. [Figure 6.4](#) shows the effective time after which the temperature difference across the web will be constant until the heating is stopped. After the heating is turned off, the temperature will rapidly begin equalizing across the rail.

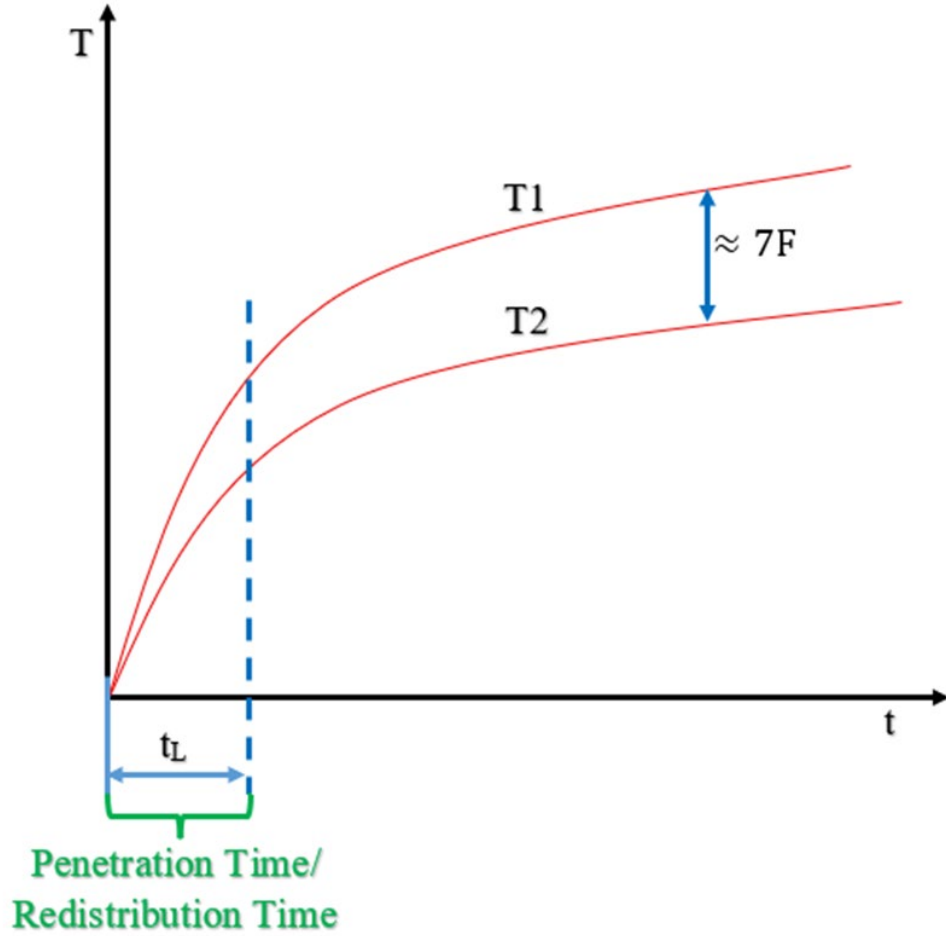


Figure 6.4 Temperature Difference after Penetration Time is Achieved

As shown in [Figure 6.2](#), considering the rail as a conducting slab, the steady state temperature difference can be shown to be

$$\Delta T_{ss} = \frac{q''_{0ave} L_{eff}}{2k} \quad (6.17)$$

q''_{0ave} is the average absorbed radiant heat flux into the surface, L_{eff} is effective slab thickness in [Figure 6.2](#) and k is thermal conductivity of steel.

The resistance of the small commercial heater used (R_H) was 14.ohm (14Ω) and voltage supplied to the heater (V) was 99.5 volts for the test shown in [Figure 6.3](#). Power supplied to the heater (P_H) can be calculated as follows:

$$P_H = \frac{V^2}{R_H} \quad (6.18)$$

Substituting values of resistance and voltage in equation (6.18) yields

$$P_H = 707.16 \text{ W} \quad (6.19)$$

From [Figure 6.2](#), height of the heater/vertical distance of the flux hitting the slab (a) is 4.5 inches and, the length of the heater/horizontal distance of the flux hitting the slab (b) is 17.5 inches. Total area for heat flux on the equivalent slab (A_H) is

$$A_H = a \times b \quad (6.20)$$

Substituting values of height of the heater (a) and length of the heater (b) in the equation (6.20), yields

$$A_H = 4.5 \times 17.5 = 78.75 \text{ in}^2 = 0.051 \text{ m}^2 \quad (6.21)$$

The actual heat flux is required to calculate average radiant heat flux and is given by

$$q''_0 = \frac{P_H}{A_H} \quad (6.22)$$

Substituting values from equations (6.19) and (6.20) in above equation (6.22) yields,

$$q''_0 = 1.392 \times 10^4 \frac{\text{W}}{\text{m}^2} \quad (6.23)$$

The average absorbed radiant heat flux into the surface is expressed as

$$q''_{0_{ave}} = \frac{q''_0 a}{H} \quad (6.24)$$

Where the height of the rail section/equivalent rectangular slab (H) is 7.313 inches as noted in [Figure 4.2](#). Substituting values for individual quantities into the above equation (6.24), yields

$$q''_{0_{ave}} = \frac{1.392 \times 10^4 \times 0.1143}{0.186} = 8.565 \times 10^3 \quad (6.25)$$

To calculate the steady state temperature difference, values from equations (6.5), (6.15) and (6.25) are substituted into equation (6.17) yielding

$$\Delta T_{ss} = \frac{8.565 \times 10^3 \times 0.046}{2 \times 50} = 3.94\text{k or } 7.1^\circ\text{F} \quad (6.26)$$

This calculation indicates that while the heater is on and heating one side of the web, the temperature difference across the web surface on opposite sides of the rail will be about 7.1°F until the heater is turned off. This is graphically represented in [Figure 6.3](#).

6.3 Transient Heating and Cooling

Prior to testing the longer rail section on the testbed, it was very important to perform basic small-scale laboratory testing on a rail section to understand the overall heating and cooling response characteristics. To complete this utmost necessary step, a rail section of 17.5” (inches) was set up on a support as shown in [Figure 6.5](#) with the small 1500W commercial heater. The setup was unique and adjustable in terms of vertical and horizontal movement of the heater with respect to the rail section to provide various heater flux conditions. In addition to providing minimal heat conducting line (steel angle) supports for the rail underneath, two concrete slabs were put on each end of the rail to reduce heat loss to the surroundings; thus creating a “per unit length” similarity between long CWR in the field and the small lab rail section.

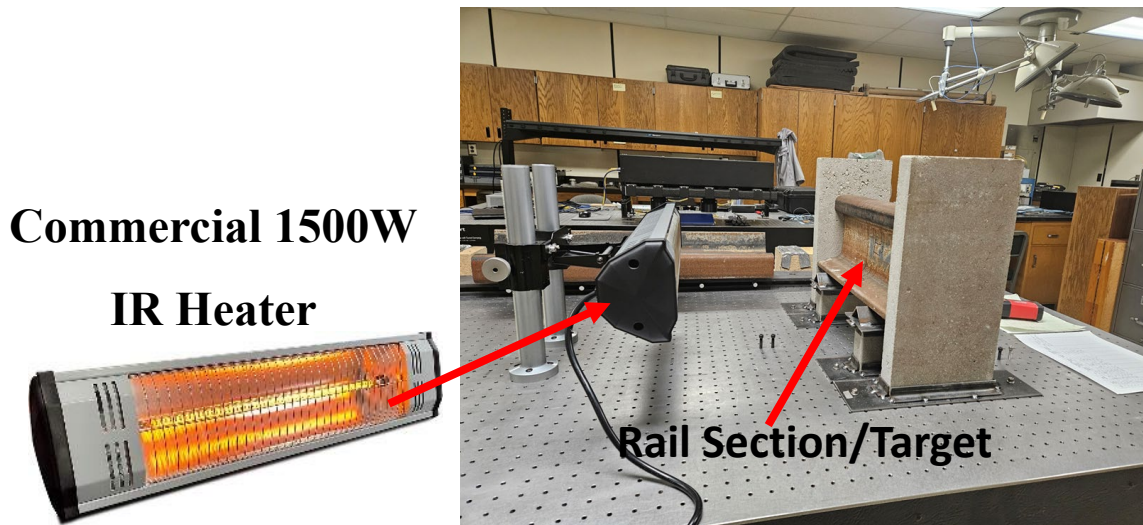


Figure 6.5 Transient Heating of a 17.5” Rail Section

It was assumed that all the power (P_H) coming from the heater was fully absorbed by the rail. A schematic is shown in [Figure 6.6](#) which indicates the rail setup, heater projection area on the rail, and equivalent rectangular slab representing a rail.

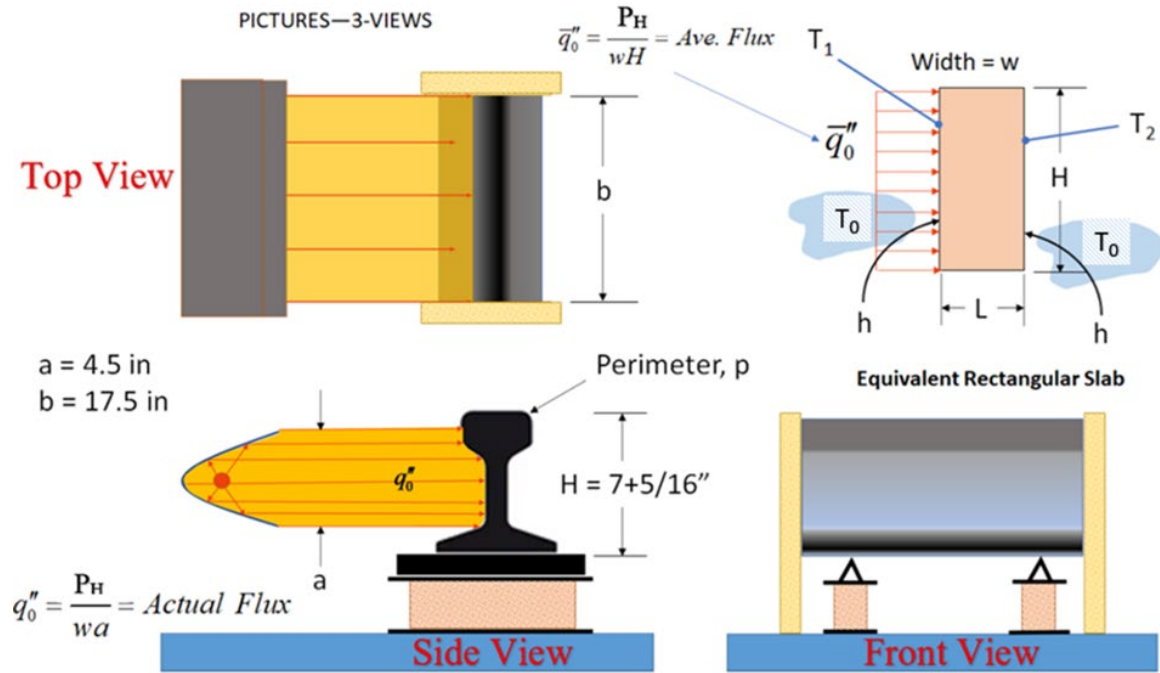


Figure 6.6 Radiation from Heater on Rail and Equivalent Rectangular Slab

A first order ordinary differential equation can be formulated to describe the transient (lumped) thermal behavior of the equivalent rectangular slab shown in [Figure 6.6](#). The basic expression is derived from the first law of thermodynamics, specifically the principle of energy conservation, applied to a control volume (equivalent rectangular slab) experiencing external heat transfer. It basically shows that the rate of internal energy storage (left hand side of equation 6.27) within the control volume (CV) is equal to the net rate of heat transfer into the CV (right side of the equation 6.27)[72]. This is expressed as

$$M C_p \frac{dT}{dt} = P_H - h P L (T - T_0) \quad (6.27)$$

Where M is mass of the slab, C_p is the constant pressure specific heat, $\frac{dT}{dt}$ is the rate of change of the slab temperature, P_H is power input to the CV, h is the convective heat transfer coefficient, P is perimeter of the rectangular slab, and L is length of the rectangular slab.

The mass can also be expressed as

$$M \text{ (mass)} = \rho V = \rho A_c L \quad (6.28)$$

where ρ is density of the material, A_c is cross-sectional area of the material, L is length of the material and V is volume of the slab.

For steady-state conditions, the temperature is represented as (T_{ss}) and there is no change in temperature over time. Hence,

$$\frac{dT}{dt} = 0 \quad (6.29)$$

Substituting values from equations (6.29) in equation (6.27) for steady-state conditions yields,

$$0 = P_H - h P L (T_{ss} - T_0) \quad (6.30)$$

Here T was replaced by T_{ss} because it is assumed that the system is in a steady-state condition.

Perimeter x Length ($P \times L$) can be substituted with A_s . Thus

$$P_H = h P L (T_{ss} - T_0) = h A_s (T_{ss} - T_0) \quad (6.31)$$

Substituting the expression for P_H from equation (6.31) into equation (6.27) yields

$$\rho \cdot A_c \cdot L C_p \frac{dT}{dt} = h A_s (T_{ss} - T) \quad (6.32)$$

Now, define a variable term θ representing temperature difference at a specific time t . Thus

$$\theta = T_{ss} - T(t) \quad (6.33)$$

Differentiating this variable with respect to time t yields

$$\frac{dT}{dt} = - \frac{d\theta}{dt} \quad (6.34)$$

Substituting equation (6.34) in equation (6.32) and rearranging yields

$$\frac{\rho.A_c.L C_p}{h A_s} \left(-\frac{d\theta}{dt} \right) = \theta \quad (6.35)$$

The term $\frac{\rho.A_c.L C_p}{h A_s}$ represents the lumped system time constant for the response and is denoted by

τ , where

$$\tau = \frac{\rho.A_c.L C_p}{h A_s} \quad (6.36)$$

Substituting the time constant from equation (6.36) in equation (6.35) yields

$$\tau \frac{d\theta}{dt} = -\theta \quad (6.37)$$

Solving this ordinary differential equation (6.37) yields

$$\theta(t) = C_1 e^{-\frac{t}{\tau}} \quad (6.38)$$

Where C_1 is an arbitrary constant term.

Applying initial conditions to equation (6.33) at time $t=0$, gives

$$\theta(t)|_{t=0} = T_{ss} - T(t)|_{t=0} = T_{ss} - T_0 \quad (6.39)$$

Substituting equation (6.38) into equation (6.39) yields the constant term C_1

$$\theta(t)|_{t=0} = C_1 = T_{ss} - T_0 \quad (6.40)$$

Substituting C_1 from equation (6.40) in equation (6.38) yields

$$\theta(t) = (T_{ss} - T_0) e^{-\frac{t}{\tau}} \quad (6.41)$$

Substituting equation (6.33) in equation (6.41) yields

$$(T_{ss} - T(t)) = (T_{ss} - T_0) e^{-\frac{t}{\tau}} \quad (6.42)$$

Rearranging terms in equation (6.42) gives

$$\frac{(T_{ss} - T(t))}{(T_{ss} - T_0)} = e^{-\frac{t}{\tau}} \quad (6.43)$$

The equation (6.43) can also be expressed in dimensionless form as follows:

$$\ln \left(\frac{(T_{ss} - T(t))}{(T_{ss} - T_0)} \right) = -\frac{t}{\tau} \quad (6.44)$$

Rail Temperature Response to IR Heating:

To measure the rail temperature response time for heating with the IR heater, and to determine the wattage requirements for the heater to be used on the longer rail section during full-scale testing, the small commercial heater shown in [Figure 6.5](#) was used on the small 17.5” rail section. This testing helped understand the power requirements before purchasing a heater for actual full-scale strain testing with new strain sensor.

To perform this test, a variac (variable ac transformer) was used to change the supplied voltage to the commercial heater. This changed the IR heat output for testing the power requirements needed to produce a desired temperature rise within a reasonable amount of time. The difference between recorded temperature and ambient temperature was plotted versus time. As seen in [Figure 6.7](#), the temperature difference (or rise) curve starts flattening as time increases, which means that continuing to supply the same power will eventually bring the rail to a final steady state temperature. In other words, it can also be said that increasing power supplied to the rail for a fixed amount of time will give increasingly elevated temperatures above the ambient.

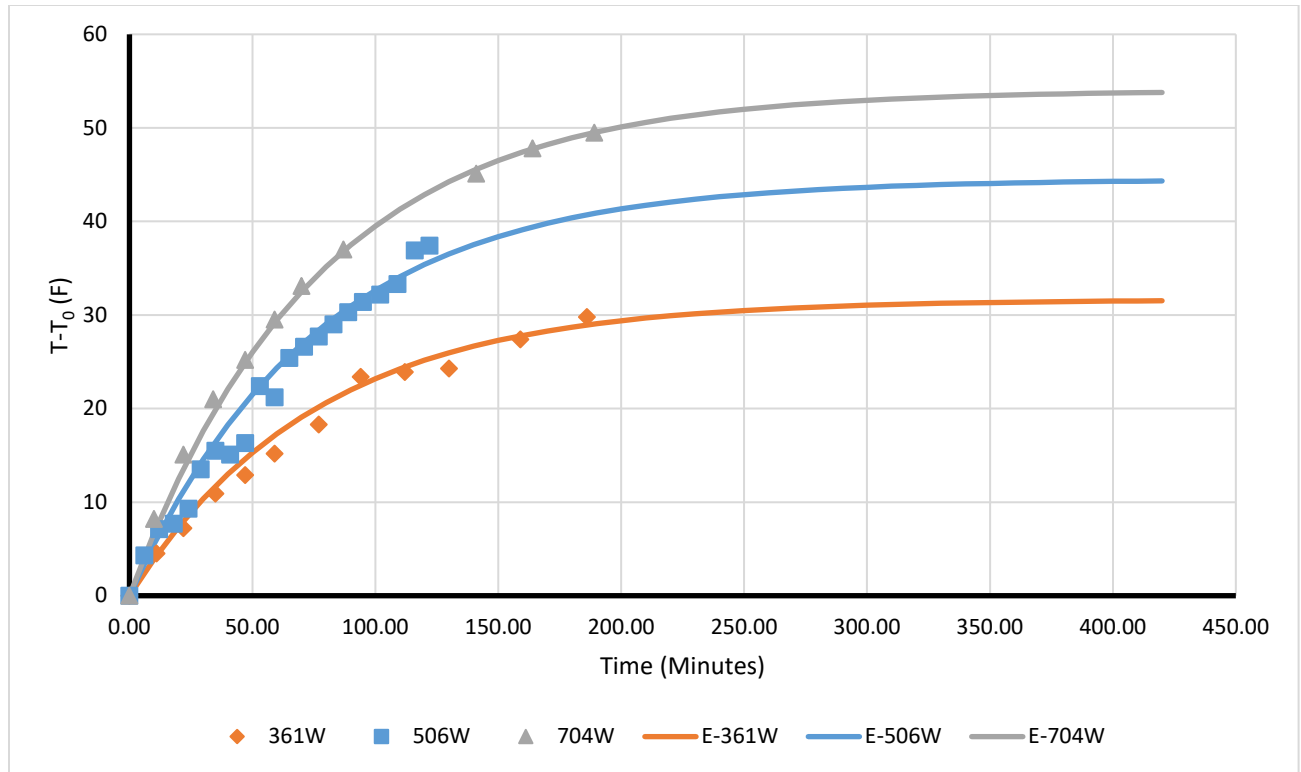


Figure 6.7 Temperature Difference vs. Time Plot for Different Power Supplied to IR Heater

A curve fit was created using the previously developed transient temperature analysis and it is shown in [Figure 6.8](#). The plot confirms that the simple lumped system theory given in equation (6.44) consolidates the plotted data points for all the different powers in [Figure 6.7](#), into a single straight line. Trendline slopes for each of the power levels are shown in [Figure 6.8](#) to be exactly the same, indicating that the time constant is same in all three power level heating situations.

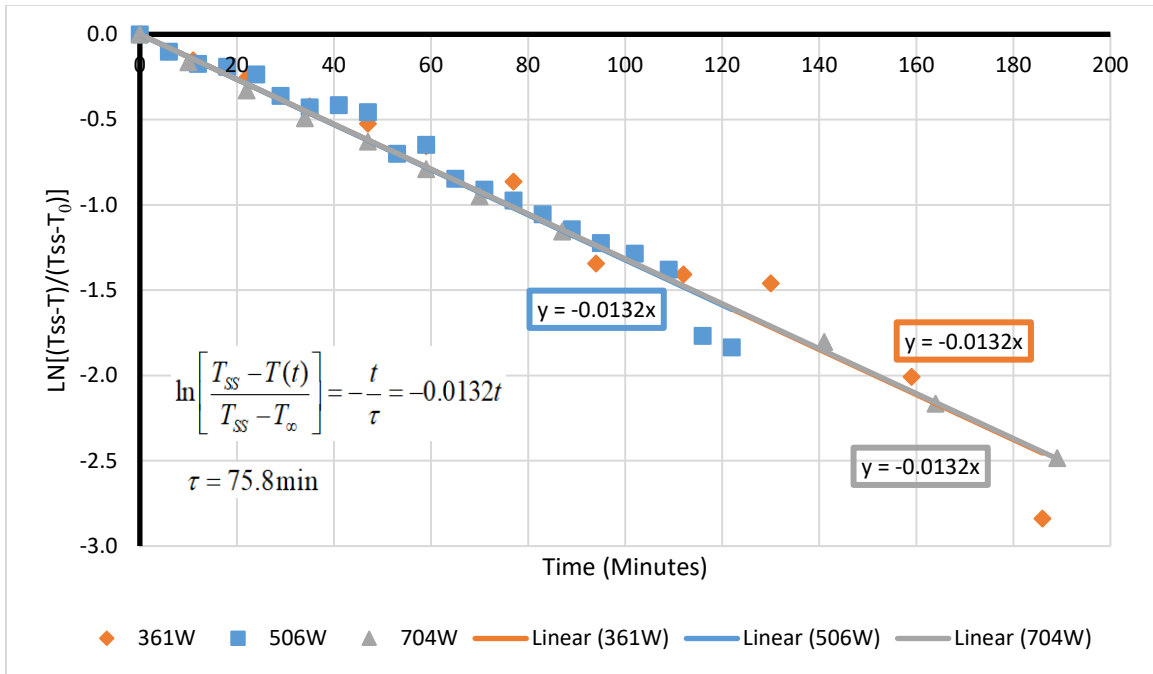


Figure 6.8 Combined Curve Fit for Transient Lumped Analysis with Different Power Levels

A combined plot was created for the difference in temperature $T_{ss}-T_0$ versus heater power to estimate the required power to achieve approximately 50°F temperature rise above ambient.

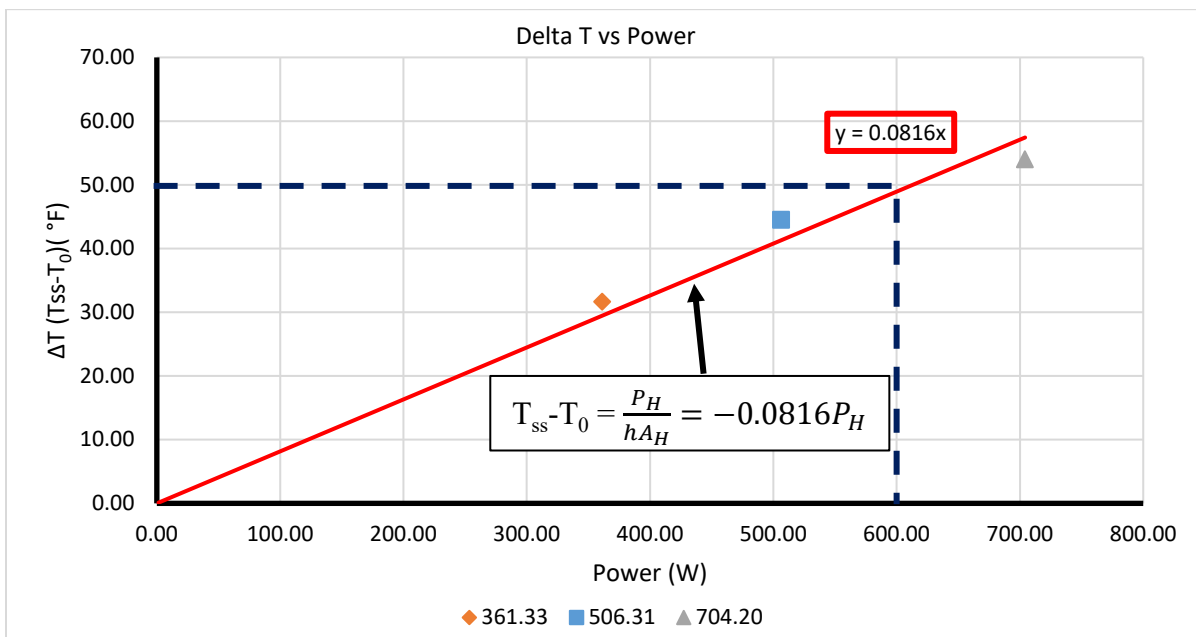


Figure 6.9 Estimation of Power Requirements for Thermal Loading of a Rail

The linear temperature rise with increasing power given in [Figure 6.9](#) shows that the power requirement would be around 600Watts if the temperature of the rail is to be increased by about 50 F from ambient.

An effective convective heat transfer coefficient (h) can be determined using equation (6.36) for the lumped system time constant, along with the value of time constant calculated in [Figure 6.8](#), yielding

$$\tau = \frac{\rho \cdot A_c \cdot L \cdot C_p}{h A_s} = \frac{\rho \cdot A_c \cdot L \cdot C_p}{h P L} = \frac{\rho \cdot A_c \cdot C_p}{h P} \quad (6.45)$$

Rearranging terms in equation (6.45) to calculate the effective convective heat transfer coefficient, gives

$$h = \frac{\rho \cdot A_c \cdot C_p}{\tau P} \quad (6.46)$$

As the rail is made of high carbon steel, using the high carbon steel density value from equation (6.12) and the specific heat from equation (6.11) yields

$$h = \frac{490.75 \times 0.0925 \times 0.112}{75.8 \times 2.297} = 1.7520 \left(\frac{\text{BTU}}{\text{ft}^2 \cdot \text{hr} \cdot \text{F}} \right) \approx 10 \left(\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \right) \quad (6.47)$$

The value of h, the convective heat transfer coefficient, is approximately the same as assumed in equation (6.8) for the earlier Biot number calculations. Hence, it can be concluded that the Biot number and the assumption made to consider rail as lumped system holds true. Also, the value convective heat transfer for air is indeed about $10 \left(\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \right)$.

Transient Cooling of the Rail:

Rail cooling temperature data was also recorded and used to calculate the transient cooling response of the rail and to extract an equivalent response time constant. Temperatures at three different locations on the rail were measured during cooling, to check the cooling rate of the overall

rail section over a period of about three hours. [Figure 6.10](#) shows the temperature response at all three rail positions along with a curve fit through the data.

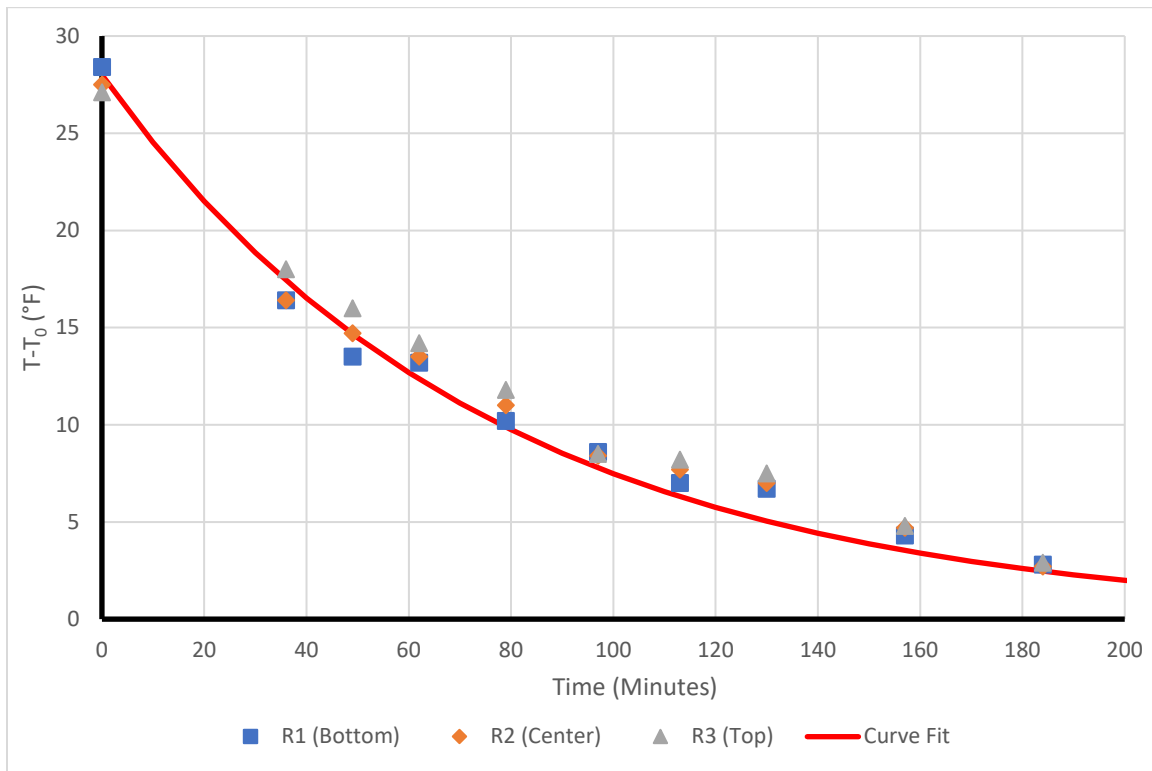


Figure 6.10 Transient Cooling Curve for Rail Section

A linear trendline fit was generated for corresponding dimensionless cooling response. As shown in [Figure 6.11](#), the resulting time constant is around 82.6 minutes, which is quite close to the previously determined time constant of about 75.8 minutes determined from the rail heating response.

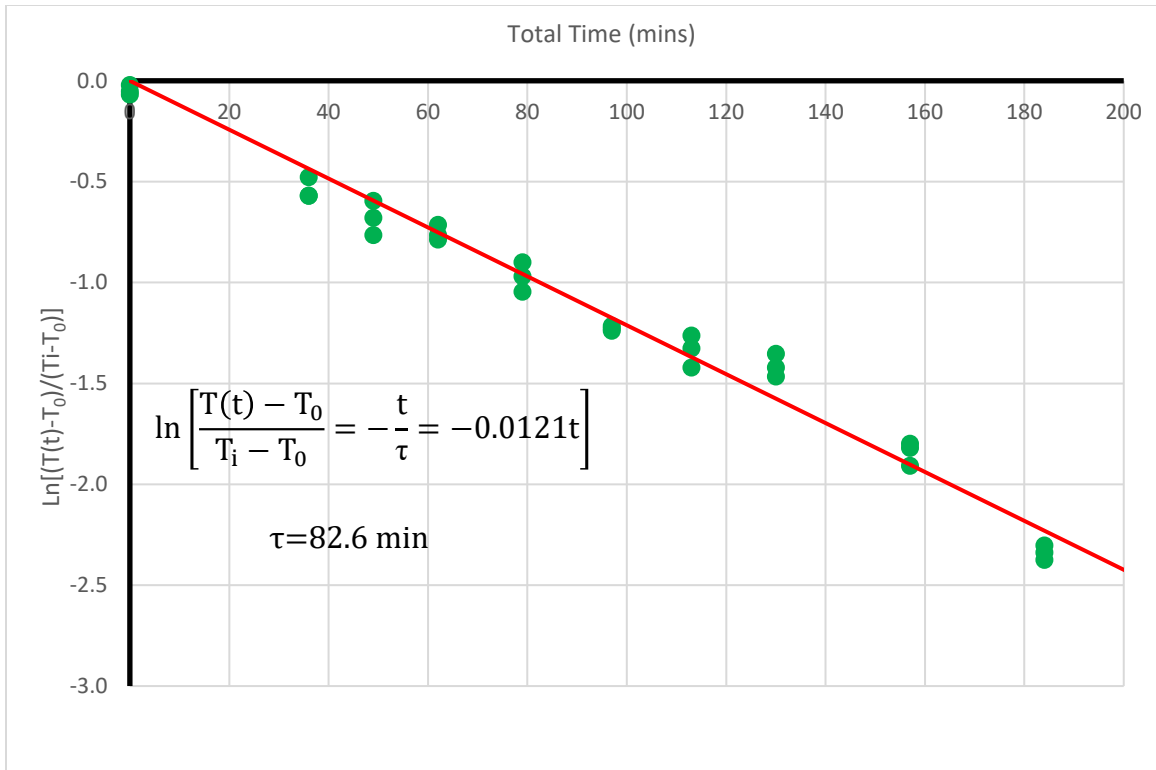


Figure 6.11 Curve Fit for Transient Cooling Data

6.4 Simple Convective Cooling/Time Constant

An important entity controlling the waiting time before starting to obtain strain readings on the steel rail is the time constant. The time constant is also very important to the current dissertation work because it controls the amount of time that will be available to make strain measurements on the surface of the rail during cooling, without appreciable rail temperature change.

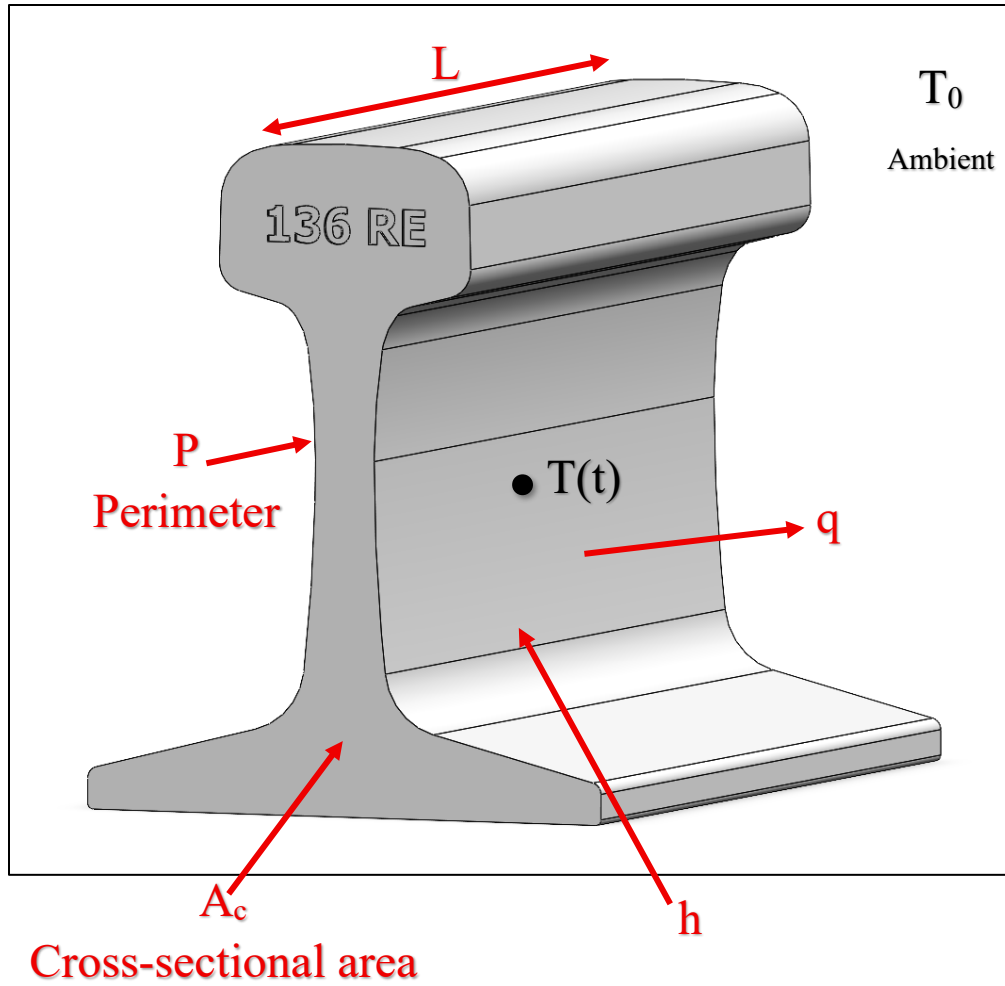


Figure 6.12 136RE Rail Section 3D View

[Figure 6.12](#) shows a rail section with various rail parameters marked including the rail temperature at a particular time, t . The convective heat transfer rate is denoted by q and is also shown in [Figure 6.12 \[72\]](#).

$$q = h P L (T - T_0) \quad (6.48)$$

It was shown earlier that the rail can be treated as a lumped system. Based on conservation of energy (1st law of thermodynamics), the rate of change of thermal energy stored in the body (rail) is equal to the rate of convection heat transfer between the body and its ambient.

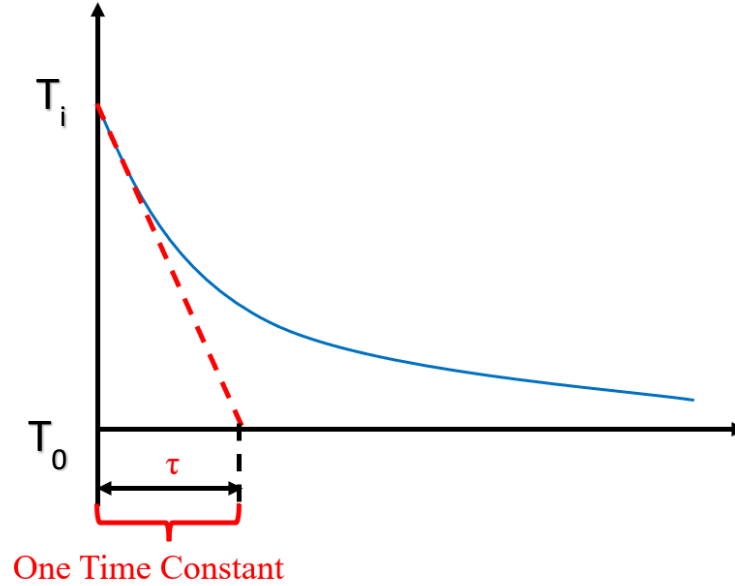


Figure 6.13 One Time Constant

[Figure 6.13](#) illustrates the graphical meaning of one time constant, which represents the amount of time it will take an object (lumped rail system) to reach ambient temperature if the rate of cooling stays the same from beginning to end of the cooling process. It is defined by the 1st order ordinary differential equation given in equation (6.49) [\[72\]](#).

$$M C_p \frac{dT}{dt} = -h P L (T - T_0) \quad (6.49)$$

Where M is mass of the body, C_p is constant pressure specific heat, $\frac{dT}{dt}$ is the rate of change of temperature, h is the convective heat transfer coefficient, P is the perimeter of the rail section, and L is length of the rail.

Following same process used in going from equation (6.28) to equation (3.36), results in a similar expression for the lumped system time constant (τ),

$$\tau = \frac{\rho \cdot A_c \cdot C_p}{hP} \quad (6.50)$$

Parameters required for evaluating τ include the high carbon steel density from equation (6.12), specific heat from equation (6.11), and the convective heat transfer coefficient from equation (6.47). A_c ($13.32 \text{ in}^2 = 0.0925 \text{ ft}^2$) is the cross-sectional area of the rail taken from [Figure 4.2](#), and P ($27.56 \text{ in} = 2.297 \text{ ft}$) is the perimeter of the rail. Substituting all these values into equation (6.50) yields

$$\tau = \frac{490.75 \times 0.0925 \times 0.112}{1.7520 \times 2.297} = 1.26 \text{ hours} = 75.6 \text{ min} \quad (6.51)$$

Which is essentially the same value determined earlier in this Chapter. The calculated time constant for cooling indicates that the rate of cooling is very slow (because of natural convection). Therefore, there will be more time to take readings while the rail is slowly cooling, before any appreciable temperature change.

6.5 IR Transient Heating – Slit Test to Determine Longitudinal Temperature Distribution

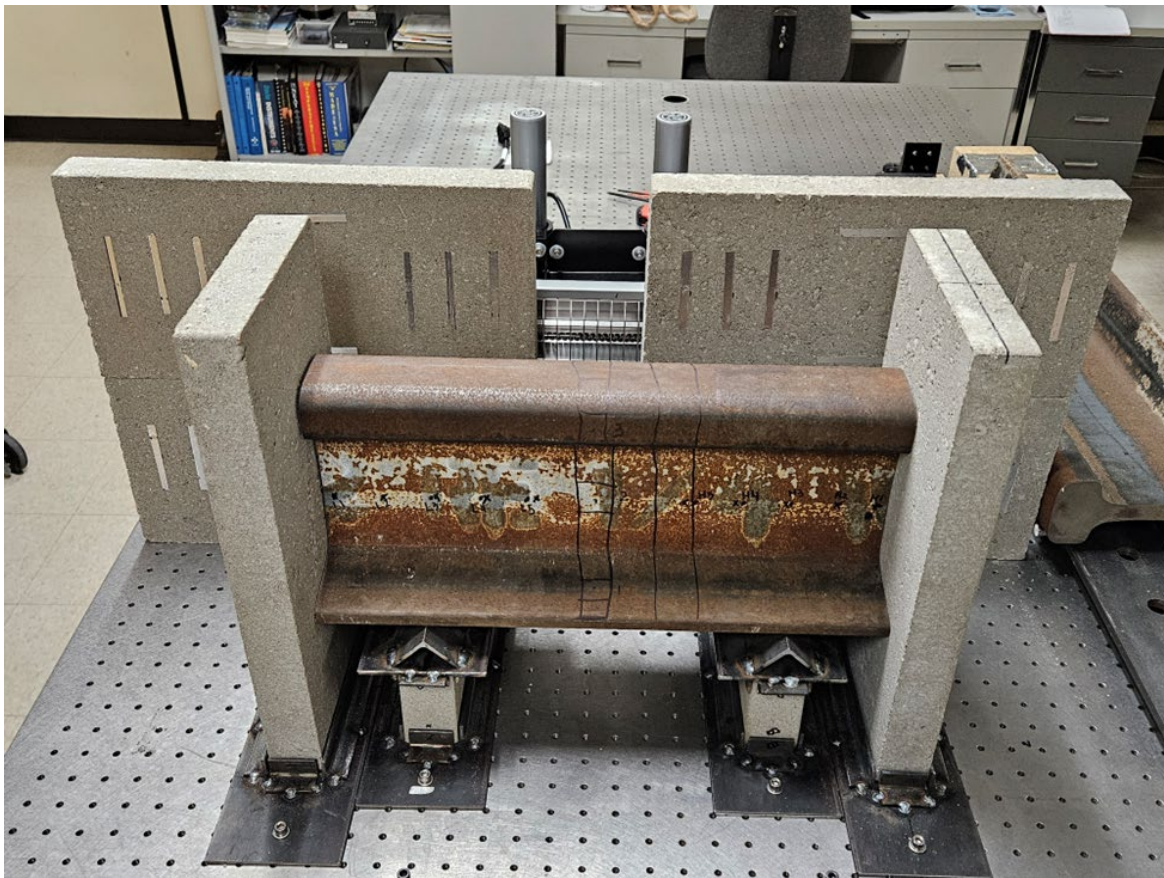
The full-scale testbed rail testing involves heating a section of rail in the middle, or in an area which will only be partially exposed to an IR heater. Once the desired elevated temperature level has been reached, the rail will then be allowed slowly cool. Initially, after power shutdown during full-scale tests, time will be given for the rail temperature to redistribute prior to initiation of sensor strain measurements. But the question is, how fast will the temperature redistribute over the entire length of the rail, in comparison to the rapid redistribution across the thickness of the rail? To answer this question, a test in the laboratory with the smaller 17.5” rail section was performed using the small commercial heater, as shown in [Figure 6.14](#) (a), (b) and (c).



(a) Front View



(b) Back View



(c) Angled Front View

Figure 6.14 Slit Testing Setup

This test can also be imagined as a slit test in which only a portion of the rail is exposed directly to the IR heater radiation. Heat loss from the outer ends of the rail was blocked by bricks,

representing an approximately adiabatic barrier. For this test, a slit of 4" was kept open between two brick walls, as shown in [Figure 6.14](#) (b) and (c), which kept all but a fraction of the IR heater radiation from reaching the back surface of the rail section. The heater was turned on, and the rail was heated until the rail was about 25 F degrees above the approximately 70F ambient temperature. Then the heater was turned off, and temperature measurements were taken using a handheld IR thermometer at 13 approximately equally spaced points along the web of the rail. These points were recorded to provide insight into the spread (redistribution) of the rail temperature over the length of the rail section after heater shutdown. There were 10 set of data measurements taken at regular intervals of time for around 80 minutes in total, until the rail temperature had cooled down close to ambient temperature.

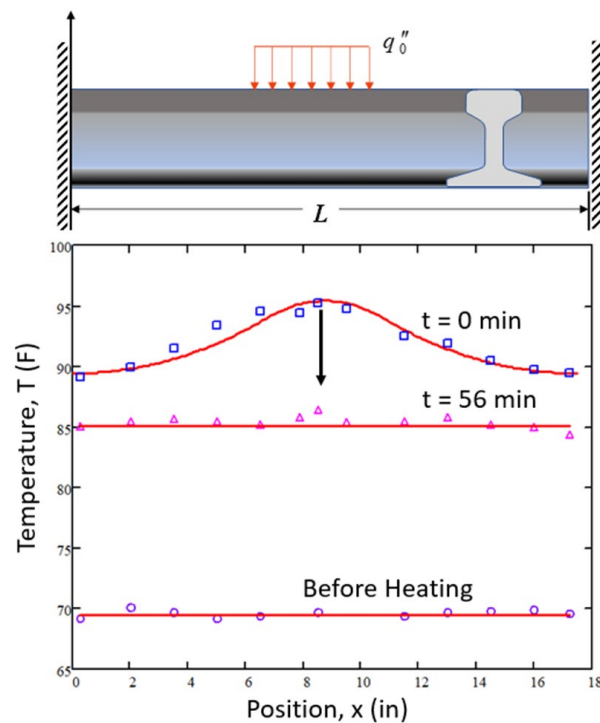


Figure 6.15 Time Required for Longitudinal Rail Temperature Redistribution

[Figure 6.15](#) shows the measured longitudinal rail temperature distribution at three separate times during cooling; one for the initial ambient conditions, and the other two for elevated

temperatures at different times. Curve fits were generated for each temperature distribution, clearly indicating the temperature trending down and spreading out longitudinally along the rail section. For this short rail section with the initial bell-shaped temperature distribution, it took approximately 56 mins for the temperature to redistribute over the entire length of the rail. It should be noted that this is much slower than the time required for the thermal penetration across the thickness of the rail.

6.6 IR Rail Heating/Power Requirements

It was very important to determine the total power required to heat up the full-scale sections of rail to desired temperature levels, in addition to how long the heating process would take. The design of the IR heater required estimation of the levels of heating required to raise the temperature of the rail significantly from ambient. Additionally, the heating time required should be reasonable, and the selected heater must cover the area of the rail to create a reasonably uniform heating pattern. Below is an attempt to estimate the steady-state power requirements to heat up a 147” section of steel rail.

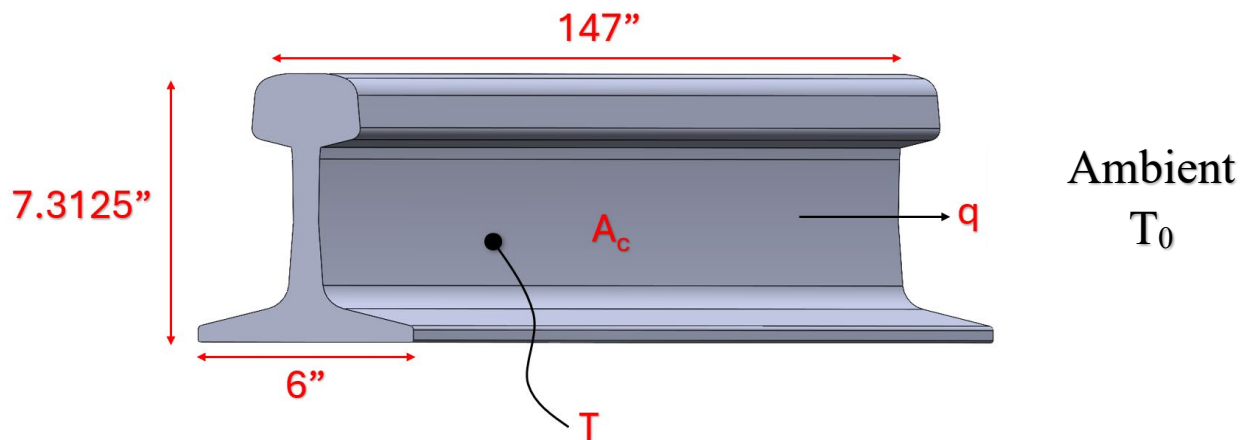


Figure 6.16 Rail Section for Mechanical and Thermal Loading Test

The rate of convective heat loss from a section of rail is denoted by q and is shown in the [Figure 6.16 \[72\]](#).

$$q \text{ (rate of heat transfer)} = h P L (T - T_0) \quad (6.52)$$

where (h) is convection heat transfer coefficient previously estimated in equation (6.47). P is the perimeter of the rail, 27.56 in (0.7 m), and L is length of the long rail section used here for estimation purposes, 3.73m (147 in).

The railway rail in the field can get really hot and the temperatures can reach up to 158 °F (70 °C)[[47](#)]. For calculation purposes here, assuming the temperature of the rail needs to be raised to this level, then T will be about 158 °F (70 °C). The ambient temperature, T_0 , is assumed to still be about 68 °F (20 °C). Substituting all the above values in equation (6.52) yields

$$q = (10) \times (0.7 \times 3.73) (70 - 20) = 1300 \text{ W} \quad (6.53)$$

Equation 6.53 indicates that, if all the power from the heater is absorbed into the rail surface, a minimum of about 1300Watts of IR heater power will be required to raise the temperature of the rail by 50 °C. However, as mentioned, this is only if all the power from heater reaches the rail surface and is fully absorbed by rail. There are losses incurred in the open air, the IR heater radiation tends to spread out when transmitting through the air, and also the rail may not absorb all the heat depending on the surface characteristics. To make up for all these losses and to avoid any heating issues while testbed testing, a heater with higher power ratings (4000Watts) was selected for use with the full-scale testbed testing.

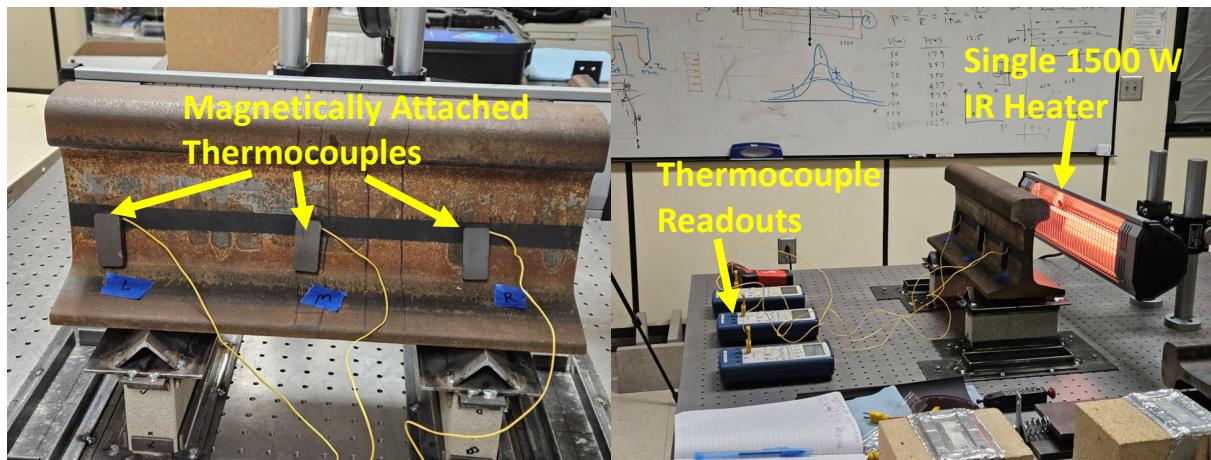
Chapter 7 - Non-Contact Rail Temperature Measurement

From [Chapter 6](#), it can be concluded that the IR heater is a good candidate for thermal loading of the rail section. However, to determine the required thermal strain associated with testing in the testbed facility, it is also necessary to create a measurement strategy for accurate temperature assessment. One of the best and oldest available methods to measure temperature is through a contact measurement, and so-called thermocouples are a common example of contact sensors. For the current rail temperature measurement application, thermocouples are not very practical to use since the rail will be sitting in the field (in-track). This makes attaching thermocouples every time for field measurements not a very feasible or practical option. Additionally, the weather may hinder the attachment of thermocouples. There are also time constraints for field measurements, because it is necessary to keep the track section being measured closed for as short a time as possible due to train schedules. To overcome all the contact measurement issues, a non-contact temperature measurement method is proposed, which is not only quick but also reliable, practical, and accurate. Two separate tests were performed to verify and cross-check three separate temperature measurement methods. One test was performed to compare readings between thermocouples and FLIR IR Imaging camera temperature scanning, and a second test was performed to compare temperature from a FLIR Handheld IR Spot thermometer and the FLIR IR Imaging camera results.

7.1 FLIR IR Imaging Camera and Thermocouple Comparison

A setup was created in the NCPM laboratory with a 17.5” rail section to test the IR Imaging camera temperature measurement capabilities, and to compare its readings with k-type thermocouples. The rail section was heated using commercial IR Heater and an IR imaging camera was placed on the opposite side of the IR heater. [Figures 7.1](#) (a), (b), and (c) show the setup with

thermocouples attached to the web (central portion) of the rail on the left, middle, and right sides to measure the temperature with the IR heater radiating the back of the rail.



(a)

(b)



(c)

Figure 7.1 IR Imaging Camera and K-Type Thermocouple Set Up for Simultaneous Temperature Measurement

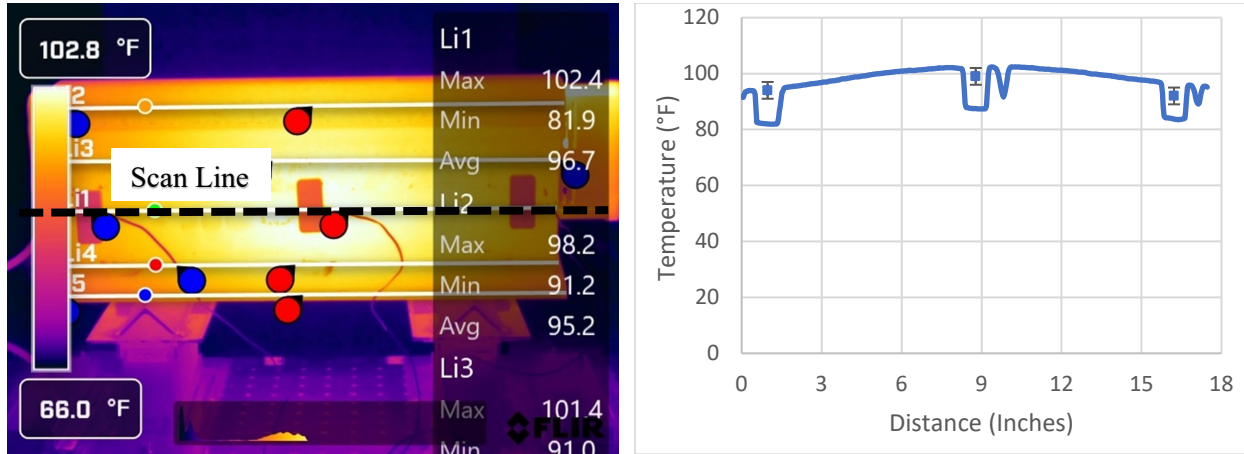
Thermocouple readings were taken manually using BK Precision Test Bench 390A Meters having manufacturer specified accuracy of $\pm(0.8\% \text{ reading} + 2^{\circ}\text{C})$. At the same time an image capture was taken with a FLIR IR Imaging camera, and the image was then converted to line scans of temperature in available FLIR thermal studioTM software.

Temperature Profile vs Thermocouple Comparison

A total of three measurements were taken at three different temperature levels (marked as High, Medium and Low) while the rail temperature was slowly dropping naturally, after shutoff of the rail heater. The line scan temperature measurements from the IR Imaging camera were compared graphically with thermocouple measurements, as shown in [Figures 7.2](#) for High, [7.3](#) for Medium, and [7.4](#) for Low temperature readings. The thermocouples were attached by small ceramic magnets.

[Figure 7.2](#) (a) shows the IR camera image for High temperature level with 5 different scan lines marked as Li 1 (web center), Li 2 (head of the rail), Li 3 (top of the web), Li 4 (top of the base) and Li 5 (bottom edge of the base). For this specific test, only Li 1 (web center) line temperature data was used which is highlighted in the [Figure 7.2](#) (a) with black dashed line. The IR Imaging camera was set at 0.95 emissivity which is commonly used in various IR Imaging devices. [Figure 7.2](#) (b) shows the temperature line made from the temperature data extracted from the center of the web line (Li 1) of the IR Camera thermal image. This line was created using temperature readings for each pixel for the length of the center line drawn in the IR Imaging camera image shown in [Figure 7.2](#) (a). The line temperature readings are then plotted against the length of the rail section which in this case was the 17.5” small rail section. The individual data points represented by blue rectangles in the plot on [Figure 7.2](#) (b) correspond to each thermocouple mounted on the rail with a magnet as shown in [Figure 7.2](#) (a). K-type thermocouples were used

for measuring the temperature on three different spots on the rail with the help of BK Precision Test Bench 390A Meters ([Appendix D](#)). [Figure 7.3](#) (a) & (b) and [Figure 7.4](#) (a) & (b) are showing exactly the same thing but at different times corresponding to medium and low temperature levels. The images were taken in sequence as the rail was cooling naturally and they show the correlation between measurements from the IR Imaging Camera and the thermocouples.



(a) IR Camera Image Scan Lines

(b) IR Scan and Thermocouple Comparison

Figure 7.2 IR Scan Data Compared with Thermocouple Measurements

(High Temperature)

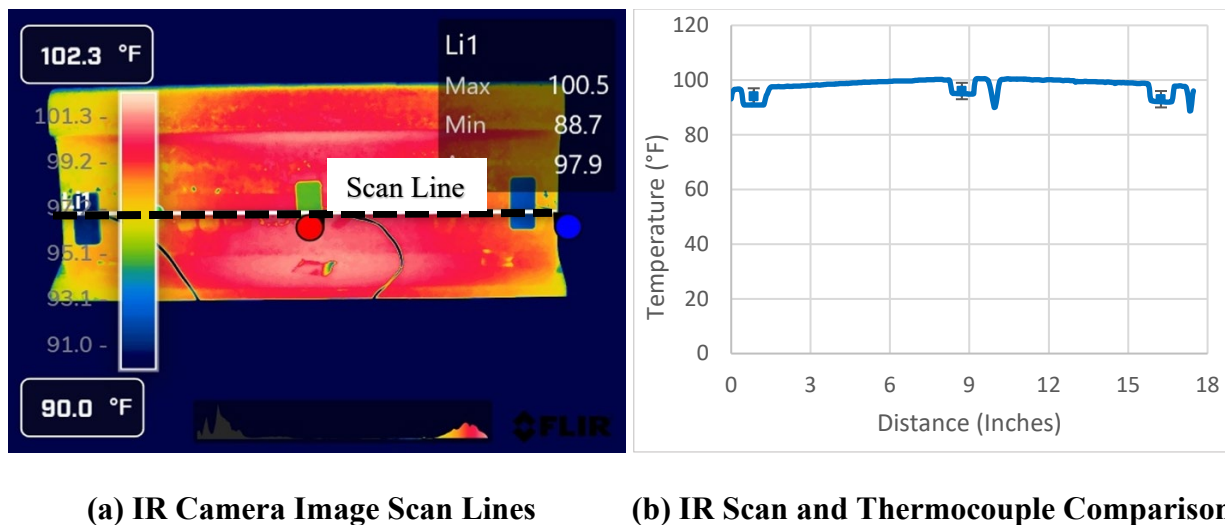


Figure 7.3 IR Scan Data Compared with Thermocouple Measurements

(Medium Temperature)

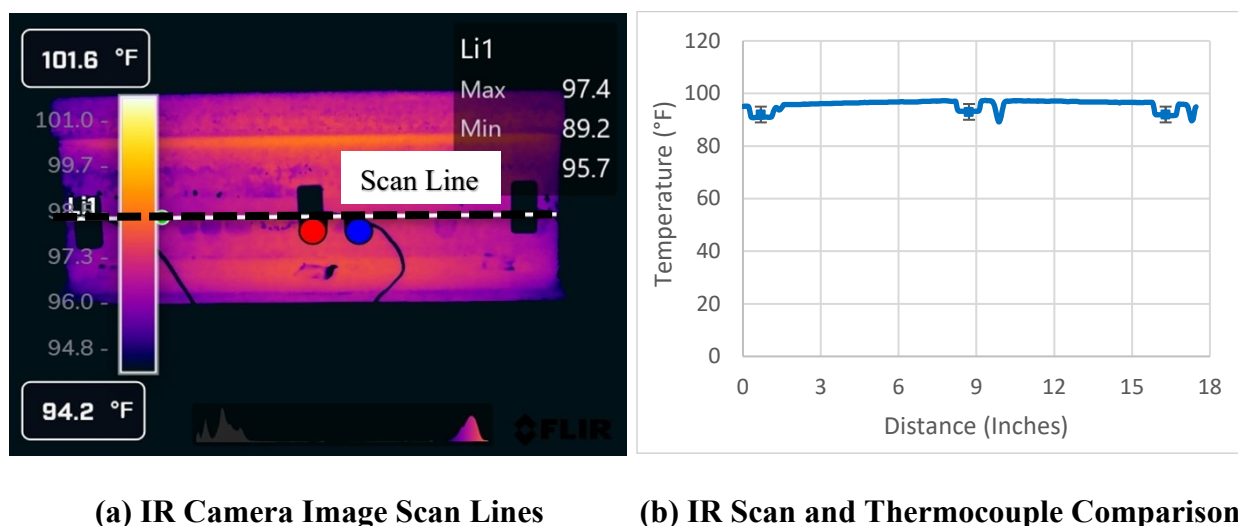


Figure 7.4 IR Scan Data Compared with Thermocouple Measurements

(Low Temperature)

The abrupt temperature drops in the continuous scan lines that are visible in all the plots is because of magnets or the thermocouple wires causing IR radiation changes when the IR camera captures the images. [Figures 7.2](#), [7.3](#), and [7.4](#) show that all the thermocouple measurements are within close proximity to the line scan temperature measurements created using the IR Imaging

camera software. In other words, the thermocouple measurements are within the expected range of uncertainty in comparison to the IR Imaging camera temperature measurements. This also indicates that the option to use either IR Imaging camera or thermocouples is viable for rail temperature measurement.

7.2 Temperature Distribution Across the Surface of Rail

Another set of comparisons was performed by making line scans and extracting surface temperature distributions on the same IR image at different locations on the rail, as shown in [Figure 7.5](#). The lines marked are Li 1 (web center), Li 2 (head of the rail), Li 3 (top of the web), Li 4 (top of the base) and Li 5 (bottom edge of the base).

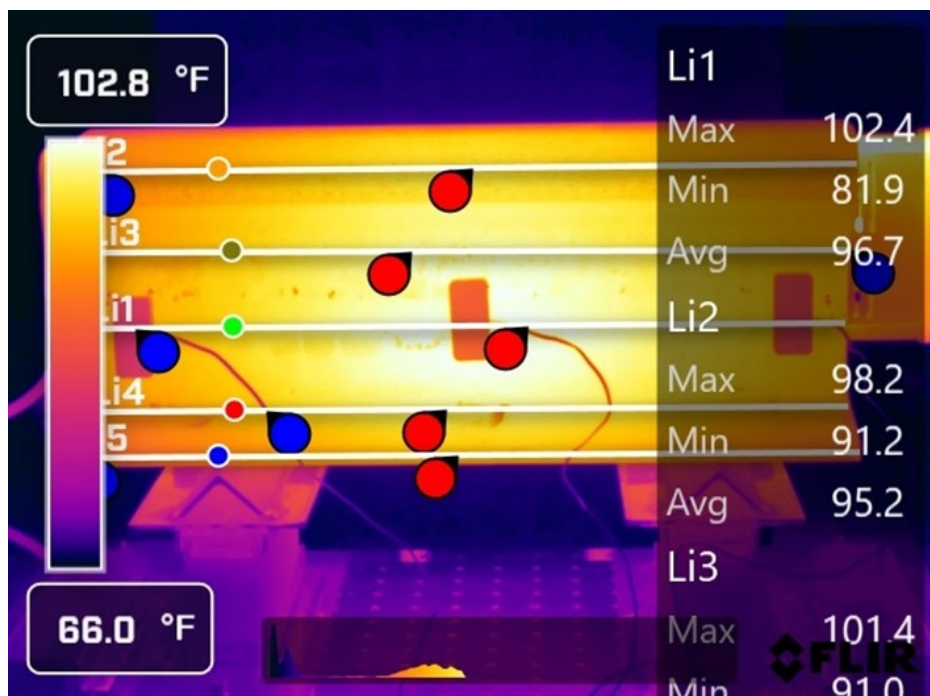


Figure 7.5 Line Scans Across the Rail Surface

These five separate scan lines were created to extract temperature distributions from a captured IR image of the entire front surface of the heated rail section. This test was performed to investigate the temperature distribution over the surface and to understand the spread in the

longitudinal direction. This will help determine the appropriate location for the temperature measurements during the mechanical and thermal loading testing for RNT extraction. Accurate and representative temperature measurements are key to successful RNT measurement.

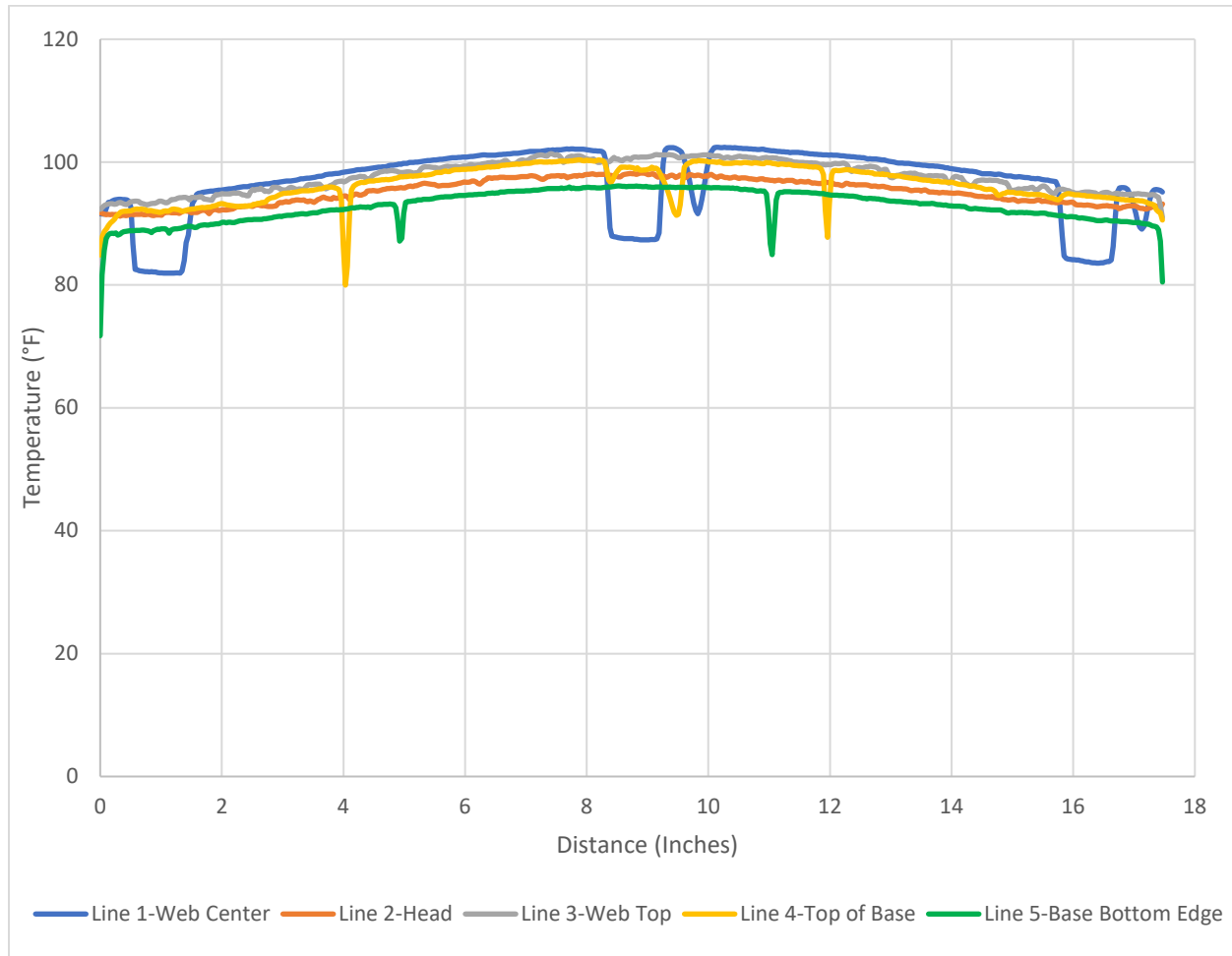


Figure 7.6 Line Scan Data Across the Rail Surface

[Figure 7.6](#) shows the temperature measurements for all the five line scans across the face of the rail in the longitudinal direction. Thus, the temperature measured over the head provides a reasonably representative rail temperature, since the temperature of the web section and head are almost the same.

7.3 Emissivity Check

It is known that the emissivity of the rail material (steel) is a major factor that can influence the temperature measurement using IR imaging or IR spot thermometer methods. In particular, line scan temperature data was extracted from Li 1 (web center) represented by black dashed line using the FLIR Thermal Imaging software on one of the IR images, as shown in [Figure 7.7](#).

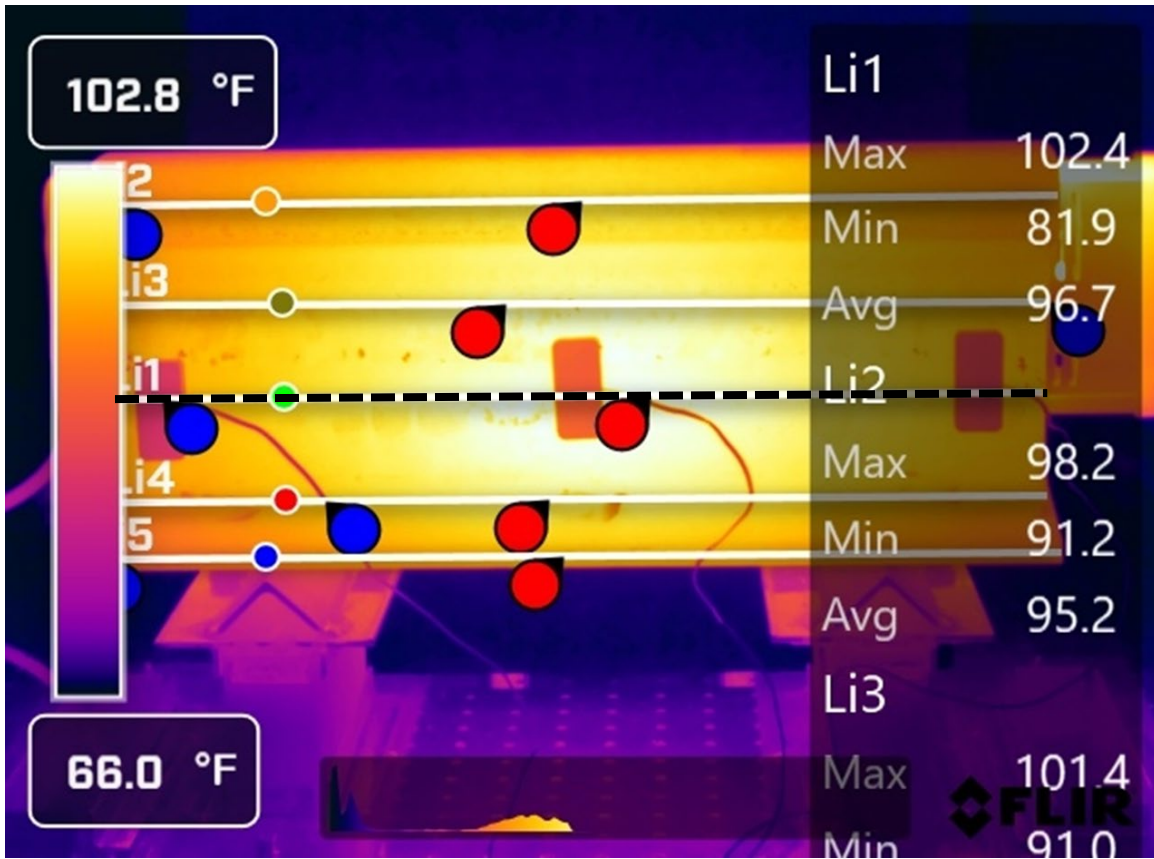


Figure 7.7 Line Scan in the Middle of the Web for Emissivity Check

Temperature distributions were extracted using three different emissivity values of 0.90, 0.95 and 1.0 for the same line generated on the center of the web of the rail. This data is compared on a plot with thermocouple readings (blue rectangles) to illustrate the effects of emissivity on the temperature measurement.

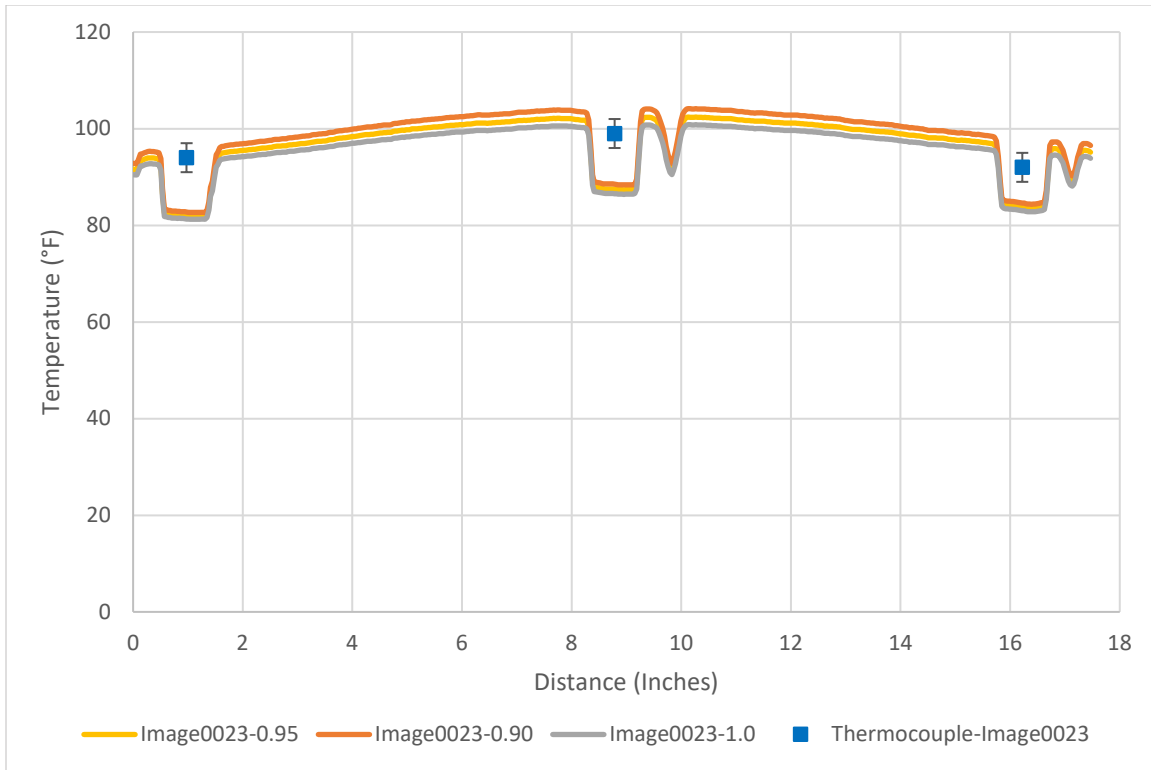


Figure 7.8 Single Line Scan Data Plotted for Different Emissivity

[Figure 7.8](#) shows that all the different emissivity settings provide measured temperatures that are close to each other. However, in general, 0.95 is used as a baseline and it can be confirmed from above plot that the thermocouple readings are closely matching with the middle blue line which corresponds to the emissivity of 0.95. The test confirms that the temperature scan results will be well within reasonable limits by using 0.95 emissivity on IR Imaging camera and IR Spot Sensor.

7.4 IR Imaging Camera and Handheld Spot Sensor Comparison

To confirm another method of temperature measurement, the FLIR IR Spot thermometer, a test was conducted using the longer rail section. The temperature was measured using the FLIR IR Imaging camera and FLIR Spot thermometer (referred as handheld temperature sensor sometimes). This was an important test because during the testbed testing, the temperature

measurement on the heated rail section was performed using the IR Spot sensor. The reason for using IR Spot sensor is the ease of use. Once the field-testing phase begins, it may be the most convenient option to use this non-contact sensor, since it is simple and easy to carry.

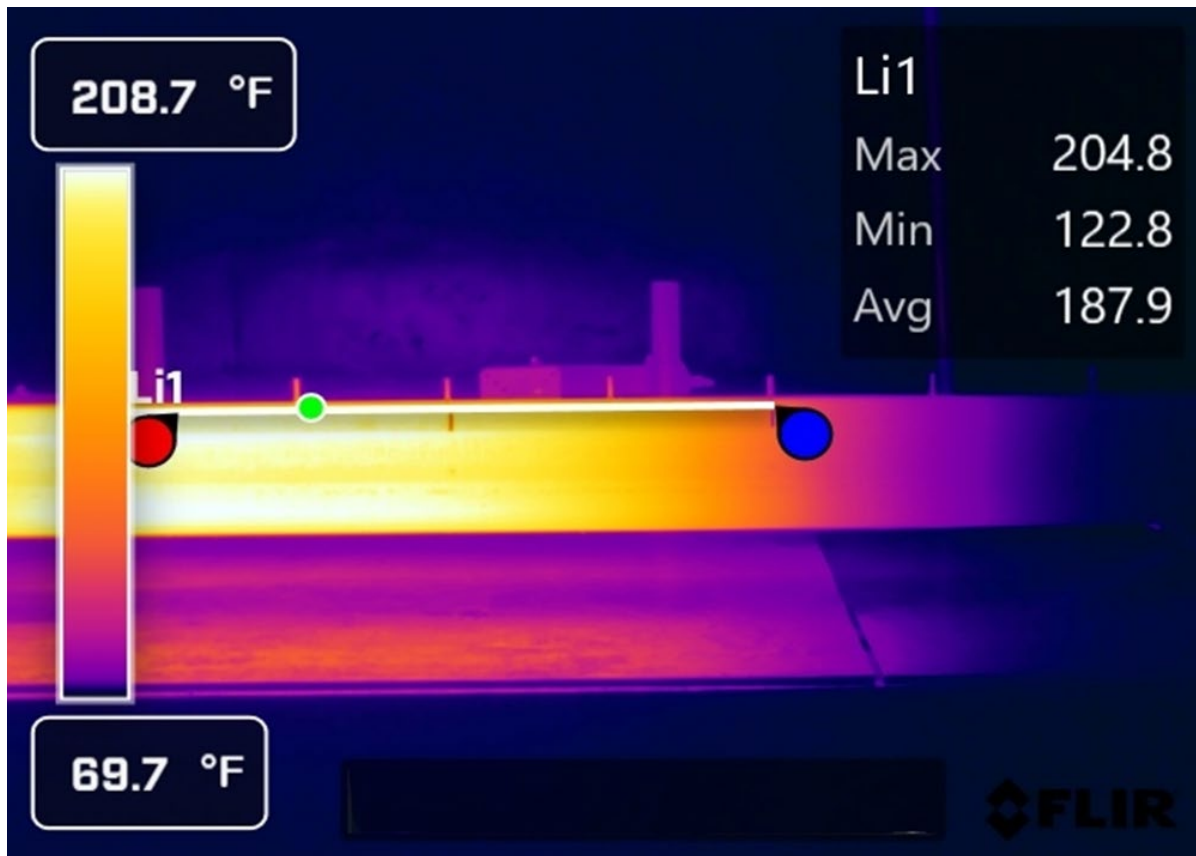


Figure 7.9 Heated Rail Section Image from IR Imaging Camera

[Figure 7.9](#) shows a rail section heated with the IR heater and the markers placed on top of the rail at 9” distance. A line was created in the thermal studio software to extract temperatures for the line scan to compare them with the handheld sensor readings taken at each marker position over the 36” of gage length region. As seen in the [Figure 7.9](#), the line spans the five-point markers where the handheld sensor readings were taken.

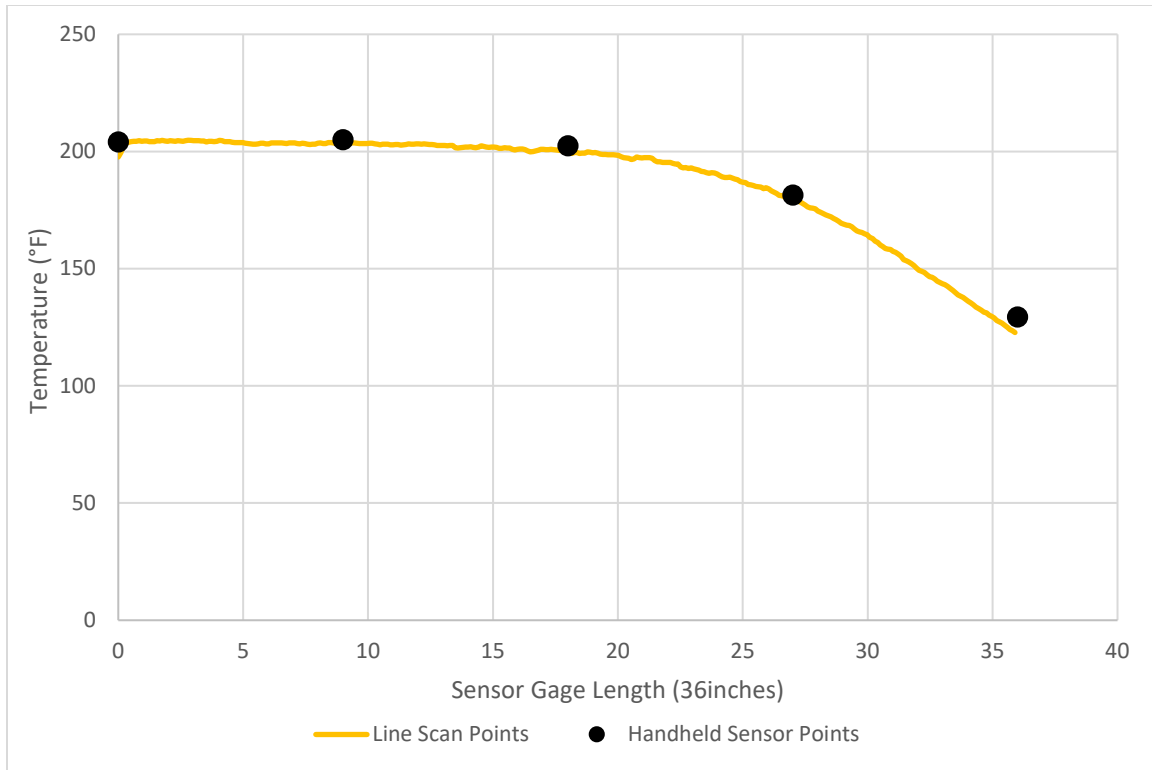


Figure 7.10 IR Imaging Camera Line Scan Data Compared to Handheld Sensor Data

[Figure 7.10](#) shows a comparison between five discrete handheld IR spot thermometer temperature measurements and the continuous line scan data extracted with 0.95 emissivity for the heated rail section. It can be seen that all the discrete handheld sensor measurements compare very well to the continuous scan line results, and agreement is nominally within the tolerance of the IR spot thermometer device (generally $\pm 3^{\circ}\text{F}$). This suggests that the handheld spot thermometer sensor is capable of measuring the rail temperature quite accurately and can be considered acceptable for use in RNT measurement.

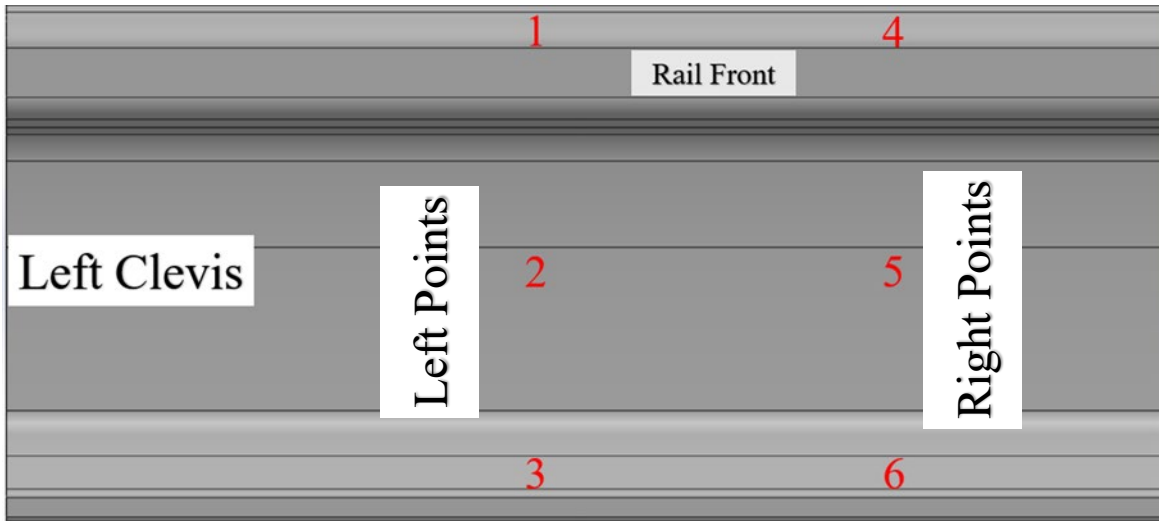
7.5 Final Discussion for Non-Contact Temperature Measurement

As discussed in [Sections 7.1](#) to [7.4](#), temperature measurements were accomplished in three different ways which included IR camera imaging, thermocouples, and the IR Spot thermometer sensor. However, since the new strain sensor is being designed for field use, it is desirable to

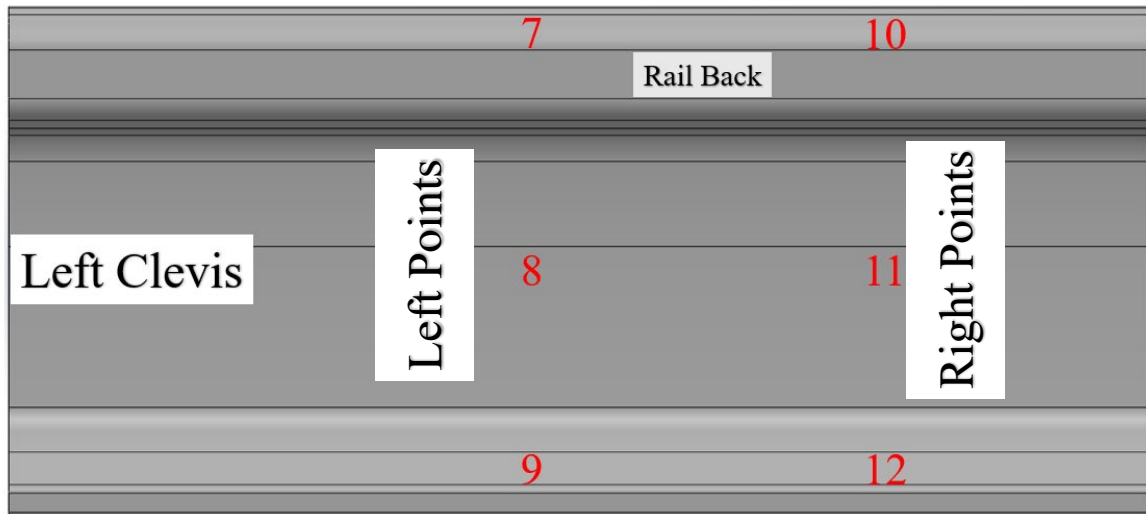
identify a device that can be used in the field easily with very minimal setup to measure rail temperature. As shown in the comparison plots in the aforementioned sections, it was shown that the readings taken using the direct contact measurement method (thermocouples), and two non-contact measurement methods (the IR Imaging Camera and the IR Spot thermometer), are all within close tolerances of each other, which suggests that either method is capable of accurately measuring the rail temperature; however, as discussed earlier the non-contact IR methods are preferable for field rail temperature measurements. It was also observed that using the emissivity value of 0.95 provides what appears to be the best temperature measurement results, that are comparable to thermocouple measurements. From the perspective of this project, use of the IR Imaging camera and the IR Spot sensor is planned for the field testing.

7.6 Temperature Variation Across Rail

In order for the handheld IR spot thermometer or IR Imaging camera to provide accurate assessment of the average rail temperature (needed for determination of the thermal strain), it is very important that the surface temperatures measured be representative of the interior rail temperatures as well. In the case of the laboratory set-up, IR heaters are mounted on stands which are very sturdy and aligned at proper distance for accurate thermal flux management. To avoid errors and re-setup issues, the rail must be heated with the IR heater in place all the time so if the test needs to be reperformed, the setup is exactly the same for next test. More importantly, it was desirable to investigate the temperature difference across the rail in the lateral direction to see how well the measurements of temperature taken on one side of the rail only are representative of the overall average rail temperature (needed for accurate assessment of thermal strain). A temperature difference test was performed on a longer section of rail mounted on the testbed.



(a) Front - Non-Heater Side



(b) Back – Heater Side

Figure 7.11 Long Rail Section with Temperature Measurement Points

The set up was very simple and included 12 measuring points for the handheld sensor for comparison in front (non-heater side) and back (heater side) of the rail. A heater was placed on one side of the rail (back side), and the other side was kept exposed to ambient air. The reason for performing this test is to confirm that if the IR heater is placed on one side of the rail heating the web area of the rail, the temperature measured on the opposite side of the web is reasonable to use

for calculating thermal strain. The long rail section was heated to about 200F, and the heater was turned off. There was around 15 minutes of settling/redistribution time before the readings were taken using the FLIR handheld sensor on front and back of the rail.

[Figure 7.11](#) (a) and (b) shows the measurement points on the rail and [Table 7.1](#) shows the temperature difference between the heater side (back) to non-heater side (front) of the rail at the same location. Readings 1, 2 and 3 belong to 3 separate sets of readings taken at different times while the rail was naturally cooling after turning the heater off. So, reading 1 was taken when the rail was hottest and reading 3 was at cooler temperature compared to reading 1.

Table 7.1 Temperature Difference Measurements Across Opposite Faces of the Rail

		Reading 1	Reading 2	Reading 3
Front Non-Heater Side	1	183.7	174	162.5
	2	173.1	166.5	157.5
	3	172.8	162.3	156.6
	4	183.2	173.7	163.9
	5	173.8	166.1	158.9
	6	172	161.8	156.2
Back Heater Side	7	181	171.3	162
	8	174.9	165.9	158.2
	9	171.7	158	154.2
	10	179.8	171.5	163.2
	11	173.8	165.9	158
	12	170.6	163.2	152.8
Temperature Delta	Head, Left	-2.7	-2.7	-0.5
	Web, Left	1.8	-0.6	0.7
	Base, Left	-1.1	-4.3	-2.4
	Head, Right	-3.4	-2.2	-0.7
	Web, Right	0	-0.2	-0.9
	Base, Right	-1.4	1.4	-3.4

[Figure 7.12](#) shows the difference between measured temperature on both sides of the rail for each set of measurements at different times (referred as reading 1, reading 2 and reading 3). For example, all three readings (reading 1, reading 2, reading 3) in [Figure 7.12](#) for “Web, Left”

are the difference between measurement point 8 (heater side) and point 2 (non-heater side) from [Figure 7.11](#).

As seen in [Table 7.1](#) and below in [Figure 7.12](#), mostly all the temperature differences fall within $\pm 3^{\circ}\text{F}$ which confirms that the rail has very short penetration time and the difference between the two sides/faces of the rail is negligible. The error/difference can be because of multiple reasons, including time taken while walking from front to the back of the rail, uncertainty in the handheld sensor itself, and human error.

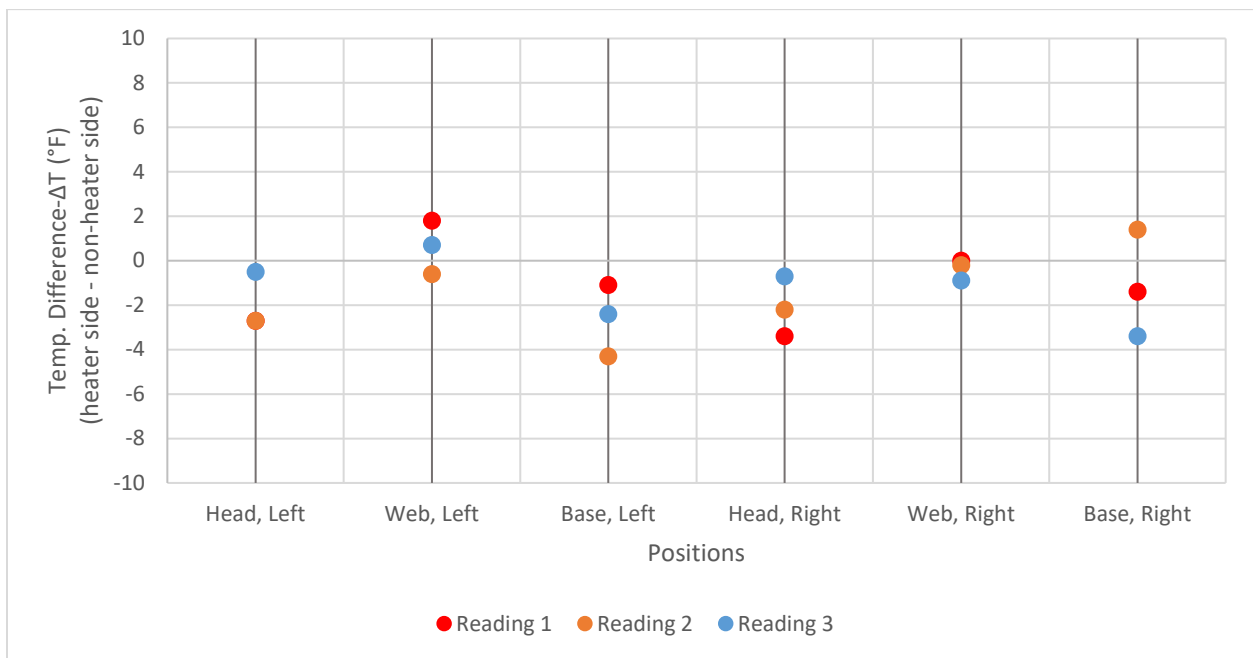


Figure 7.12 Temperature Difference/Delta between Front and Back of the Rail at Same Location

Chapter 8 - Combined Mechanical and Thermal Analysis

8.1 Mechanical and Thermal Loading Setup

This chapter discusses the main experimental work associated with the research, where the rail is subjected to combined mechanical and thermal loading. The strain is measured using the new strain sensor and temperature measurements are taken using the IR Spot thermometer and the IR Imaging camera. The temperature measurements are then used to calculate thermal strain so it can be removed from the total strain (measured by the strain sensor), leaving the extracted mechanical strain for calculation of the rail neutral temperature.

A photograph of the testbed, with a long rail test section installed, is shown in [Figure 8.1](#). The rail is connected to the testbed via clevis pins and high strength 1.75" diameter threaded steel rods for controlled mechanical loading. Straps were used on both ends of the rail for secondary support and for alignment due to the rail weight.



Figure 8.1 Long Rail Section Installed on Testbed

Additionally, the testbed is also set up for providing controlled heating of the rail, as shown in [Figure 8.2](#). Up to two 4000 W 208 VAC IR heaters can be used to heat the rail on the back side simultaneously, creating controlled thermal loading and thermal strain. The strain sensor was removed during heating of the rail to avoid any thermal effects on the parts of strain sensor.



Figure 8.2 IR Heaters Installed on Testbed for Controlled Thermal Heating

During the combined thermal and mechanical testing, thermal loading calculations (assessment of thermal strain) were based on the average rail surface temperature within the sensor gage length region. The presence of any heated portion of steel rail on either side of the gage length region will be considered to have negligible effect on the assessment of strain by the sensor. It is further assumed that, for the assessment of thermal strain, temperature variation across the rail cross-section will be negligible.

8.2 Short Rail Section

8.2.1 Combined Mechanical and Thermal Testing on Testbed

Thermal testing of a small 77" section of steel rail involved first subjecting it to an initial tension load of P_0 , which was 50,000 psi. One 4000W IR heater assembly was used, and the rail was heated to a maximum temperature of around 200 F. The setup of the short rail section with heater on the testbed is shown in [Figure 8.3](#). The heater was then turned off and the temperature in the rail was allowed to redistribute for about 15-20 minutes. The rail steel has a high thermal diffusivity, and this results in a very small Biot number, on the order of 0.003. This will distribute the temperature very fast laterally bringing the rail to nearly uniform temperature, but it will take a much longer time to distribute longitudinally. The advantage of slow longitudinal temperature distribution is that it will give more time to take multiple strain/displacement measurements. Temperature was recorded via the FLIR IR Spot thermometer on the head of the rail.



Figure 8.3 Short Rail (77") Section on Testbed with IR Heater Installed

Determination of the effect of thermal strain on a test section of steel rail requires accurate assessment of the mean rail temperature. A total of five equally spaced points (9” apart) on the head of the rail were scanned for temperature measurements in the sensor gage length region using the IR Spot sensor. The emissivity was set to 0.95 as discussed in [Section 7.3](#), which appears to be a fair representation of weathered steel rail. The mean temperature was calculated using a 3rd order polynomial curve fit. The total thermal deflection can be expressed as the integration of an incremental thermal deflection over the entire 36” gauge length for the measured rail temperature distribution. Equation 8.1 shows the total thermal deflection.

$$\Delta L_{\text{total}} = \frac{1}{L_G} \int_0^{L_G} \alpha [T(x) - T_0] dx = \alpha \frac{1}{L_G} \int_0^{L_G} [T(x) - T_0] dx \quad (8.1)$$

ΔL_{total} is the total thermal deflection in the gage length region, L_G is gage length, α is coefficient of thermal expansion, $T(x)$ is the measured rail temperature distribution and T_0 is the ambient temperature. Re-writing equation (8.1) in terms of the mean (or average) temperature yields

$$\Delta L_{\text{total}} = \alpha [T_{\text{ave}} - T_0] \quad (8.2)$$

Where T_{ave} is the average temperature obtained using the 3rd order polynomial fit. See equation (8.23) for the details behind the 3rd order polynomial fit and assessment of average temperature.

The plot for each temperature measurement is shown in [Figure 8.4](#) along with the 3rd order polynomial fits to the discrete temperature data.

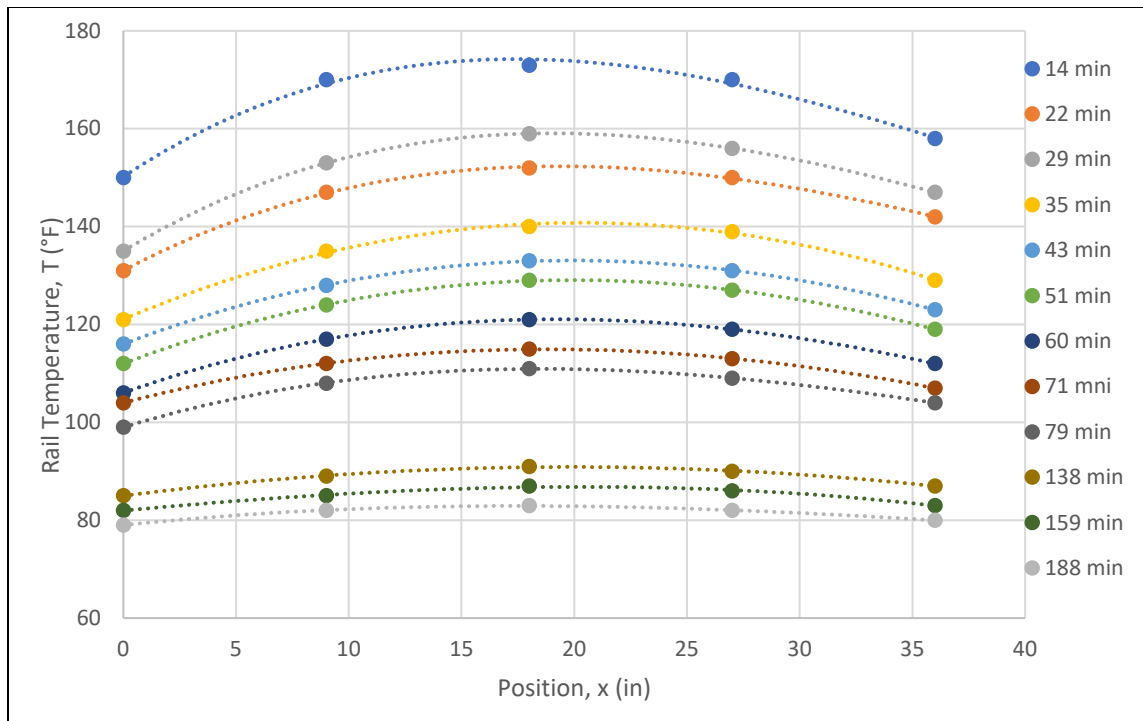


Figure 8.4 3rd Order Polynomial Temperature Data for Short Rail Thermal Loading

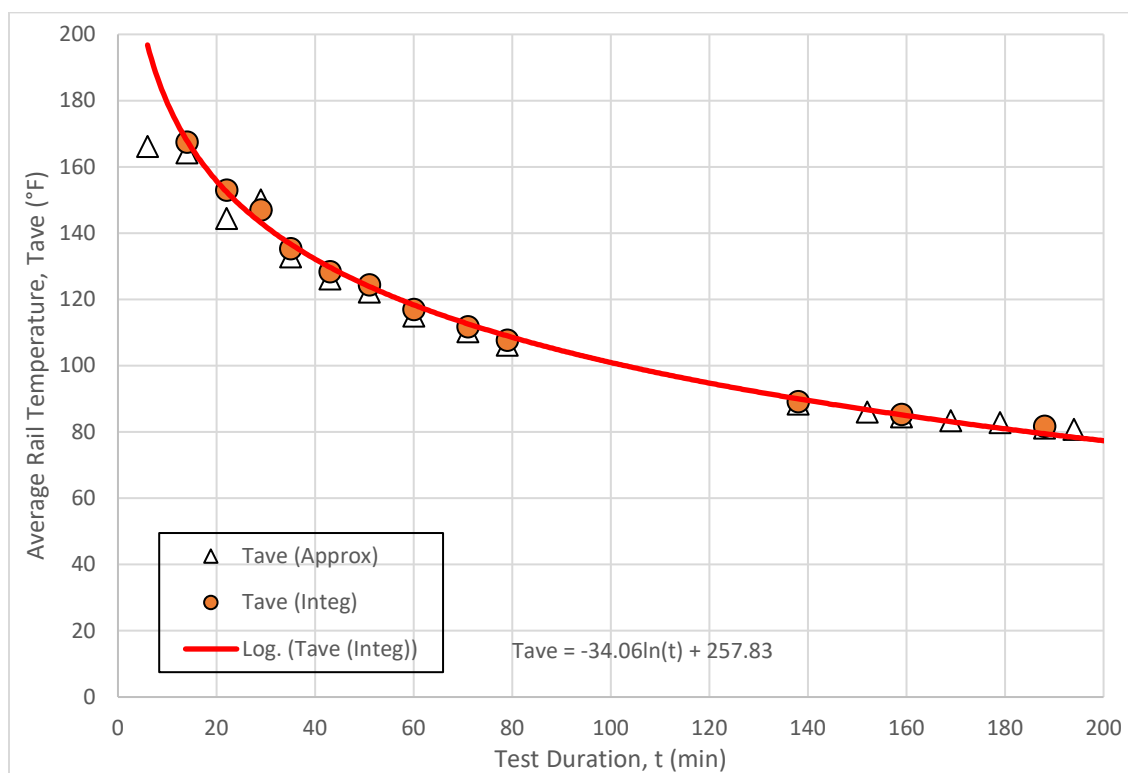


Figure 8.5 Arithmetic Average vs 3rd Order Polynomial Average Data Comparison

[Figure 8.5](#) shows comparison between arithmetic averages of the temperature measurements and 3rd order polynomial averages over time for the same temperature measurements, correlated with a common logarithmic trendline.

8.2.2 Mechanical and Thermal Loading – Theoretical Analysis

The results presented here represents the first test performed on the testbed with mechanical and thermal loading combined. It served as the first attempt to investigate the behavior of both temperature effects (thermal strain) and load application in the testbed.

Assumptions used in theoretical calculations are as follows:

1. Rail temperature distribution spans the entire length of the rail.
2. Rods and clevis mounts are at room temperature, T_0 .
3. No overall change in length of the testbed once the mechanical load is set by screw jack.
4. T_R spans the entire length of the rail – defined by an average using polynomial fit (3rd order).

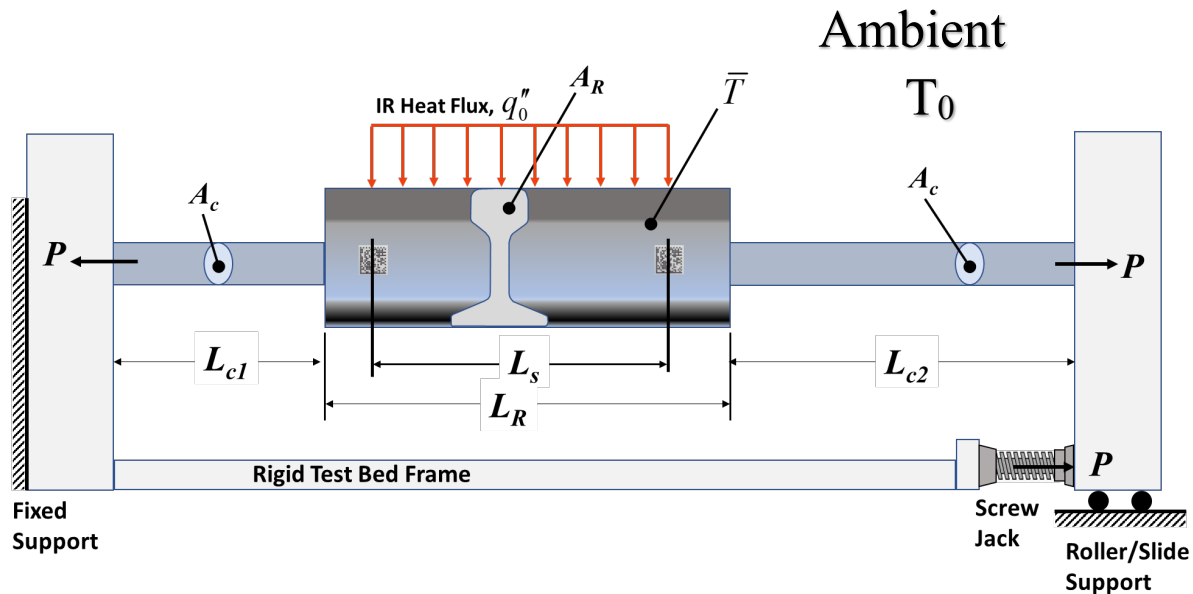


Figure 8.6 Schematic Drawing of Short Rail Section on Testbed

[Figure 8.6](#) shows a schematic image of the testbed subjected to combined thermal loading and mechanical loading, P. Equation (8.3) shows a general expression for the total deflection of the system (rail and connecting rods on both ends of the rail) for a given mechanical loading, P.

$$\delta_{\text{total}} = \delta_{c1} + \delta_R + \delta_{c2} = \left[\frac{L_{C1}}{A_C} + \frac{L_R}{A_R} + \frac{L_{C2}}{A_C} \right] \frac{P}{E_R} = \text{constant} \quad (8.3)$$

As mentioned in [Section 8.2.1](#), the initial loading on the rail applied was 50,000 psi denoted as P_0 . Now the deflection of the system will be dependent on the new loading, and the equation will change to include the initial loading condition, P_0 , yielding

$$\delta_{\text{total},P_0} = \left[\frac{L_{C1}}{A_C} + \frac{L_R}{A_R} + \frac{L_{C2}}{A_C} \right] \frac{P_0}{E_c} \quad (8.4)$$

Then heating/thermal loading was applied to the rail section to raise the temperature of the rail section to around 200 F. This process added a thermal deflection component in the rail section in addition to the mechanical deflection as shown in equation (8.4). As a note, the rail heating covers the portion of the rail under the strain sensor, also called the gage length L_G , and the rest of the length of the rail ($L_R - L_G$) is unheated. The new deflection equation must include the thermal portion, as follows:

$$\delta_{\text{total},P} = \left[\frac{L_{C1}}{A_C} + \frac{L_{C2}}{A_C} \right] \frac{P}{E_R} + \left[\frac{L_R - L_G}{A_R} \right] \frac{P}{E_R} + L_G \left[\frac{P}{E_R A_R} + \alpha [\overline{T_R} - T_0] \right] \quad (8.5)$$

With some rearrangement and combining terms in equation (8.5), the new equation is,

$$\delta_{\text{total},P} = \left[\frac{L_{C1}}{A_C} + \frac{L_R}{A_R} + \frac{L_{C2}}{A_C} \right] \frac{P}{E_R} + L_G \alpha [\overline{T_R} - T_0] \quad (8.6)$$

Subtracting equation (8.4) from equation (8.6), and noting the assumption of no change in the length of the testbed, yields

$$\left[\frac{L_{C1}}{A_C} + \frac{L_R}{A_R} + \frac{L_{C2}}{A_C} \right] \frac{(P - P_0)}{E_R} + L_G \alpha [\overline{T_R} - T_0] \quad (8.7)$$

Equation (8.7) shows that during the cooling process after heater shutdown the gauge length region is represented by the measured average temperature. The rest of the system under tension in the testbed, the remaining portion of steel rail $L_R - L_G$, and the supporting rods of lengths L_{C1} and L_{C2} , are assumed to be at approximately the ambient room temperature T_0 .

Separating out the sensor gauge length region from the overall rail test section, and noting that the overall length of the system and the total system deflection before and after heating must be the same, yields

$$(P_0 - P) = \frac{E_R L_G \alpha [\overline{T_G} - T_0]}{\left[\frac{L_{C1}}{A_C} + \frac{L_R}{A_R} + \frac{L_{C2}}{A_C} \right]} \quad (8.8)$$

The left-hand side of equation (8.8) represents the theoretical drop-off (loading offset) of the mechanical force in the system as a function of the average elevation of rail temperature above ambient.

[Figure 8.7](#) shows the predicted and measured load reduction vs. elevated average rail temperature. The average rail temperatures were determined using the 3rd order polynomial mean temperatures, and the actual load was determined from direct load cell measurements.

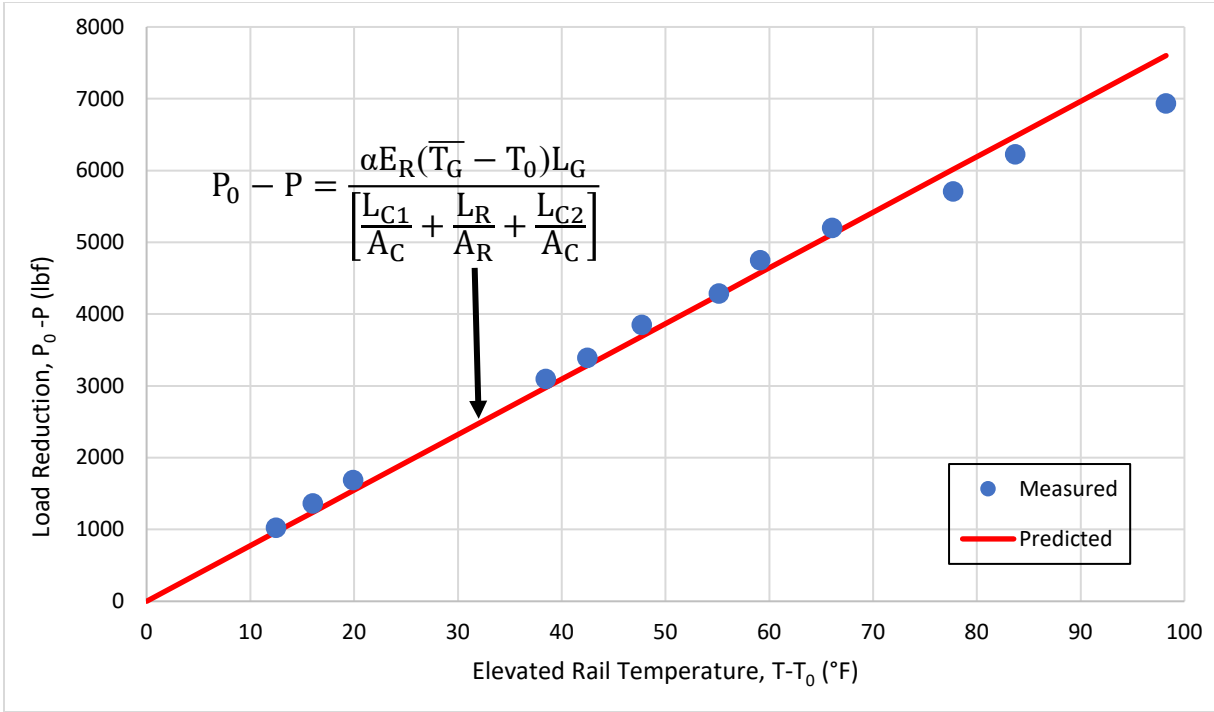


Figure 8.7 Loading Offset Due to Elevated Rail Temperature

[Figure 8.7](#) shows that there is an approximate linear relationship between measured load drop-off (loading offset) of the mechanical force in the testbed system as a function of the average elevation of rail temperature above ambient. The plot also shows that the measurements are well-predicted by the simple theory presented above. Furthermore, this provided some initial confirmation that the testbed and load cells for tension measurement appeared to capture the combined mechanical and thermal loading effects on the steel railroad rail test section.

8.3 Long Rail Section

After performing combined mechanical and thermal loading test on the short rail section and processing some initial strain measurements, it was determined that the rod/clevis and rail connection locations were likely affecting the readings. Possible departure from St. Venant's principle, as described in [Section 5.3](#), was considered one of the causes for apparent measurement inaccuracies. To avoid any further delays in testing and to investigate the reason for this suspicious

behavior, a long rail section (147") was installed on the testbed to perform the next phase of pure mechanical and combined mechanical and thermal testing. The setup for the long rail section on the testbed is shown in [Figure 8.1](#), with heater mounted adjacent to the back of the rail.

The testing included heating the rail section to temperatures well above ambient and allowing time for thermal redistribution to take place before starting to take measurements. Also, while taking measurements with the new strain sensor, temperatures were recorded using the IR Spot thermometer and the IR Imaging camera to extract the thermal portion from the total deflection measured by the strain sensor. Additionally, to calculate the rail neutral temperature apparent error (difference between calculated rail neutral temperature and actual rail neutral temperature), load cell readings were recorded to be used as actual load at that instant.

8.3.1 Single Deflection Measurement on Non-Heater Side

A 147" long rail section was used on the testbed for mechanical and thermal load testing. The set up was created such that the rail was heated in the middle and time was allotted for thermal re-distribution along the rail before the readings are taken. Only one set of dot-peen patterns were marked in the middle of the rail for this testing.

The testing began with the initial "Rail Neutral" condition with no strain at ambient temperature of T_0 as shown in [Figure 8.8](#).

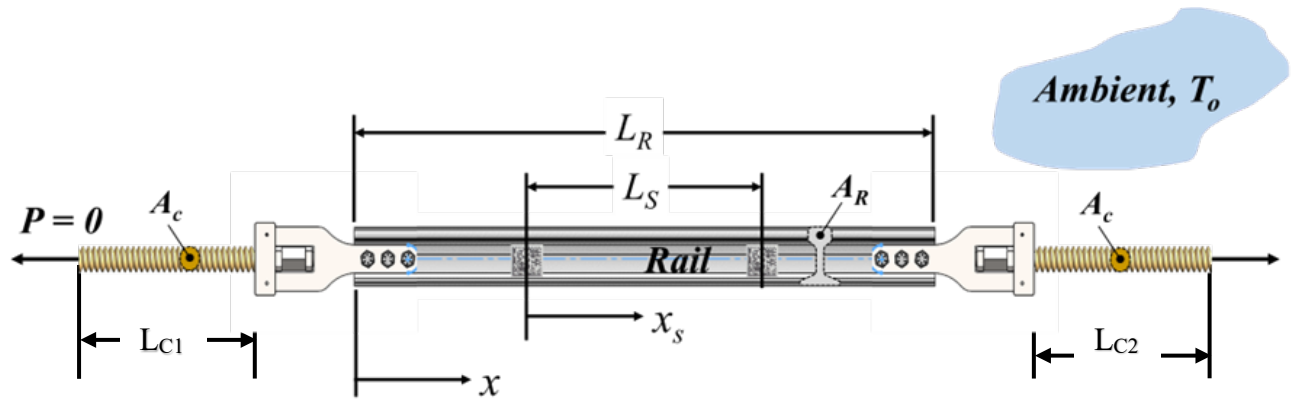


Figure 8.8 Initial Rail Neutral Condition

To begin the process, the rail was first put under known tension (P_0) to move from the rail neutral condition. This is same as the rail getting installed on the track after being tensioned or by raising its rail neutral temperature via heating the rail. This situation is the same as pure mechanical loading, where there is no thermal strain induced yet. See [Figure 8.9](#) for a schematic showing the initial load application and [Table 8.1](#) for basic steel rail characteristics.

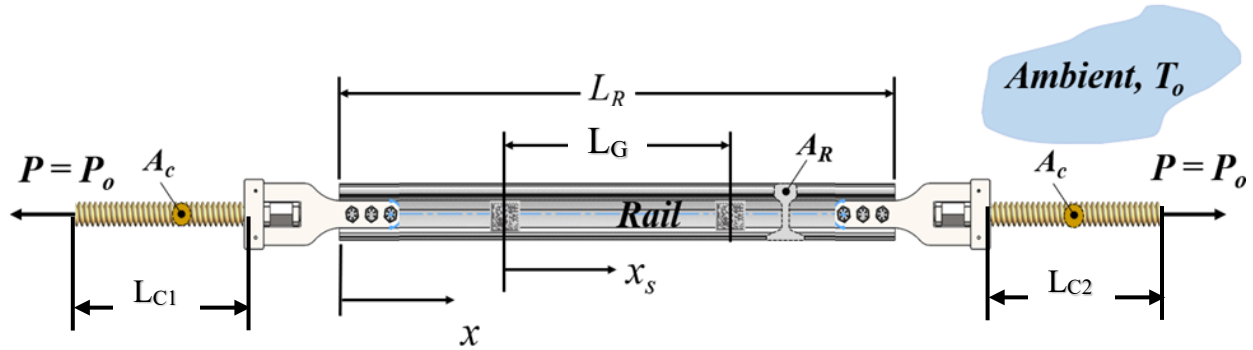


Figure 8.9 Mechanical Loading with no Thermal Load Application

Table 8.1 Steel Rail Characteristics

Steel Rail Characteristics		
Entity	Value	Unit
Coefficient of Thermal Expansion (CTE) or (α)	6.50E-6	$\frac{1}{F}$
E_R (Young's Modulus of the rail)	2.90E+7	$\frac{lb f}{in^2}$
A_R (Area of the Rail)	13.32	in^2
L_{C1} (Length of the rod-non-jack side)	36	in
L_{C2} (Length of the rod-jack side)	67	in
A_C (Area of the rod)	2.405	in^2
L_R (Length of the rail section)	147	in
L_G (Gage length of the strain sensor)	36	in

This section begins with example calculations of mechanical strain and an equivalent Rail Neutral Temperature, using known mechanical deflection relationships.

The formula to calculate mechanical deflection/strain is given as

$$\varepsilon = \frac{\Delta L}{L_G} \quad (8.9)$$

Where ΔL is change in length and L_G is the gage length.

Strain can also be defined in terms of Young's Modulus as,

$$E = \frac{\sigma}{\varepsilon} \quad (8.10)$$

Here E is Young's Modulus, and σ is the mechanical stress.

Stress is defined as total force acting on a particular cross-sectional area and is expressed as follows:

$$\sigma = \frac{P}{A} \quad (8.11)$$

Where P is the applied force and A is the cross-sectional area the force is acting upon.

Merging equations (8.9), (8.10) and (8.11) yields

$$\Delta L = \frac{P_0 L_G}{A_R E_R} \quad (8.12)$$

Here P_0 represents the initial loading, L_G is the gage length of the sensor, A_R is cross-sectional area of the rail and E_R is Young's Modulus for the steel railroad rail section as given in [Table 8.1](#).

The ambient temperature during this test in the laboratory housing testbed was approximately 68.2 F, which is denoted as (T_0) , having the value

$$T_0 = 68.2 \text{ } ^\circ\text{F} \quad (8.13)$$

The initial tension applied to the rail section on the testbed was 80,350 lbf, and as mentioned above, this initial loading is denoted by (P_0) , therefore

$$P_0 = 80,350 \text{ lbf} \quad (8.14)$$

The mechanical deflection can be calculated using equation (8.12) as follows:

$$\Delta L_{\text{mech}} = \frac{P_0 L_G}{A_R E_R} = \frac{80,350 \times 36}{2.90E7 \times 13.32} = 0.007488 \text{in (or 0.1902mm)} \quad (8.15)$$

The mechanical strain can be calculated using equation (8.9) yielding

$$\epsilon_{\text{mech}} = \frac{\Delta L_{\text{mech}}}{L_G} = \frac{0.007488}{36} = 0.0002080 \text{ (or } 208\mu\epsilon) \quad (8.16)$$

The general formula for calculating thermal strain is expressed as

$$\epsilon = \alpha(\Delta T) \quad (8.17)$$

where α is coefficient of thermal expansion (CTE) and ΔT is the difference between reference and current temperature.

Equation (8.17) can be modified to yield the rail thermal strain as

$$\epsilon_{\text{therm}} = \alpha(T_{\text{Ref}} - T_0) \quad (8.18)$$

With T_{Ref} being the current rail temperature and T_0 being the ambient temperature.

In this particular example of initial mechanical loading, there was no thermal portion involved.

Rewriting equation (8.18) to include terms from mechanical strain, yields

$$\epsilon_{\text{mech}} = \frac{\Delta L_{\text{mech}}}{L_G} = \alpha(T_{\text{RN,mech}} - T_0) \quad (8.19)$$

Rearranging equation (8.19) to calculate an equivalent Rail Neutral Temperature ($T_{\text{RN,mech}}$)

yields

$$T_{\text{RN,mech}} = \frac{\Delta L_{\text{mech}}}{\alpha L_G} + T_0 \quad (8.20)$$

Substituting values from equations (8.16), [Table 8.1](#) and (8.13) into equation (8.20) gives

$$T_{\text{RN,mech}} = \frac{0.007488}{6.5E-6 \times 36} + 68.2 = 100.2^\circ\text{F} \quad (8.21)$$

This exercise shows the basics of calculating strain and rail neutral temperature using the measured displacement and known coefficient of thermal expansion.

The next steps involve imposing thermal loading with the IR heater. The rail and the heater was set as shown in [Figure 8.1](#) and [8.2](#) for initiating combined mechanical and thermal loading. The schematic in [Figure 8.10](#) shows the heat flux for the same setting of the rail with induced initial tension and [Figure 8.11](#) shows the resulting rail temperature distribution causing onset of thermal strain with $T(x) > T_0$.

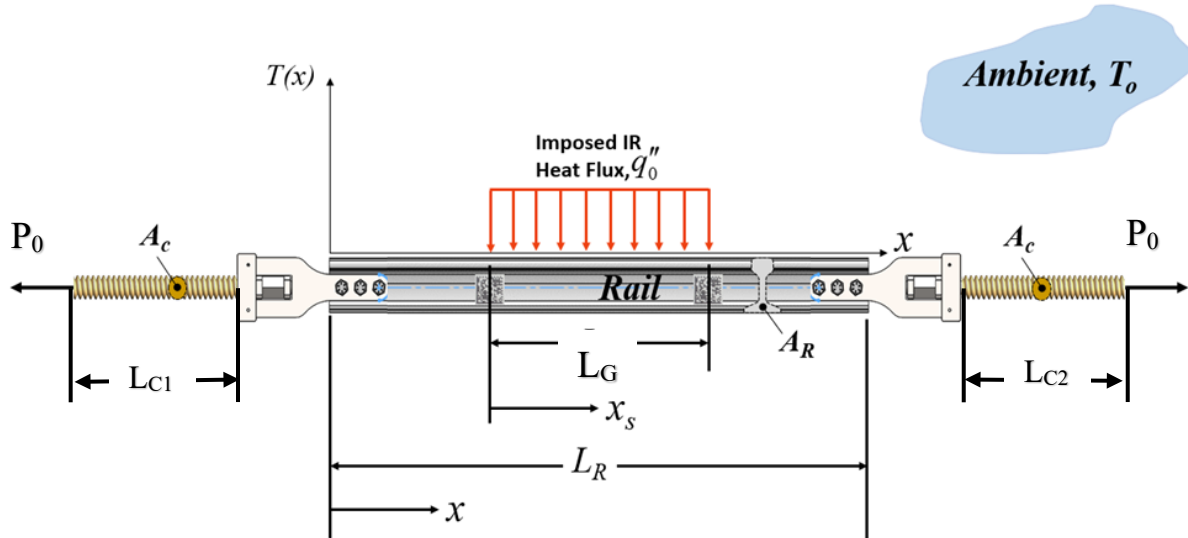


Figure 8.10 Heat Flux on the Rail Section

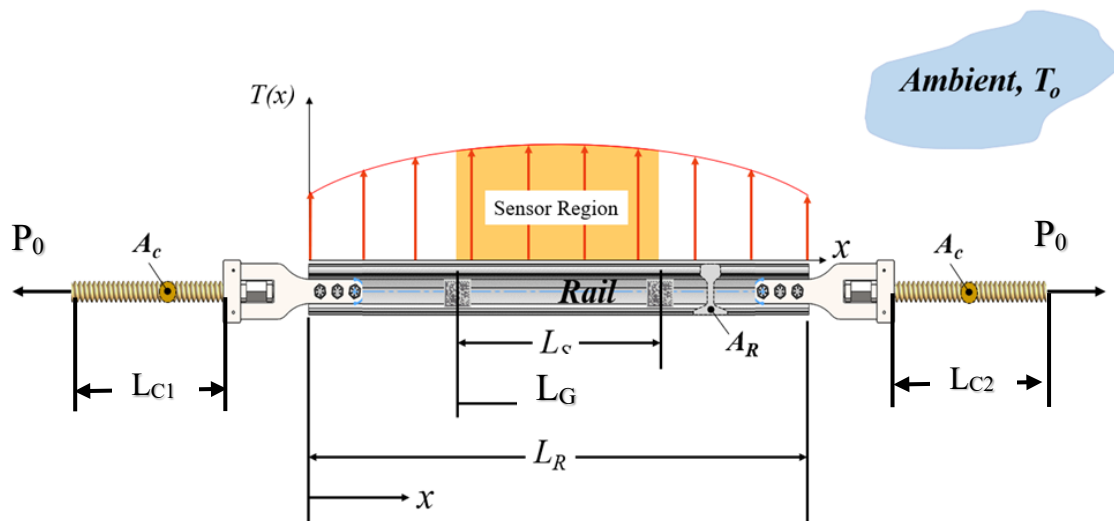


Figure 8.11 Temperature Distribution in the Steel Rail Section

The rail was heated up to an elevated temperature from ambient and then the IR heater was turned off. In this particular test, the rail was heated until it reached about 200 F and then a time for relaxation/redistribution of about 15 minutes (significantly greater than the thermal penetration time) was allowed before measurements were taken.

Measurements involved recording discrete rail temperatures at 16 different locations 9” apart on the head of the rail, starting from one end of the rail. This exercise will provide information on temperature redistribution in the rail over time as the rail cools. [Figure 8.12](#) shows the 3rd order polynomial temperature profiles for each set of data recorded at different times starting from the first reading taken 15 minutes after turning off the heater.

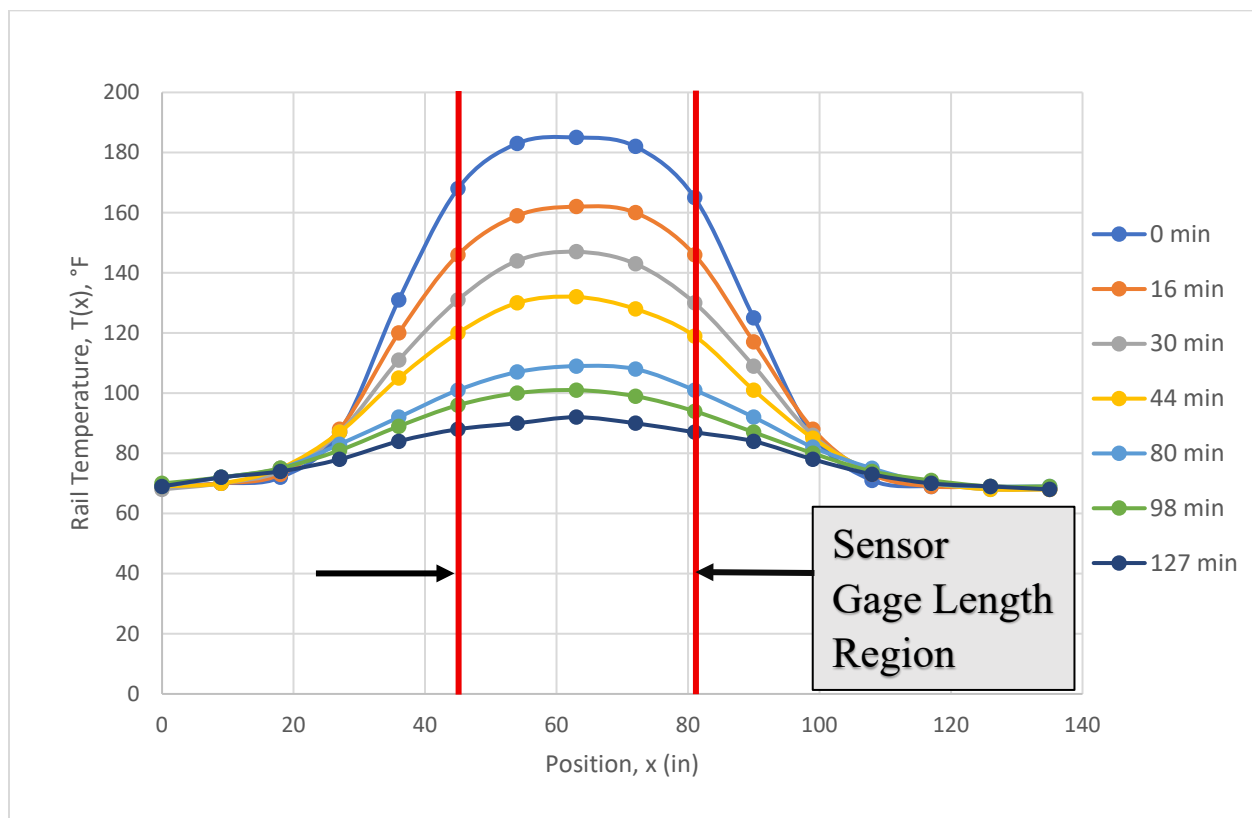


Figure 8.12 Temperature Profiles for Full Scale Rail Thermal Loading

Another step in the process was to achieve the goal of the project by extracting mechanical strain and calculating the equivalent RNT. To do that, thermal strain is needed. For the analysis of

thermal strain and to deduce mechanical stress, temperature measurements were taken within the (36") gage length region at locations equidistant at 9" spacing using the IR Spot thermometer. This temperature distribution data was used to calculate mean temperatures for the gage length region using 3rd order polynomial fits as discussed in [Section 8.2.1](#) using equation (8.1). The plot in [Figure 8.13](#) shows the temperature measurement points and the curves created using 3rd order polynomial fits.

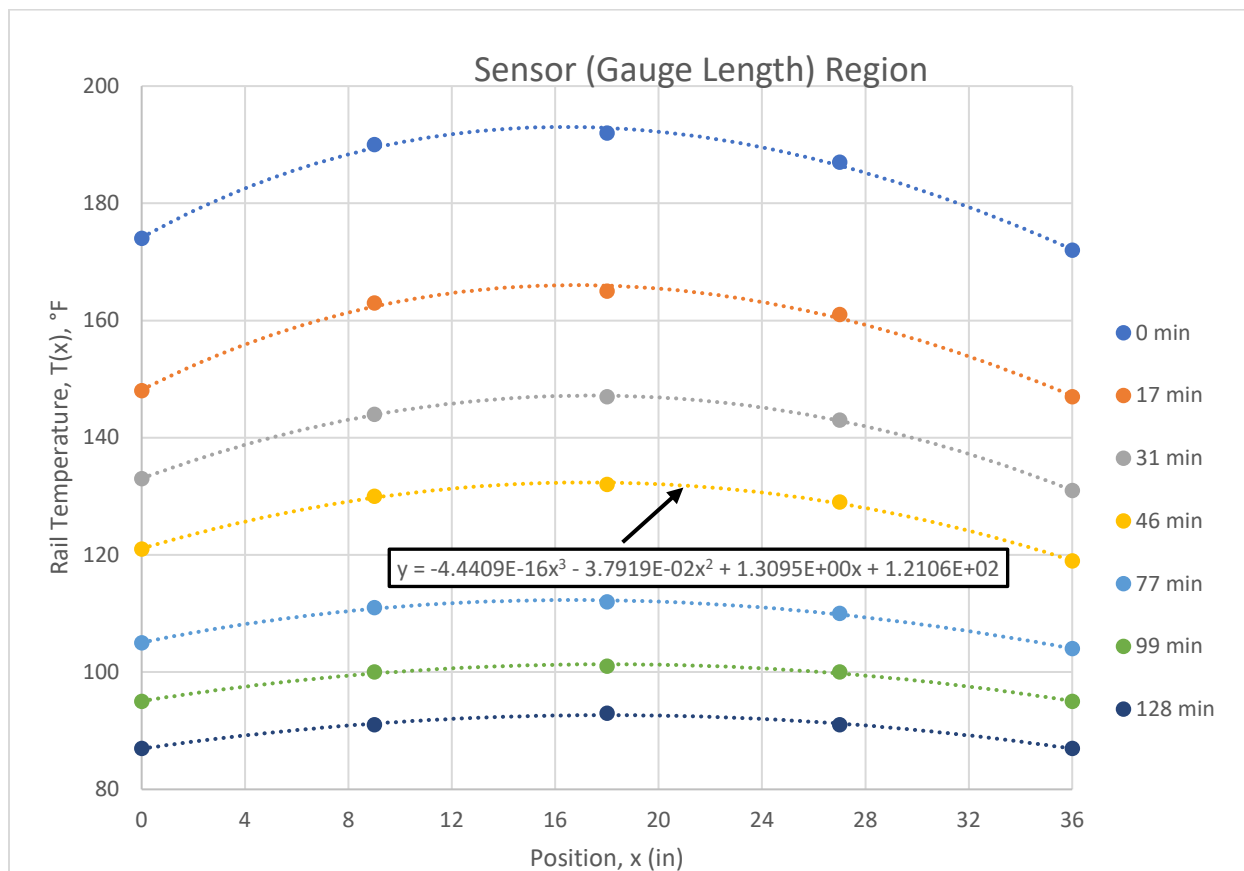


Figure 8.13 3rd Order Polynomial Data for Thermal Loading of Long Steel Rail Section

The calculation of average temperature using the polynomial fits is important because simple arithmetic averaging would not provide as accurate estimate of average temperatures in the rail, as noted in [Figure 8.5](#). One of the main reasons for using the polynomial function (integration method) is that the rail temperature is not uniform longitudinally.

Table 8.2 3rd Order Polynomial Coefficients

Duration (min)	a3	a2	a1	a0	T _{ave} (Integrated)
0	0.00046	-0.08554	2.43122	174.14286	186.3
17	0.00034	-0.07496	2.22619	148.15714	159.8
31	0.00000	-0.04674	1.62698	133.02857	142.1
46	0.00000	-0.03792	1.30952	121.05714	128.2
77	0.00011	-0.02998	0.90344	105.04286	109.7
99	0.00000	-0.01940	0.69841	95.05714	99.2
128	0.00000	-0.01764	0.63492	86.94286	90.8

An accurate determination of average rail temperature in the gage length region, T_{ave} , is necessary to accurately calculate thermal strain portion. The 3rd order polynomial integration method for determination of the average temperature is given as

$$T_{ave} = \frac{1}{L_G} \int_{x=0}^{L_G} T(x) dx \quad (8.22)$$

Since this procedure involves 3rd order polynomials, there will be four constant terms for integration of the temperature distribution within the gage length region, and equation (8.22) can be evaluated to yield

$$T_{ave} = \frac{1}{L_G} \int_{x=0}^{L_G} [a_3 x^3 + a_2 x^2 + a_1 x^1 + a_0] dx \quad (8.23)$$

Where the terms a_3 , a_2 , a_1 , and a_0 are the polynomial coefficients that can be evaluated either from individual regression fits or by using the built-in Excel “linest” function. [Table 8.2](#) shows the individual polynomial coefficients calculated for evaluating the average temperature.

The final formula after evaluating the integral expression in equation (8.23) is as follows:

$$T_{ave} = a_3 \left(\frac{L_G^3}{4} \right) + a_2 \left(\frac{L_G^2}{3} \right) + a_1 \left(\frac{L_G}{2} \right) + a_0 \quad (8.24)$$

For example, take the data highlighted in yellow in [Table 8.2](#) for the time 46 minutes. [Table 8.2](#) shows all the constants calculated using excel sheet for the readings taken at time 46 minutes.

Substituting these coefficients into equation (8.24), along with the gage length (L_G) of the sensor from [Table 8.1](#), yields the following value for T_{Ave} :

$$T_{ave} = a_3 \left(\frac{L_G^3}{4} \right) + a_2 \left(\frac{L_G^2}{3} \right) + a_1 \left(\frac{L_G}{2} \right) + a_0 = 128.2 \text{ } ^\circ\text{F} \quad (8.25)$$

This same method was used to calculate the rest of the average temperatures given in [Table 8.2](#).

The next step is to calculate the thermal deflection portion of the total rail strain using the average temperatures calculated in [Table 8.2](#) for each set of measurements.

$$\epsilon_{therm} = \frac{\Delta L_{G,therm}}{L_G} = \alpha(T_{ave} - T_0) \quad (8.26)$$

Rearranging terms in equation (8.26), yields the thermal deflection as

$$\Delta L_{G,therm} = L_G \alpha (T_{ave} - T_0) \quad (8.27)$$

The formula in equation (8.27) will now be used to calculate thermal deflection for each set of temperatures measured during the testbed testing.

The same average temperature measurement (T_{ave}), 128.2 $^\circ\text{F}$ evaluated at 46 minutes, will be used in this continued example. Introducing the ambient temperature (T_0) of 68.2 $^\circ\text{F}$ as per equation (8.13), and the applied load on the testbed (P_0) of 80,350 lbf from equation (8.14), into equation (8.27) to calculate thermal deflection yields

$$\Delta L_{G,therm} = 36\text{in} \times 6.5\text{E-}6\text{F}^{-1} \times (128.2\text{F} - 68.2\text{F}) = 0.01405 \text{ in.} = 0.3569\text{mm} \quad (8.28)$$

Before calculating the final mechanical deflection, one more step must be performed to accommodate the zero-stress condition of the rail because the rail neutral temperature calculation is always a comparison between rail at no stress with the current inherent stress in the rail. The sensor deflection was measured relative to the initial loading condition at (P_0) of 80,350 lbf and not from the rail neutral condition when the rail was at zero stress ($P=0$). To accommodate the stress free (zero stress) condition in the calculation the deflection corresponding to the load 80,350 lbf from 0 lbf load must be added, which will bring the total sensor deflection measurement from

the zero-stress condition. The total sensor deflection from zero stress condition can be calculated as follows:

$$\Delta L_{G,\text{total}} = \Delta L_{\text{zero stress}} + \Delta L_{G,\text{sensor}} \quad (8.29)$$

Here $\Delta L_{\text{zero stress}}$ corresponds to the deflection from zero stress to the initial loading condition (P_0) and $\Delta L_{G,\text{sensor}}$ is the deflection that the sensor outputs “relative” to the initial loading condition at P_0 .

The values from [Table 8.3](#) for the test time used for the current example are

$$\Delta L_{\text{zero stress}} = 0.1902 \quad (8.30)$$

$$\Delta L_{G,\text{sensor}} = 0.3674 \quad (8.31)$$

Substituting values from equations (8.30) and (8.31) in equation (8.29) to calculate total mechanical displacement yields

$$\Delta L_{G,\text{total}} = 0.1902\text{mm} + 0.3674\text{mm} = 0.5576\text{mm} \quad (8.32)$$

The next and final step is the extraction of the mechanical deflection portion from the total deflection measured by the sensor. This is achieved by removing the thermal deflection portion calculated previously, as follows:

$$\Delta L_{G,\text{mech}} = \Delta L_{G,\text{total}} - \Delta L_{G,\text{therm}} \quad (8.33)$$

Using values from equations (8.32) and (8.28) and substituting them into equation (8.33) yields

$$\Delta L_{G,\text{mech}} = 0.5576 - 0.3569 = 0.2007\text{mm} \quad (8.34)$$

To calculate the current mechanical force in the rail, equation (8.12) can be rearranged. Thus, the force in the rail corresponding to the deflection $\Delta L_{G,\text{mech}}$ calculated in equation (8.34) can be expressed as

$$P_{\text{mech}} = \frac{\Delta L_{G,\text{mech}} E_R A_R}{L_G} \quad (8.35)$$

Substituting values from [Table 8.1](#) and equation (8.34) into equation (8.35), yields

$$P_{\text{mech}} = \frac{0.2007 \times 2.9\text{E}7 \times 13.32}{36 \times 25.4} = 84,773 \text{ lbf} \quad (8.36)$$

This is the inherent mechanical force in the rail at the time when the measurement was taken. This value would be very important for the railroads and their maintenance schedule, to decide if the force in the rail is detrimental enough to cause rail buckling or rail fracture potentially causing derailments.

The equivalent RNT is the calculated by combining equations (8.15) and (8.20), yielding

$$T_{\text{RN}} = \frac{P_{\text{mech}}}{\alpha E_R A_R} + T_0 \quad (8.37)$$

Calculating the equivalent RNT for the mechanical force calculated from sensor deflection in equation (8.36), corresponding to an RNT equivalent to 84,773 lbf, gives

$$T_{\text{RN,calc}} = \frac{P_{\text{mech}}}{\alpha E_R A_R} + T_0 = \frac{84,773}{6.5 \times 10^{-6} \times 2.9 \times 10^7 \times 13.32} + 68.2 = 102.0^\circ\text{F} \quad (8.38)$$

It is important to know whether the measurements made by the strain sensor and the calculations performed here are representative of the actual force or rail neutral temperature in the rail. To make such a comparison, information on actual force in the rail is needed and this is where the testbed comes into play. The load cells on the testbed were installed so as to have some kind of baseline comparison between actual force and calculated force using the new strain sensor.

As mentioned in the beginning of this chapter, load cell readings were recorded to be used as actual loads in the rail at the time of testbed measurements. Every time temperature measurements were recorded, actual load (load cell measurement) were also recorded. Comparing P (tension recorded from the load cells) to the above calculated P_{mech} in equation (8.36) provides insight into the inherent RNT apparent error in the measurement made by the new strain sensor and thermal deflection results.

Equation (8.37) can be used to calculate an equivalent RNT from the load cell reading (actual load in the rail at the time of measurement). The recorded value of load at that instant using the load cells was 73,023 lbf. Thus, the equivalent RNT for the recorded load cell reading is,

$$T_{RN,actual} = \frac{P_{mech}}{\alpha E_R A_R} + T_0 = \frac{73,023}{6.5 \times 10^{-6} \times 2.9 \times 10^7 \times 13.32} + 68.2 = 97.3^\circ\text{F} \quad (8.39)$$

An apparent RNT error in the measurement is now expressed as,

$$\Delta T_{RN,error} = T_{RN,calc} - T_{RN,actual} \quad (8.40)$$

Substituting values from (8.38) and (8.39) into equation (8.40) to calculate apparent error in rail neutral temperature measurement yields

$$\Delta T_{RN,error} = 102.0 - 97.3 = 4.7^\circ\text{F} \quad (8.41)$$

The apparent RNT error of 4.7 °F indicates that the rail neutral temperature calculated using the new strain sensor data, combined with the IR Spot sensor temperature measurements to evaluate the thermal strain, is within reasonable limits from the rail neutral temperature calculated using the actual load. The goal of the research is to be able to calculate the rail neutral temperature within $\pm 5^\circ\text{F}$ as mentioned in the objectives of this dissertation. These results are very encouraging.

[Table 8.3](#) shows all the calculated apparent RNT errors corresponding to the tests performed on the same day as the above example using CTE value of $6.5\text{E-}6^\circ\text{F}^{-1}$.

Table 8.3 Apparent RNT Error for Long Rail Steel Section Test

3 rd Order Polynomial Average Temperature (T_{ave})	Rail Reference Temperature (T_0)	Thermal Deflection ($\Delta L_{G,therm}$)	Sensor Deflection ($\Delta L_{G,sensor}$)	Initial Deflection for 80,350lbf ($\Delta L_{zero\ stress}$)	Total Deflection ($\Delta L_{G,total} = \Delta L_{G,sensor} + \Delta L_{zero\ stress}$)	Mechanical Deflection ($\Delta L_{G,mech}$ $= \Delta L_{G,total} - \Delta L_{G,therm}$)	Mechanical Force (P_{mech})	Apparent RNT Error ($\Delta T_{RN,error}$)
[°F]	[°F]	[mm]	[mm]	[mm]	[mm]	[mm]	[lbf]	[°F]
186.29	68.20	0.7019	0.7454	0.1902	0.9356	0.2338	98759.03	12.39
159.85	68.20	0.5447	0.5527	0.1902	0.7429	0.1982	83738.49	5.44
142.12	68.20	0.4394	0.4753	0.1902	0.6655	0.2261	95523.84	9.50
128.25	68.20	0.3569	0.3674	0.1902	0.5576	0.2007	84772.94	4.68
109.69	68.20	0.2466	0.2292	0.1902	0.4194	0.1728	73006.92	-0.81
99.25	68.20	0.1845	0.1952	0.1902	0.3854	0.2009	84874.50	3.52
90.75	68.20	0.1340	0.1450	0.1902	0.3352	0.2012	84984.46	3.19

Looking at the apparent RNT error in [Table 8.3](#) it is clear that the data looks a little biased on the positive side.

It should be recognized that values of the CTE different from the value used in the above example were obtained during thermal-only testing of the rail section, as reported in [Appendix E](#). This suggests re-calculating the apparent RNT error for different values of CTE and investigating the possible existence of an optimum CTE value which minimizes this apparent RNT error.

To calculate an optimized CTE value using current data, a root mean square method was used. In this method the root mean square (RMS) of the apparent rail neutral temperature error ($\Delta T_{RN,error}$) was calculated by manually varying the CTE and plotting the resulting apparent RNT error against the CTE, as shown in [Figure 8.14](#). The low point on the graph, or in other words the minimum deviation (error) represents an optimized value of CTE. It should be noted that this “optimized” CTE is quite a bit higher than the “accepted” CTE currently in use for rail steel.

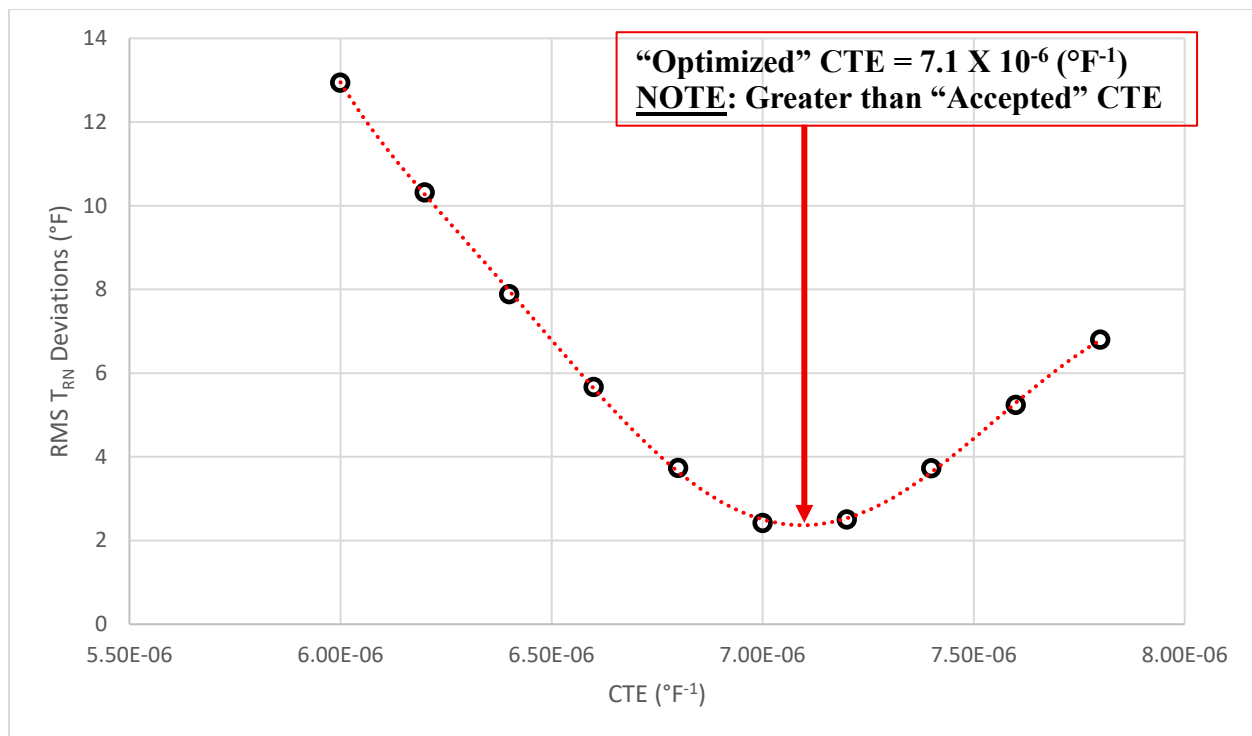


Figure 8.14 RMS Method for Optimizing CTE

Using the optimized CTE value of $7.1\text{E-}6\text{ }^{\circ}\text{F}^{-1}$, all the calculations were re-performed, and the new apparent errors for RNT are summarized in [Table 8.4](#).

Table 8.4 Apparent RNT Error for Long Rail Steel Section Test with Optimized CTE

3 rd Order Polynomial Average Temperature (T_{ave})	Rail Reference Temperature (T_0)	Thermal Deflection ($\Delta L_{G,therm}$)	Sensor Deflection ($\Delta L_{G,sensor}$)	Initial Deflection for 80,350lbf ($\Delta L_{zero\ stress}$)	Total Deflection ($\Delta L_{G,total} = \Delta L_{G,sensor} + \Delta L_{zero\ stress}$)	Mechanical Deflection ($\Delta L_{G,mech} = \Delta L_{G,total} - \Delta L_{G,therm}$)	Mechanical Force (P_{mech})	Apparent RNT Error ($\Delta T_{RN,error}$)
[°F]	[°F]	[mm]	[mm]	[mm]	[mm]	[mm]	[lbf]	[°F]
186.29	68.20	0.7666	0.7454	0.1902	0.9356	0.1690	71390.54	1.37
159.85	68.20	0.5950	0.5527	0.1902	0.7429	0.1479	62497.50	-2.77
142.12	68.20	0.4799	0.4753	0.1902	0.6655	0.1856	78390.67	2.45
128.25	68.20	0.3898	0.3674	0.1902	0.5576	0.1677	70855.83	-0.79
109.69	68.20	0.2693	0.2292	0.1902	0.4194	0.1501	63391.86	-4.24
99.25	68.20	0.2016	0.1952	0.1902	0.3854	0.1839	77678.65	0.60
90.75	68.20	0.1464	0.1450	0.1902	0.3352	0.1888	79757.54	1.01

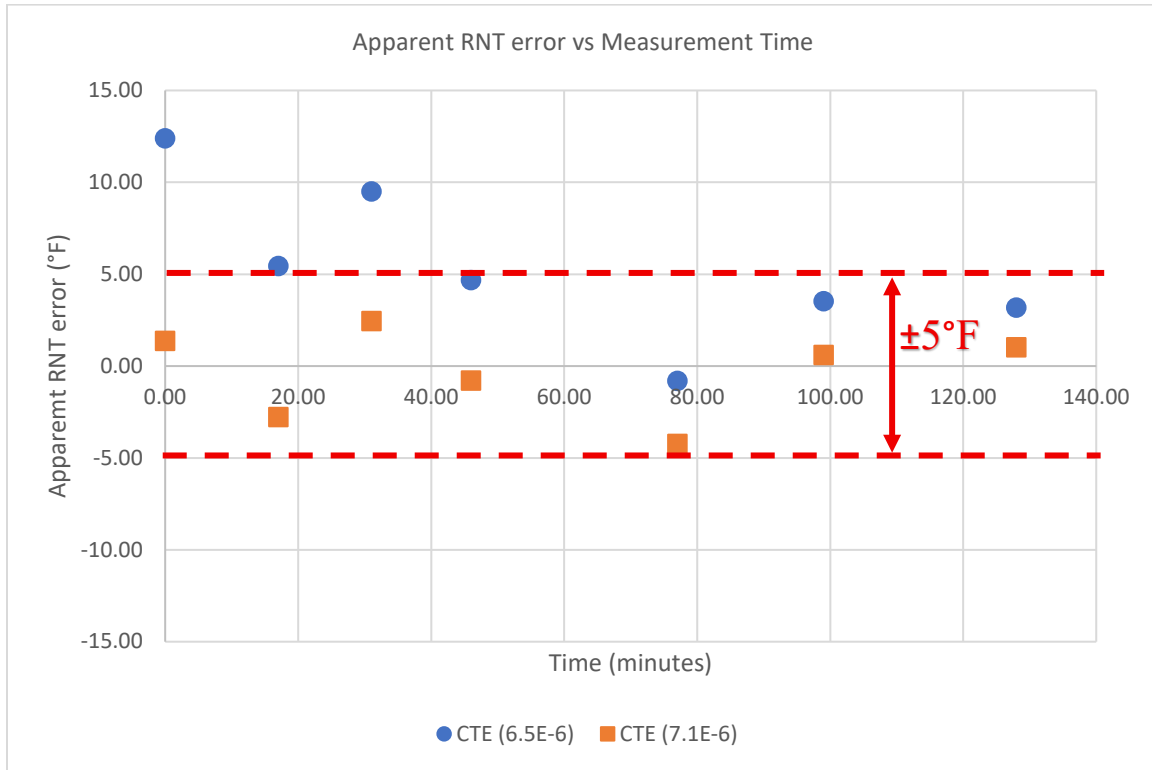


Figure 8.15 Combined Apparent RNT Errors for CTE $6.5\text{E-}6^{\circ}\text{F}^{-1}$ and $7.1\text{E-}6^{\circ}\text{F}^{-1}$

[Figure 8.15](#) shows the apparent RNT error calculated using CTE values of $6.5\text{E-}6^{\circ}\text{F}^{-1}$ and $7.1\text{E-}6^{\circ}\text{F}^{-1}$. From the plot it is very easy to visualize that all the data for apparent RNT error calculated with CTE of $7.1\text{E-}6^{\circ}\text{F}^{-1}$ fall within the desired $\pm 5^{\circ}\text{F}$ limits, whereas the apparent RNT

error calculated using the “accepted” CTE of $6.5\text{E-}6^{\circ}\text{F}^{-1}$ are all biased on the positive side with some having errors significantly greater than $+5^{\circ}\text{F}$.

Looking at the significantly reduced apparent errors with the optimized CTE value in [Figure 8.15](#) suggests that the currently accepted CTE value may need to be re-visited. The current CTE is an average number for steel rail, but the CTE can be dependent on various things including carbon content of the rail, and direction of the expansion (longitudinal, lateral, or axial). Since changes/advancements may have happened in rail manufacturing methods (such as carbon content) since the currently accepted value of CTE was established, the typical average CTE value for rail may be a little different now. The detailed investigation of CTE is not part of the current research; however, based on the above results this certainly is something that needs to be investigated at a later stage.

8.3.2 Dual Deflection Measurements on the Non-Heater Side of the Rail

After completing successful testing in [Section 8.3.1](#) for single deflection measurements on the non-heater side of the rail, it was determined to update the testing process to understand more aspects of mechanical and thermal loading effects. It is well-known that with steel rails in the field (in-track) sometimes there may be shade of a tree covering a portion of the rail, or the rail may be passing under a bridge where a portion of the rail is shielded from direct sunlight. How do these shadow effects influence the rail neutral temperature and mechanical stress? Do they actually have a major effect, or is it negligible? All these questions need to be answered, and one way to investigate this is to include heating with one heater on one end of the rail and perform mechanical and thermal loading test at two different (dual) rail locations on the same side of the rail. An additional benefit with this dual testing is that essentially twice the number of measurements can

be taken over essentially the same testing period required for the previously discussed single deflection measurement case.

[Figure 8.16](#) shows a single IR heater positioned on one end of the rail (left end) and two sets of dot-peen patterns for dual deflection measurements using the new strain sensor.

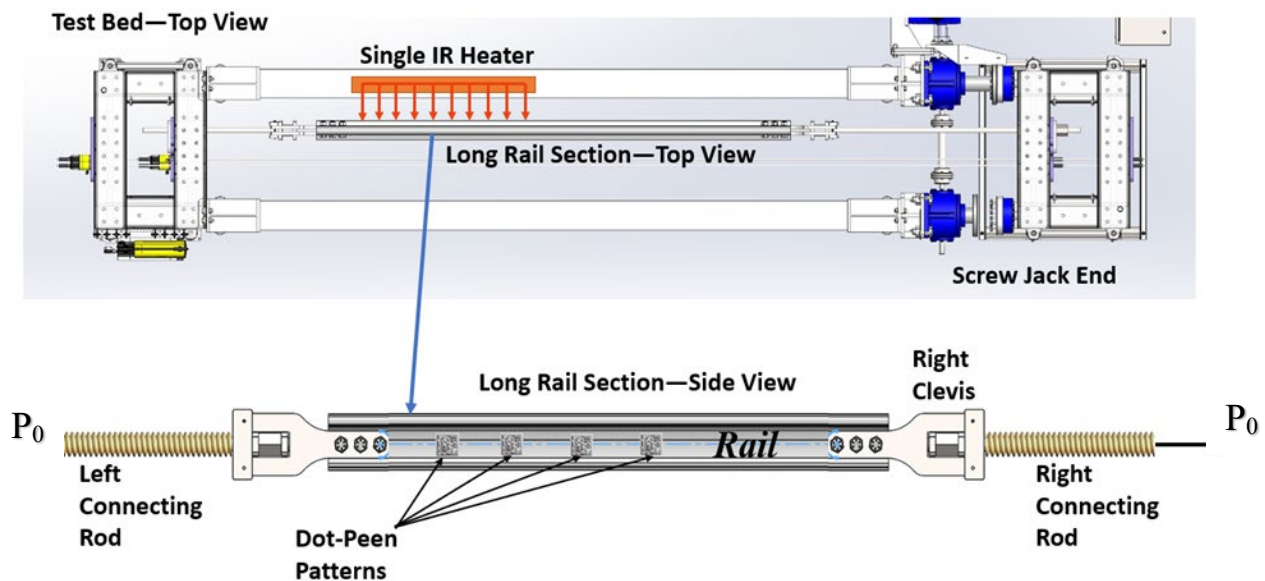


Figure 8.16 Image of Long Steel Rail Section with Two Sets of Dot-Peen Patterns

The same basic testing procedure was followed as in [Section 8.3.1](#). Initially, the rail was tensioned to a load value approximating a RNT of about 105 °F, representative of the recommended RNT in the state of Kansas[78]. This corresponded to an initial tension of about 93,500 lbs. Mechanical settling was allowed to take place for a period of about 2 hours prior to heating of the rail, and the tension finally settled down to about 92,232 lbs. The IR heater was then turned on, and the rail was heated until it reached about 205 °F. The heater was then turned off, and the wait/relaxation time was around 15 minutes allowing the rail temperature to re-distribute before starting to take deflection measurements with the strain sensor. The readings were taken in the following sequence: left sensor position first and then center sensor position, for each

dual set of strain sensor measurements. The process for each set of dual measurements as shown in [Figure 8.17](#) was as follows:

1. Take an IR Imaging camera image of the gage length region.
2. Mount the sensor on the left side, as shown in [Figure 8.17](#) , and take strain sensor readings.
3. Remove the strain sensor and take temperature measurements on the head of the rail with the IR Spot sensor at 7 equidistant (9" apart) locations.
4. Take an IR Imaging camera image of the gage length region.
5. Mount the sensor on the center position, in [Figure 8.17](#), and take strain sensor readings.
6. Remove the strain sensor and take temperature measurements on the head of the rail with the IR Spot sensor at 7 equidistant (9" apart) locations.

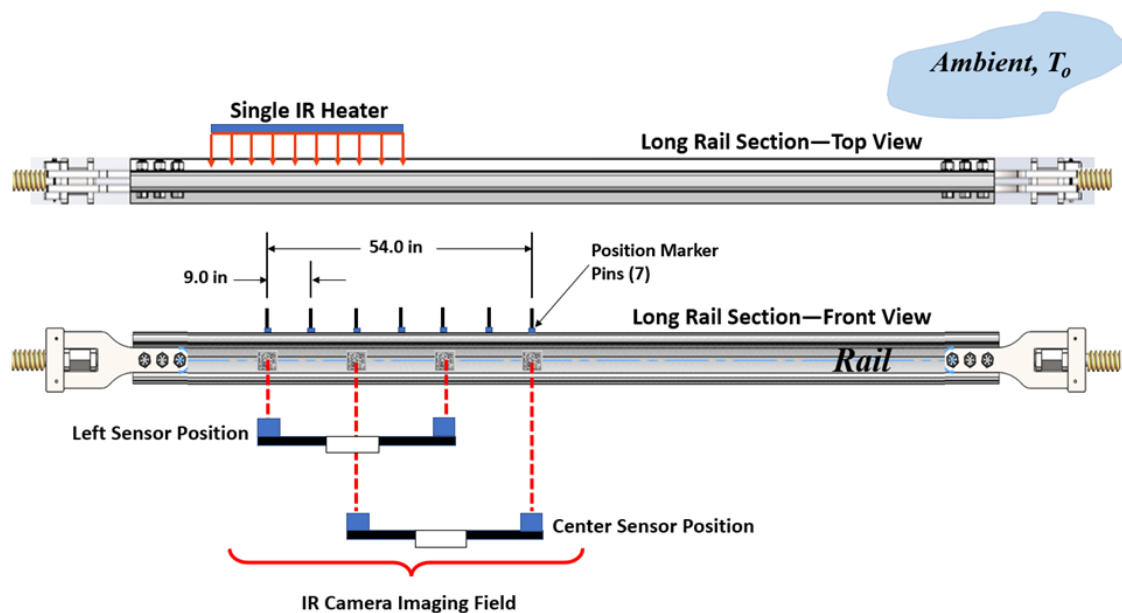


Figure 8.17 Sensor Position for Dual Dot-Peen Locations for Strain Measurement

All the temperature measurements were averaged within the sensor gage length region using an approach similar to the 3rd order polynomial integration method introduced earlier in this chapter. The temperature measurements were again taken in 9" increments starting from the left end of the left sensor position to the right end of the center sensor position. To identify the locations

of the temperature measurement points on the rail, position marker pins were placed on the top (head) of the rail, as shown in [Figure 8.17](#). A total of 7 temperature measurements were taken for each deflection measured by the sensor, covering a total length of 54” as shown in [Figure 8.17](#).

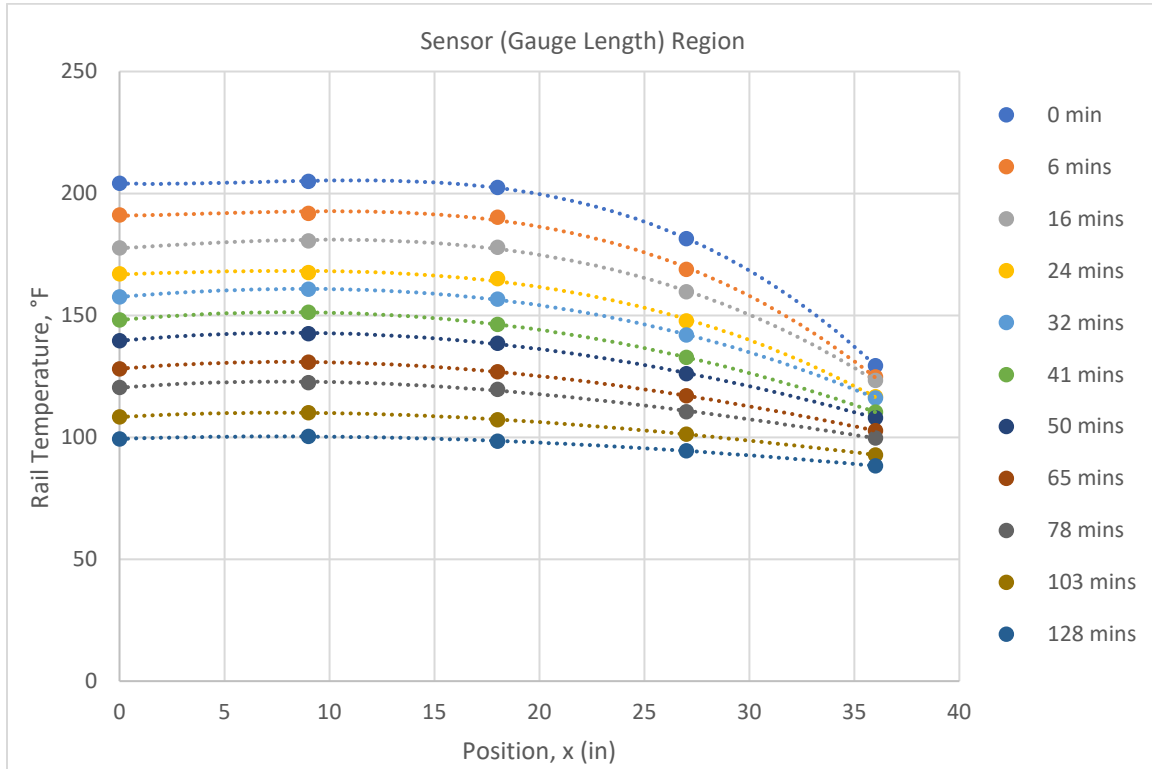


**Figure 8.18 3rd Order Polynomial Data for Thermal Loading of Long Steel Rail Section-
Left Dot-Peen Positions**

Table 8.5 3rd Order Polynomial Coefficients for Left Dot-Peen Positions

Duration (min)	a3	a2	a1	a0	T _{ave} (Integrated)
0	-0.00314	0.06005	-0.16283	204.05857	190.4
6	-0.00233	0.02945	0.11746	190.89143	178.5
16	-0.00143	-0.00582	0.55304	177.48714	168.3
24	-0.00123	-0.00212	0.27619	166.81714	156.5
32	-0.00047	-0.03510	0.71812	157.56429	149.9
41	-0.00011	-0.04656	0.77434	148.09714	140.6
50	0.00014	-0.05203	0.81746	139.53143	133.4
65	0.00025	-0.04885	0.72725	128.08571	123.0
78	0.00035	-0.04744	0.67368	120.30429	116.1
103	0.00024	-0.03377	0.47421	108.31857	105.1
128	0.00009	-0.01949	0.27751	99.32286	97.0

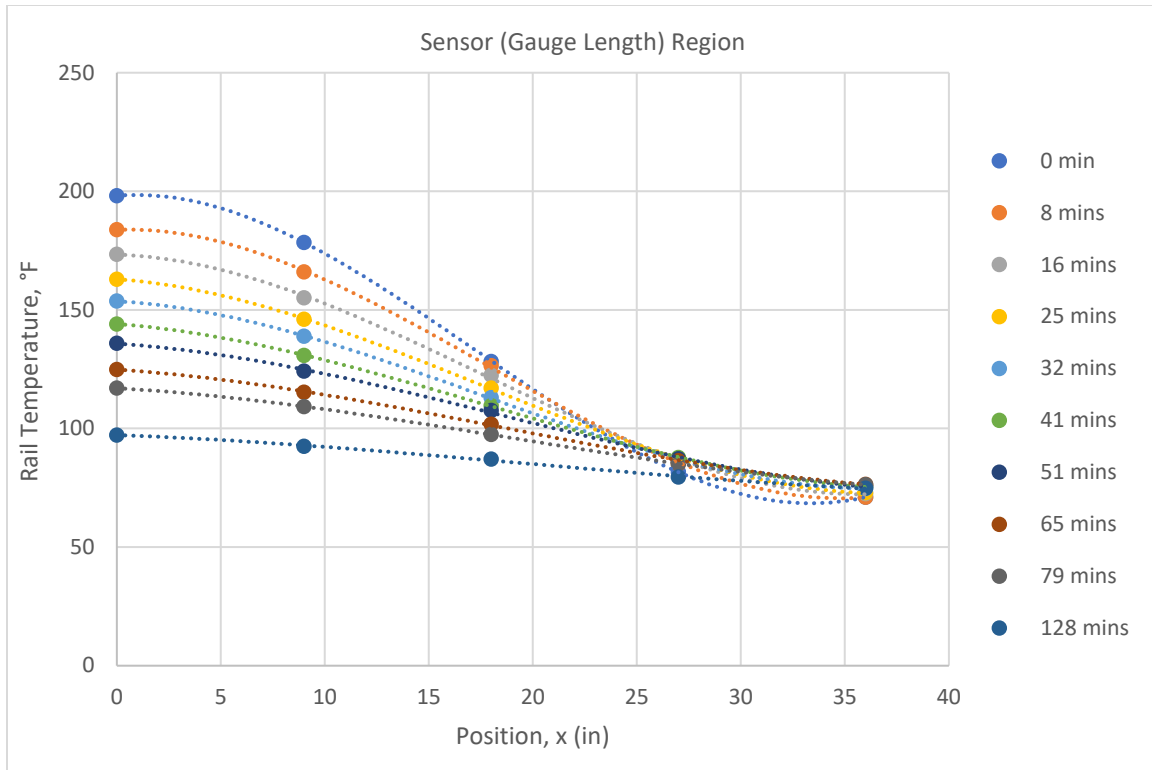


Figure 8.19 3rd Order Polynomial Data for Thermal Loading of Long Steel Rail Section- Center Dot-Peen Positions

Table 8.6 3rd Order Polynomial Coefficients for Center Dot-Peen Positions

Duration (min)	a3	a2	a1	a0	T _{ave} (Integrated)
0	0.00761	-0.39206	0.71984	198.12571	130.5
8	0.00562	-0.29859	0.32698	183.76857	126.3
16	0.00421	-0.22196	-0.26693	173.28286	121.7
25	0.00314	-0.16587	-0.60542	162.93857	117.1
32	0.00290	-0.15220	-0.47804	153.64286	113.2
41	0.00198	-0.10573	-0.66495	144.06143	109.5
51	0.00154	-0.08660	-0.55754	135.74143	106.3
65	0.00107	-0.06023	-0.56878	124.82286	101.1
79	0.00086	-0.04868	-0.48929	116.98429	97.1
128	0.00040	-0.02337	-0.30225	97.20429	86.3

[Figure 8.18](#) and [Table 8.5](#) show the 3rd order polynomial fits and the corresponding polynomial coefficients calculated for the left position dot-peen mark measurements, and [Figure 8.19](#) and [Table 8.6](#) shows the same for the center position dot-peen measurements. This data was used to calculate the thermal deflection needed in order to extract the mechanical strain.

The sensor was mounted for taking measurements and then removed every time before taking another measurement, in order to give full access of the rail frontal area to the IR Imaging camera. The images taken from the IR Imaging camera were used to corroborate the temperature measurements taken using IR Spot sensor. The thermal software available from FLIR for the imaging camera was used to create line scans to compare with the point-wise handheld sensor readings, and also to further investigate other methods for temperature averaging (for example, box averaging, which is further discussed in [Appendix B](#)). [Figure 8.20](#) shows an image from the IR Imaging camera for the heated rail section, showing the markers on top of the rail for identifying the IR Spot thermometer measurement locations.

As shown in [Figure 8.20](#), because the IR heater was positioned more toward the left end of the rail, the rail was much hotter on the left side compared to the right side of the rail image. This shows the resulting asymmetry of the temperature distribution from left to right within the rail geometry. As discussed in previous chapters, the rail longitudinal thermal re-distribution time is quite long giving many opportunities to take multiple strain measurements in the left and center sensor positions before the rail returned (cooled) to ambient temperature.

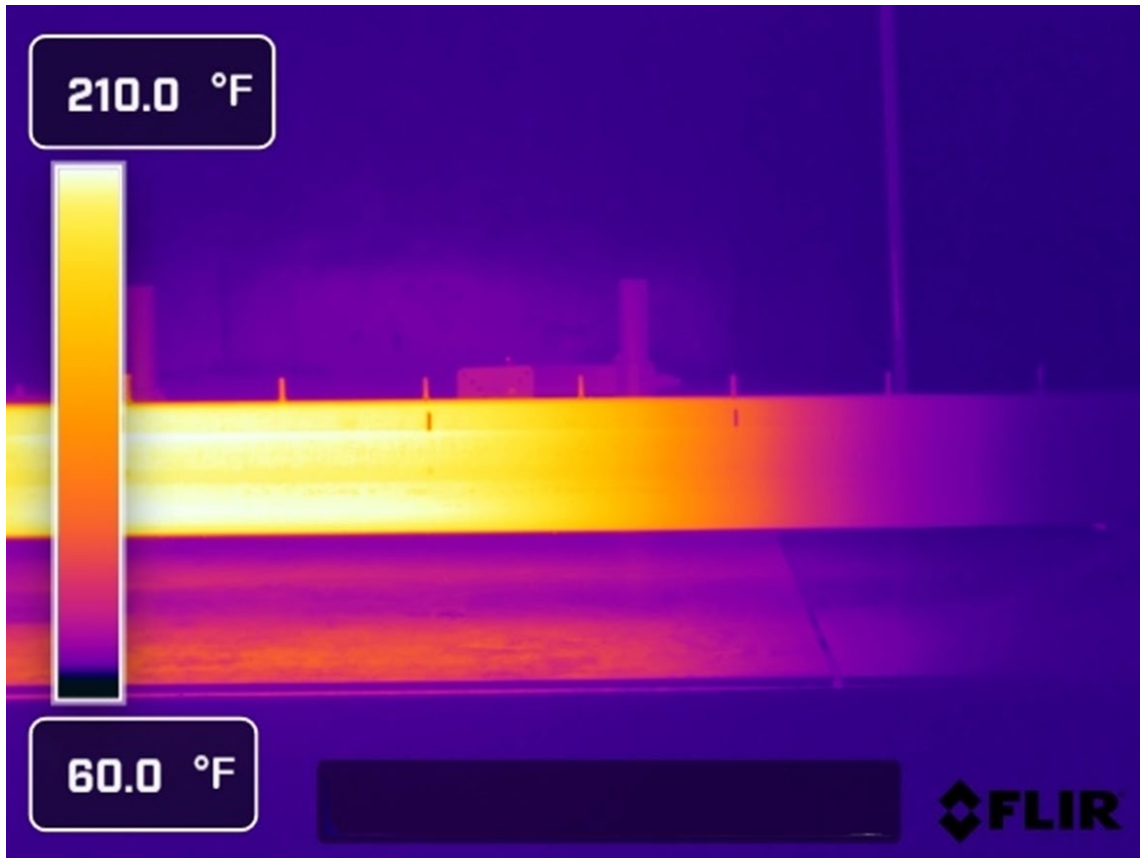


Figure 8.20 IR Camera Image Capture of Thermally Loaded Long Rail Section

After performing calculations similar to those discussed in [Section 8.3.1](#), the apparent RNT error was calculated for the dual (left and center) sensor measurements covering a range of average rail temperatures from about 190 °F down to just under 90 °F. The CTE value of $6.5\text{E-}6 \text{ }^{\circ}\text{F}^{-1}$ was used for the set of calculations shown in [Tables 8.7](#) and [8.8](#). The tabulated results are shown in [Tables 8.7](#) and [8.8, respectively](#).

Table 8.7 Apparent RNT Error for Long Rail Steel Section Test-Left Sensor Position

3 rd Order Polynomial Average Temperature (T _{ave})	Rail Reference Temperature (T ₀)	Thermal Deflection ($\Delta L_{G,therm}$)	Sensor Deflection ($\Delta L_{G,sensor}$)	Initial Deflection for 92,232lbf ($\Delta L_{zero\ stress}$)	Total Deflection ($\Delta L_{G,total} = \Delta L_{G,sensor} + \Delta L_{zero\ stress}$)	Mechanical Deflection ($\Delta L_{G,mech}$ $= \Delta L_{G,total} - \Delta L_{G,therm}$)	Mechanical Force (P _{mech})	Apparent RNT Error ($\Delta T_{RNT,error}$)
[°F]	[°F]	[mm]	[mm]	[mm]	[mm]	[mm]	[lbf]	[°F]
190.40	69.00	0.7216	0.6571	0.2183	0.8754	0.1539	64997.37	-5.99
178.53	69.00	0.6510	0.6068	0.2183	0.8251	0.1741	73550.11	-3.05
168.26	69.00	0.5900	0.5407	0.2183	0.7591	0.1691	71435.91	-4.39
156.47	69.00	0.5199	0.4527	0.2183	0.6710	0.1511	63835.03	-7.83
149.86	69.00	0.4806	0.3811	0.2183	0.5994	0.1188	50188.64	-13.59
140.59	69.00	0.4255	0.3635	0.2183	0.5818	0.1563	66044.39	-7.59
133.37	69.00	0.3826	0.3131	0.2183	0.5315	0.1489	62889.38	-9.15
123.00	69.00	0.3210	0.2621	0.2183	0.4805	0.1595	67373.17	-7.75
116.07	69.00	0.2798	0.1789	0.2183	0.3972	0.1174	49608.23	-15.12
105.06	69.00	0.2143	0.1443	0.2183	0.3627	0.1483	62650.63	-10.33
96.97	69.00	0.1662	0.1287	0.2183	0.3470	0.1808	76378.21	-5.18

Table 8.8 Apparent RNT Error for Long Rail Steel Section Test-Center Sensor Position

3 rd Order Polynomial Average Temperature (T _{ave})	Rail Reference Temperature (T ₀)	Thermal Deflection ($\Delta L_{G,therm}$)	Sensor Deflection ($\Delta L_{G,sensor}$)	Initial Deflection for 92,226lbf ($\Delta L_{zero\ stress}$)	Total Deflection ($\Delta L_{G,total} = \Delta L_{G,sensor} + \Delta L_{zero\ stress}$)	Mechanical Deflection ($\Delta L_{G,mech}$ $= \Delta L_{G,total} - \Delta L_{G,therm}$)	Mechanical Force (P _{mech})	Apparent RNT Error ($\Delta T_{RNT,error}$)
[°F]	[°F]	[mm]	[mm]	[mm]	[mm]	[mm]	[lbf]	[°F]
130.51	69.00	0.3656	0.3265	0.2183	0.5448	0.1792	75722.36	-1.92
126.26	69.00	0.3404	0.3069	0.2183	0.5252	0.1848	78077.53	-1.41
121.66	69.00	0.3130	0.2585	0.2183	0.4768	0.1638	69212.55	-5.41
117.05	69.00	0.2856	0.2342	0.2183	0.4526	0.1670	70532.47	-5.27
113.15	69.00	0.2624	0.1489	0.2183	0.3672	0.1048	44263.71	-16.04
109.48	69.00	0.2406	0.1884	0.2183	0.4067	0.1661	70161.10	-6.05
106.30	69.00	0.2217	0.1829	0.2183	0.4012	0.1795	75839.25	-4.07
101.10	69.00	0.1908	0.1513	0.2183	0.3696	0.1788	75529.91	-4.56
97.15	69.00	0.1673	0.0776	0.2183	0.2959	0.1286	54310.30	-13.30
86.34	69.00	0.1030	0.1152	0.2183	0.3335	0.2304	97345.26	3.14

Looking at apparent error in the RNT calculations above, it can be noted that some of the values exceed the desired $\pm 5^\circ\text{F}$ tolerance. but most of the errors are around $\pm 5^\circ\text{F}$ as per the goal of the project.

As discussed in previous section, the CTE value can have a very high influence on the apparent RNT error. To check the effect of CTE on apparent RNT errors for these measurements, three different plots were created with combined data from left and center sensor position measurements. The plots shown in [Figure 8.21](#), [8.22](#), [8.23](#) corresponds to CTE values of $6.0\text{E-}6\ ^\circ\text{F}^{-1}$, $6.5\text{E-}6\ ^\circ\text{F}^{-1}$ and $7.1\text{E-}6\ ^\circ\text{F}^{-1}$. The apparent RNT error data for left position sensor displacements and center

position sensor displacements were merged to create an overall data set to investigate the extent to which the apparent RNT error falls within the desired $\pm 5^{\circ}\text{F}$ range for each of these three values of CTE. Dashed lines indicate $\pm 5^{\circ}\text{F}$ upper and lower limits of error about each trend line shown.

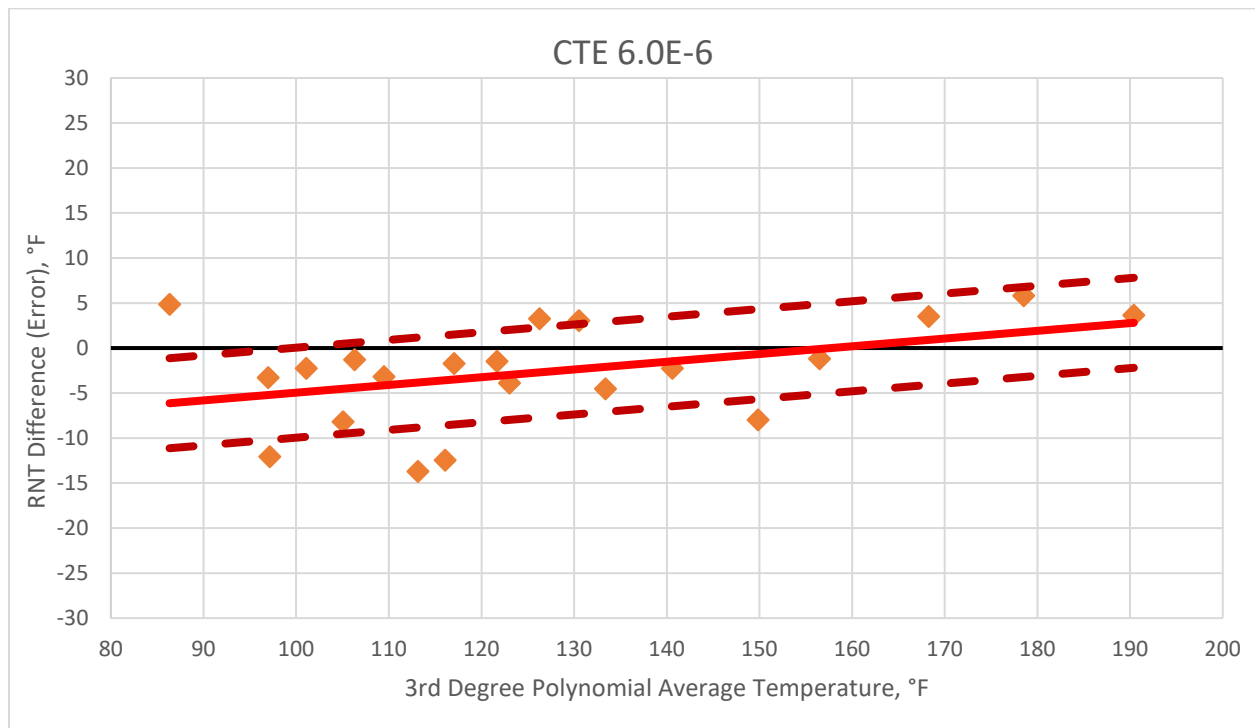


Figure 8.21 Dual Location Displacement Measurement Data Using $6.0\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ CTE

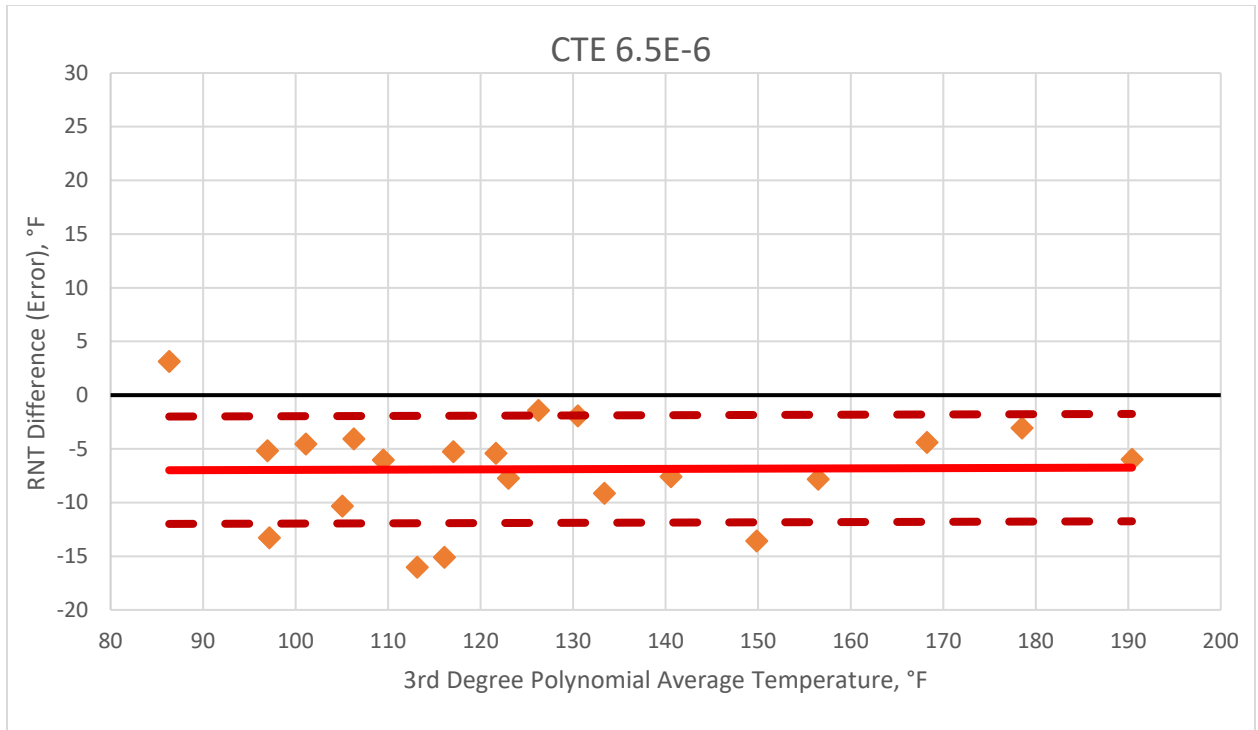


Figure 8.22 Dual Location Displacement Measurement Data Using $6.5\text{E-}6$ °F⁻¹ CTE

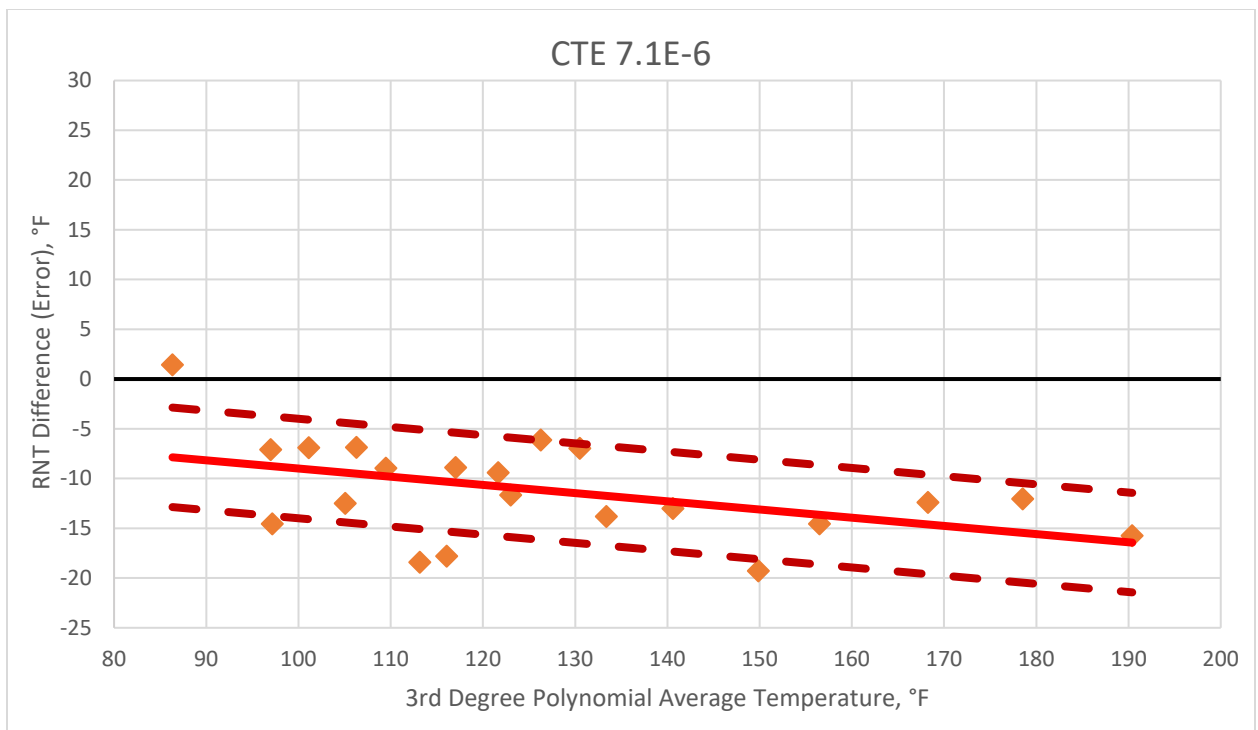


Figure 8.23 Dual Location Displacement Measurement Data Using $7.1\text{E-}6$ °F⁻¹ CTE

It can be seen from [Figures 8.21, 8.22 and 8.23](#), that as the CTE values are changed in order of increasing magnitude, the slope of the data/trendline is changing as well. For the $6.0\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ CTE, the trendline is observed to pass through the horizontal axis with a positive slope. For the $6.5\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ CTE, the trendline is biased on the negative side of the data (and nearly all RNT errors are negative) but the slope is almost zero. For the CTE of $7.1\text{E-}6\text{ }^{\circ}\text{F}^{-1}$, not only is the data is biased on the negative side but the trendline also has a negative slope.

This research has brought some exciting outcomes showing that the apparent RNT error is not only dependent on, but is highly sensitive to the CTE value. Further analysis is on-going to understand the reasons for the observed bias in the data, and also to potentially correct for it.

One more thing that can be confirmed from all these results is that, even though the different data sets have different slopes and amounts of bias, the majority of the results fall within $\pm 5^{\circ}\text{F}$ of the trendlines. The expectation would be that, once the bias issues are resolved, the results will be even better.

To further this research, work is on-going to find the sources of error that affect the measurement of RNT and result in RNT error higher than the desired $\pm 5^{\circ}\text{F}$. Different methods for calculating temperature averaging are being explored, with one being “box averaging” which can be calculated from IR Imaging camera images using FLIR Thermal Studio software. Further information about this work is mentioned in [Appendix B](#).

Chapter 9 – Summary and Conclusions

This dissertation began with the rail neutral temperature concept, which refers to the temperature at which the stresses in the rail are zero (neutral). Non-contact measurement of rail neutral temperature is considered by some to be the holy grail of the railroad industry because no reliable non-contact method exists for monitoring the stress and rail neutral temperature in the field at an arbitrary location. There are various contact methods available to measure rail stress and RNT with some being destructive while others are non-destructive methods. However, almost all of them require track shutdown, which can cause significant delays and result in longer train travel times. All the available methods require the rail to be destroyed or removed from track for measuring the state of stress; or, the method itself is time consuming, includes expensive instruments, or affects the rail geometry, structure or surface.

Among the existing contact methods to measure stress by first measuring surface strain, the resistance strain gage is one of the most common and widely used methods. However, considering its use on steel rail in the field, it is very hard to install because the surface of the rail is not sufficiently smooth for proper strain gage mounting. Also, surface bonding is likely not rugged enough to maintain strain gage measurement capability for a long period of time. A more feasible and practical idea would be to use a non-contact method to avoid any pre-conditioning or damaging of the installed rail. A review of the various non-contact methods available is given in this dissertation, while also comparing their ease of use and practicality along with their respective uncertainty. Although all of them tend to have high accuracy, in principle, most of them are not of practical use for monitoring of rail stress because of the changing nature of the rail surface. All these methods require some kind of surface tag for sensing surface displacement. Such tags include laser speckle, speckle paint, and surface features, neither of which can be relied upon for

surface strain measurement on steel rail. To overcome this issue, a robust tagging method called dot-peening has been proposed in this research, as it has the potential to enable the monitoring of track surface strain (and related stress) for a long period of time.

A new and practical method of assessing the state of stress in continuously welded steel railway rail is proposed and demonstrated in this dissertation. It involves development of a new non-contact rail strain sensor that can measure the state of rail stress by measuring total strain and subsequently extracting from this the mechanical stress, resulting in an equivalent rail neutral temperature. Prior non-contact strain sensors were primarily designed to measure smaller displacements over small surface areas. However, continuously welded steel rail can extend over thousands of miles. This new strain sensor was designed to have a longer gage length than typical existing surface sensors to achieve the desired rail strain measurement resolution. However, it was not so long that it would be difficult to carry and periodically mount on steel rail. The design of the sensor and the creation of a program to calculate the state of rail stress and the equivalent RNT were major tasks associated with the overall project, which was funded by the Federal Railroad Administration (FRA). The initial development of the design involved uncertainty analysis assessing the effect of gage length with different camera and lighting arrangements. An existing non-contact multi-camera strain measurement system was used to investigate varying strain resolution, in conjunction with the testing of ring lighting features to evaluate its effectiveness on camera image captures. A program was created within the LabVIEW interface associated with the multi-camera system, which pre-processed the image captures (two cameras) and completed pattern matching to calculate a relative displacement from an initial baseline reference. The method is very basic and works by first taking a reference image prior to any kind of surface movement (or stress induced displacement), and then a follow-up image is taken and correlated

with the first image to yield a relative displacement measurement. The Technology Development Institute (TDI) at Kansas State University, comprised of a team of engineers led by John Bloomfield at TDI, was responsible for designing and fabricating the proposed new strain sensor. This included the development of a LabVIEW interface, and magnetic sensor mounting hardware to enable quick mounting and dismounting of the new sensor from steel rail. A dot-peen pattern was proposed (by TDI) for marking the steel rail with a displacement tag for assessing rail surface strain. As part of the current experimental dissertation research, a cross pattern of indents was selected and generated using a commercially available dot-peen machine.

In addition to the above sensor development, there was a need to complete a full-scale laboratory proof of concept. For this purpose, a full-scale testbed facility was fabricated and calibrated at KSU (by TDI) with a loading capacity of 250kips tension. It was equipped with calibrated load cells to measure the tension with an error less than 1% error of the full-scale bed capacity. This testbed allowed for complete mechanical and combined mechanical & thermal loading tests on sections of steel rail with controlled conditions. This testing was necessary not only to understand the accuracy of the proposed sensor system, but also to verify the viability of the overall method of RNT measurement, which involved extracting thermal strain from the total strain (measured by the sensor) and assessing the resultant mechanical strain, from which the rail stress could be determined. A primary focus of this dissertation work was to conduct detailed full-scale testing of the new strain sensor on this testbed and provide the first proof-testing of the proposed RNT measurement procedure.

The first detailed calibration of the new sensor took place in the NCPM laboratory at KSU, on a bench-top setup which provided calibrated metal plate displacement using a micrometer stage and a digital indicator with a displacement resolution of ± 0.001 mm. Performing calibration of the

new strain sensor demonstrated that the sensor was able to capture displacement within ± 0.001 mm of the actual calibrated displacement, verifying its potentially high capability to measure very minute strain on a rail surface (even likely beyond the digital indicator's resolution). This bench calibration was followed by later calibration testing on the new full-scale testbed. Starting with the actual rail testing on the testbed, the first tests were mechanical loading tests performed on a 77 in long rail section to compare the readings between load cell and the new strain sensor. Mechanical testing revealed that too small of a rail section can result in hysteresis, which became apparent while decreasing the applied load. Placing the sensor too close to the clevis pin end connections for tensioning tests caused problems, because of the likely existence of stress concentrations near the clevis pin bolt holes, indicating the need to properly address St. Venant's principle. It was concluded that a longer 147 in rail section would be a better option for the mechanical testing, and this found to greatly improve the measurements by allowing mounting of the sensor further away from the clevis pins. All the strain sensor measurements were very close to load cell readings with comparison trendlines having R^2 values of about 0.99 for increasing and decreasing loading. Blind tests were also conducted where a known tension was set in the rail by one of the advisors and the undisclosed tension was then measured with the new sensor. The blind test measurements were very close to actual readings, within less than 3% error.

Before the combined thermal and mechanical loading, purely thermal loading was investigated in the laboratory. This testing concluded that the rail may have thermal expansion characteristics a little different than represented by the "universally" accepted coefficient of thermal expansion (CTE) of $6.5E-6$ $^{\circ}\text{F}^{-1}$. One more thermal expansion test was conducted in the laboratory with manual mechanical Whittemore Gage which basically provided similar results

showing the CTE of rail is not around $6.5\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ but it is a little higher than that, in the range of $7\text{-}7.1\text{E-}6\text{ }^{\circ}\text{F}^{-1}$.

Some preliminary thermal tests were performed on a bench top setup using a small 17.5” rail section in the NCPM lab. These tests revealed the Biot number to be very small (nominally less than about 0.003) indicating the small rail section can be assumed as a thermally lumped system. Thermal penetration time through the rail web was estimated to be around 0.4 minutes, and the lumped system transient heating time was measured to be about 72 minutes. Longitudinal temperature re-distribution time was measured to be approximately 56 minutes for the small rail section, which indicates that rail temperature quickly redistributes (equalizes) in the transverse direction compared to longitudinally. Also, as part of this initial small case testing, the rail heater power requirements were estimated and a 4000W IR heater was selected to provide the required full-scale rail heating in an acceptable amount of time.

Accurate temperature measurement of the rail is very important because determination of the average rail temperature forms the basis for calculating the thermal strain component, which must be removed from the total strain measured by the sensor in order to yield the inherent mechanical stress. Various tests were performed comparing thermocouples, a FLIR IR spot sensor, and an IR Imaging camera. The tests revealed good results with all three different measurement methods. These comparison tests were performed to validate the non-contact temperature measurement procedure, and to reveal any important measurement issues associated with temperature measurements on the rail.

Finally, full-scale testing with mechanical and thermal loading combined was performed as a very important prerequisite check on the new sensors capability to perform in a simulated field environment. The first combined testing was performed by taking displacement and temperature

measurements on one side in the middle of the long 147 in rail section. This testing revealed that if an optimized CTE value of $7.1\text{E-}6^{\circ}\text{F}^{-1}$ is used, instead of the generally accepted CTE value of $6.5\text{E-}6^{\circ}\text{F}^{-1}$, the apparent rms RNT error is minimized and all the RNT measurements are within $\pm 5^{\circ}\text{F}$ error, the goal of the project. Another set of tests was performed by taking two separate sensor measurements on the same side of the rail, one with the sensor positioned on the left and one with the sensor positioned approximately in the center of the rail. This was done as additional verification of the temperature distribution (average) measurements and to check the sensors ability to perform in a simulated field environment. This test revealed that using different CTE values ranging from $6.0\text{E-}6^{\circ}\text{F}^{-1}$ to $7.1\text{E-}6^{\circ}\text{F}^{-1}$, the slope of the RNT deviation (error) trendline changes from positive to 0 to negative. Additionally, it was noticed that even though the RNT was resolved approximately within a scatter of about $\pm 5^{\circ}\text{F}$ error, there is a bias in the data with most of the deviation data on the negative side. Further investigation into the reasons for this behavior in the data, and some different approaches for determining average temperature, is underway.

The results of this dissertation imply that the new strain sensor with the proposed new RNT measurement procedure, is very capable of measuring inherent stress in the rail, including its equivalent rail neutral temperature for maintenance of the railway tracks. The encouraging results from this dissertation research, and the demonstrated methodology, should significantly contribute to the practical goal of developing a means to determine and periodically monitor the state of stress and the RNT. This represents a new approach for continuous monitoring of rail stress. Whenever track is cut/replaced for maintenance, a growing network of baseline track sections will develop, allowing an ever-increasing database of track stations that can be accessed for periodic monitoring of the state of rail stress using this new technology—establishing a completely new paradigm for in-track monitoring of the state of rail stress for CWRs.

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Appendix A – Uncertainty Analysis

This Appendix discusses the uncertainty analysis of the rail neutral temperature measurements performed in the main body of the dissertation. It is very important to know and understand the uncertainty in the measurements performed in the experiment for data validation. It provides the range of possible values around a measurement. The methodology is taken from Coleman and Steele Jr.[71].

A.1 General Equation (2 Variable)

This sub-section explains the generalized equation for uncertainty analysis pertaining to 2 different variables.

Assume,

$$z = f(x, y) \quad (A.1)$$

Where x and y are two independent variables.

Performing total differential of equation (A.1)

$$dz = \left(\frac{\partial f}{\partial x}\right) dx + \left(\frac{\partial f}{\partial y}\right) dy \quad (A.2)$$

Here dz signifies error in z. Replace $dz = E_z$ (Error in z) in equation (A.2)

$$E_z = \left(\frac{\partial f}{\partial x}\right) E_x + \left(\frac{\partial f}{\partial y}\right) E_y \quad (A.3)$$

Taking RMS (root mean square) of equation (A.3)

$$\overline{E_z^2} = \left(\frac{\partial f}{\partial x}\right)^2 \overline{E_x^2} + \left(\frac{\partial f}{\partial y}\right)^2 \overline{E_y^2} + \left[2 \left(\frac{\partial f}{\partial x}\right) \left(\frac{\partial f}{\partial y}\right) \overline{E_x E_y}\right] \quad (A.4)$$

The RMS error can also be represented in terms of standard deviation as follows,

$$\sigma_z^2 = \frac{1}{n-1} \sum_{i=1}^n \overline{E_z^2} \quad (A.5)$$

Substituting equation (A.5) in equation (A.4) for each error term,

$$\sigma_z^2 = \left(\frac{\partial f}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 \sigma_y^2 \quad (\text{A.6})$$

Absolute uncertainty (U_x) is defined as,

$$U_z = \pm t_{n-1} \sigma_z \quad (\text{A.7})$$

For $n \geq 30$: $t_{n-1} = 1.96 (\approx 2)$

Yielding,

$$U_z = \pm 2 \sigma_z \quad (\text{A.8})$$

Similar to equation (A.8), the uncertainty in x and y can be written as

$$U_x = \pm 2 \sigma_x \text{ and } U_y = \pm 2 \sigma_y \quad (\text{A.9})$$

Substituting all the values from equations (A.8) and (A.9) in equation (A.6) yields,

$$U_z^2 = \left(\frac{\partial f}{\partial x}\right)^2 U_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 U_y^2 \quad (\text{A.10})$$

A.2 General Equation (3 Variable)

This sub-section explains the generalized equation for uncertainty analysis for 3 variables.

Following same steps as indicated in the [Section A.1](#) except for 3 variables instead of 2 variables.

Assume,

$$z = f(w, x, y) \quad (\text{A.11})$$

Performing total differential on equation (A.11)

$$dz = \left(\frac{\partial f}{\partial w}\right) dw + \left(\frac{\partial f}{\partial x}\right) dx + \left(\frac{\partial f}{\partial y}\right) dy \quad (\text{A.12})$$

After performing the same steps as performed in [Section A.1](#), the final general uncertainty

equation for 3 variables is

$$U_z^2 = \left(\frac{\partial f}{\partial w}\right)^2 U_w^2 + \left(\frac{\partial f}{\partial x}\right)^2 U_x^2 + \left(\frac{\partial f}{\partial y}\right)^2 U_y^2 \quad (\text{A.13})$$

A.3 Uncertainty Equations for Different Mathematical Operations

This sub-section discusses uncertainty equations for each mathematical operation for the use in uncertainty analysis of the experimental data in this dissertation.

A.3.1 Multiplication (2 Variables)

$$z = f(x, y) = xy \quad (\text{A.14})$$

Performing total differential on equation (A.14),

$$\left(\frac{\partial f}{\partial x}\right) = y \text{ and } \left(\frac{\partial f}{\partial y}\right) = x \quad (\text{A.15})$$

substituting values from equation (A.15) in equation (A.2),

$$dz = y dx + x dy \quad (\text{A.16})$$

Using similar process on equation (A.16) as performed in [Section A.1](#) yields,

$$U_z^2 = y^2 U_x^2 + x^2 U_y^2 \quad (\text{A.17})$$

A.3.2 Multiplication (3 Variables)

$$z = f(w, x, y) = wxy \quad (\text{A.18})$$

Performing total differential on equation (A.18),

$$\left(\frac{\partial f}{\partial w}\right) = xy ; \left(\frac{\partial f}{\partial x}\right) = wy ; \left(\frac{\partial f}{\partial y}\right) = wx \quad (\text{A.19})$$

substituting values from equation (A.19) in equation (A.12),

$$dz = xy dw + wy dx + wx dy \quad (\text{A.20})$$

Using similar process on equation (A.20) as performed in [Section A.2](#) yields,

$$U_z^2 = x^2 y^2 U_w^2 + w^2 y^2 U_x^2 + w^2 x^2 U_y^2 \quad (\text{A.21})$$

A.3.3 Addition

$$z = f(x, y) = (x + y) \quad (\text{A.22})$$

Performing total differential on equation (A.22),

$$\left(\frac{\partial f}{\partial x}\right) = 1 \text{ and } \left(\frac{\partial f}{\partial y}\right) = 1 \quad (\text{A.23})$$

substituting values from equation (A.23) in equation (A.2),

$$dz = dx + dy \quad (\text{A.24})$$

Using similar process on equation (A.24) as performed in [Section A.1](#) yields,

$$U_z^2 = U_x^2 + U_y^2 \quad (\text{A.25})$$

A.3.4 Subtraction

$$z = f(x, y) = (x - y) \quad (\text{A.26})$$

Performing total differential on equation (A.26),

$$\left(\frac{\partial f}{\partial x}\right) = 1 \text{ and } \left(\frac{\partial f}{\partial y}\right) = -1 \quad (\text{A.27})$$

substituting values from equation (A.27) in equation (A.2),

$$dz = dx - dy \quad (\text{A.28})$$

Using similar process on equation (A.28) as performed in [Section A.1](#) yields,

$$U_z^2 = U_x^2 + U_y^2 \quad (\text{A.29})$$

A.4 Uncertainty Analysis for Important Equations

1. Change in Length Due to Thermal Expansion Effects

$$\Delta L_{G, \text{therm}} = L_G \alpha [T_{\text{ave}} - T_0] \quad (\text{A.30})$$

Where,

L_G = Gage Length

$\Delta L_{G, \text{therm}}$ = Thermal Displacement

α = Coefficient of Thermal Expansion (CTE)

T_0 = Ambient Temperature

T_{ave} = (Average Temperature of the Rail under Strain Sensor)

Apply equation (A.21) to equation (A.30),

$$U_{\Delta L_{G,therm}}^2 = L_G^2 [T_{ave} - T_0]^2 U_{\alpha}^2 + L_G^2 \alpha^2 U_{[T_{ave}]}^2 + L_G^2 \alpha^2 U_{[T_0]}^2 + [T_{ave} - T_0]^2 \alpha^2 U_{L_G}^2 \quad (A.31)$$

2. Total Displacement Measured by the Strain Sensor

$$\Delta L_{G,total} = \Delta L_{G,mech} + \Delta L_{G,therm} \quad (A.32)$$

Rearranging equation (A.32) gives mechanical displacement (thermal displacement removed)

$$\Delta L_{G,mech} = \Delta L_{G,total} - \Delta L_{G,therm} \quad (A.33)$$

Where,

$\Delta L_{G,mech}$ = Mechanical Displacement

$\Delta L_{G,total}$ = Total Displacement Calculated by New Strain Sensor

Apply similar process of equation (A.29) to equation (A.33),

$$U_{\Delta L_{G,mech}}^2 = U_{\Delta L_{G,total}}^2 + U_{\Delta L_{G,therm}}^2 \quad (A.34)$$

3. Rail Neutral Temperature (T_{RN}):

Rail neutral temperature for equivalent mechanical strain/displacement can be calculated using the formula mentioned in equation (8.20) in the main body of the dissertation.

$$T_{RN} = \frac{\Delta L_{G,mech}}{L_G \alpha} + T_0 \quad (A.35)$$

Applying similar processes in equations (A.17) and (A.25) to equation (A.35) yields

$$U_{T_{RN}}^2 = \left(\frac{1}{\alpha L_G} \right)^2 U_{\Delta L_{G,mech}}^2 + \left(\frac{\Delta L_{G,mech}}{\alpha^2 L_G} \right)^2 U_{\alpha}^2 + U_{T_0}^2 \quad (A.36)$$

A.5 Individual Uncertainties for Variables Under Consideration

To complete uncertainty analysis of rail neutral temperature ($U_{T_{RN}}$), it is necessary to calculate individual uncertainties and substitute these in equations (A.31), (A.34) and (A.36).

Below are the variables that are the sources of uncertainty in determining RNT in general. The notation for absolute uncertainty is U_x , where x is the individual variable under consideration.

- U_α (α is the coefficient of thermal expansion-CTE)
- $U_{T_{ave}}$ (T_{ave} is the average temperature under strain sensor)
- U_{T_0} (T_0 is the ambient temperature)
- U_{L_G} (L_G is the gage length of the strain sensor)
- $U_{\Delta L_{G,total}}$ ($\Delta L_{G,total}$ is the total displacement measured by the strain sensor)
- U_E (E is Young's Modulus)
- U_A (A is Area of the Rail)

A.5.1 Uncertainty in Coefficient of Thermal Expansion (CTE), U_α

The approximate temperature range for the data captured in [Chapter 8, Section 8.3.1](#) was between 70 °F and 190 °F. CTE was measured for steel rail in one of the research papers [76] and was converted into Fahrenheit units to use for this research. Looking at the plot in [Figure A.1](#), it can be seen that the CTE varies between $6.75E-6$ °F⁻¹ and $7.04E-6$ °F⁻¹.

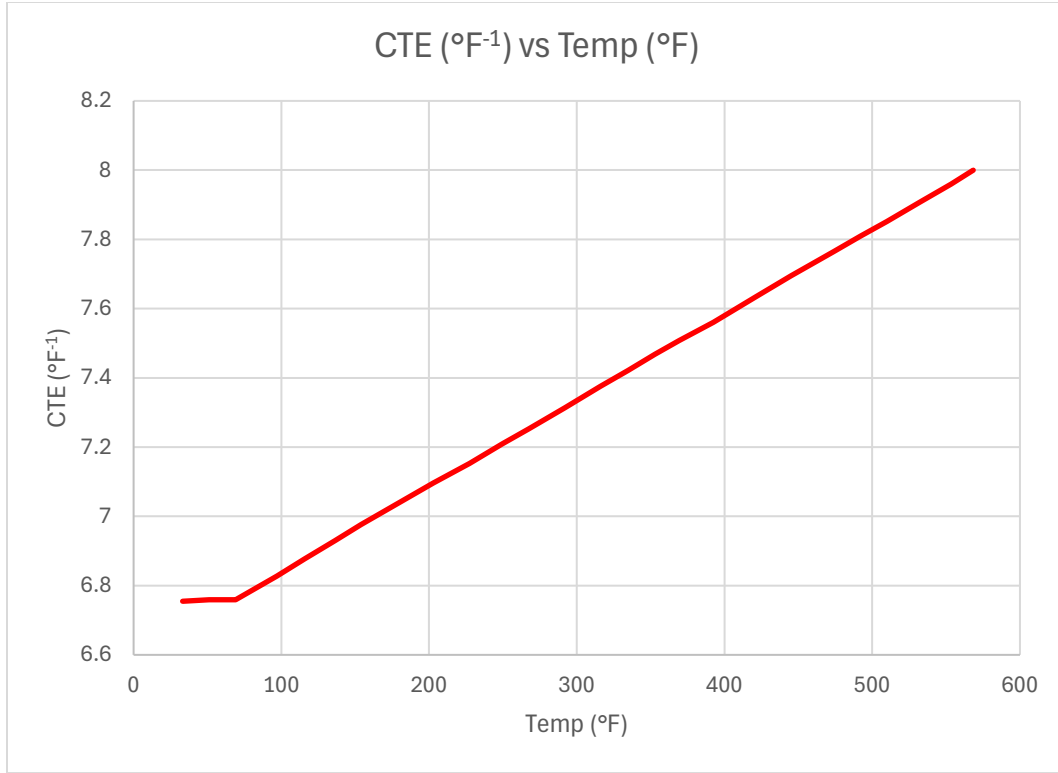


Figure A.1 Coefficient of Thermal Expansion for Steel Rail (°F⁻¹) vs Temperature (°F)(Plot Data Copied from [76] for Informational Purpose)

With the variation being around $0.28\text{E-}6 \text{ }^{\circ}\text{F}^{-1}$, the uncertainty in coefficient of thermal expansion is assumed to be around

$$U_{\alpha} = \pm 0.14\text{E-}6 \text{ }^{\circ}\text{F}^{-1} \quad (\text{A.37})$$

A.5.2 Uncertainty in Average Temperature Measured, $U_{T_{\text{ave}}}$

It was verified that the arithmetic average and 3rd order polynomial average for temperature measurements taken in the gage length region during the thermal testing of the steel rail are within reasonable limits. To complete uncertainty analysis on the average temperature, the arithmetic average method will be used for ease of analysis. As discussed in [Chapter 8](#), and shown in [Figure 8.13](#), a total of 5 temperature measurements were taken using the IR Spot temperature sensor within the gage length region with fixed emissivity set at 0.95. Hence,

$$T_{ave} \approx \frac{1}{5} (T_1 + T_2 + T_3 + T_4 + T_5) \quad (A.38)$$

Using the general uncertainty formula for addition (A.25),

$$U^2_{T_{ave}} = \frac{1}{5^2} (U^2_{T_1} + U^2_{T_2} + U^2_{T_3} + U^2_{T_4} + U^2_{T_5}) \quad (A.39)$$

Two things are important to consider related to the averaging issues here. One is the possible bias uncertainty of the individual temperature measurements (IR Spot Thermometer) and the other is the random “scatter” uncertainty about the 3rd order polynomial curve fit (or the arithmetic average). For simplicity in calculations, the above equation will be used to estimate the averaging of the random “scatter” about the polynomial fit; therefore, equation (A.39) should represent the approximate random uncertainty in T_{ave} .

For the purpose of initial uncertainty estimation, the values of random uncertainty for $U^2_{T_1}$ up to $U^2_{T_5}$ will be assumed nearly equal to ± 2 °F ([Appendix D](#), point 3-basic accuracy) for each because of the accuracy of the IR Spot Thermometer. Substituting the accuracy value in equation (A.39),

$$U^2_{T_{ave}} = \frac{1}{25} (5 \times 2^2) = 0.8 \text{ °F}^2 \quad (A.40)$$

$$U_{T_{ave}} = 0.89 \text{ °F} \quad (A.41)$$

This value just gives an estimate of the random uncertainty in the average temperature based on deviations due to the polynomial fit (3rd order). However, each individual measurement has a potential temperature measurement bias uncertainty as well, which must be accounted for in the final uncertainty. For simplicity, this will be approximated by using the root mean square (rms) of equation (A.41) and the same value of ± 2 °F for the IR Spot thermometer bias uncertainty.

$$U_{T_{ave}} = \sqrt{(0.89)^2 + (2)^2} = \pm 2.19 \text{ °F} \quad (A.42)$$

Other potential sources of temperature measurement uncertainty include

- Effect of steel emissivity.

- Distance and orientation of measurement axis relative to the steel rail surface.
- Background radiation from temperature sources different than the ambient air. For example, outside radiation being reflected on the steel rail surface and directed to the IR thermometer.

These other potential sources will not be considered in this initial uncertainty analysis but will be a part of detailed calibration checks during later stages in the project not directly connected with this dissertation research.

A.5.3 Uncertainty in Ambient Temperature Measured, U_{T_0}

The rail temperature in ambient conditions was measured using the same method as described above in point 2 for $U_{T_{ave}}$. Considering the same situation and conditions, the uncertainty in the measured ambient temperature U_{T_0} is expected to be the same as $U_{T_{ave}}$. Taking the uncertainty value from equation (A.42), gives

$$U_{T_0} = \pm 2.19 \text{ }^\circ\text{F} \quad (\text{A.43})$$

A.5.4 Uncertainty in Gage Length of the New Strain Sensor, U_{L_G}

In this method a tape measure (with the accuracy of 0.0625 inch) was placed under both cameras and images are taken simultaneously. The center-to-center distance from the camera 1 and camera 2 is measured and the strain sensor is calibrated with that distance.

Assume that the two sensor cameras are located at positions x_1 and x_2 , with the distance between them defined as L_G .

According to the uncertainty relation in equation (A.29) for subtraction mentioned in the beginning of this Appendix,

$$U_{L_G}^2 = U_{x_1}^2 + U_{x_2}^2 \quad (\text{A.44})$$

With discrete increment spacings (divisions), the uncertainty is typically taken to be $\pm \frac{1}{2}$ of the smallest division. Since both the cameras have uncertainties, the lowest possible resolution of the tape measure which is 0.0625" will therefore be a conservative estimate. Equation (A.46) can be modified as follows:

$$U_{LG}^2 = 2U_{x1/2}^2 \quad (A.45)$$

$$U_{LG} = \sqrt{2} U_{x1/2} \quad (A.46)$$

Here,

$$U_{x1/2} = 0.0625" \quad (A.47)$$

Substituting value from equation (A.47) to equation (A.46),

$$U_{LG} = 0.088" \quad (A.48)$$

Relative uncertainty for the gage length is expressed as,

$$u_{LG} = \frac{U_{LG}}{L_G} \quad (A.49)$$

With 36" being the nominal gage length of the strain sensor, the relative uncertainty becomes

$$u_{LG} = \frac{0.088"}{36"} = 0.0025 \text{ or } 0.25\% \quad (A.50)$$

Hence equations (A.48) and (A.50) indicate that the absolute and relative uncertainties in the gage length are very small and will likely have negligible effect on the final uncertainty calculations.

A.5.5 Uncertainty in Total Strain Measured by the Strain Sensor, $U_{\Delta L_G, \text{total}}$

The strain uncertainty is a combination of random scatter and bias. Random uncertainty is taken from the calibration data given in [Figure 3.30](#), showing that the deviations from a linear calibration trendline are within $\pm 0.001\text{mm}$. The other contribution to uncertainty is bias of the trendline. [Figure 3.29](#) shows the slope value of 1.017, meaning that there is some bias in the calibration when the measured sensor displacement is plotted against actual (calibrated) digital indicator

displacements. A deviation plot was created to estimate the bias by plotting the strain sensor data with respect to a trendline with slope of value 1 as shown in [Figure A.2](#).

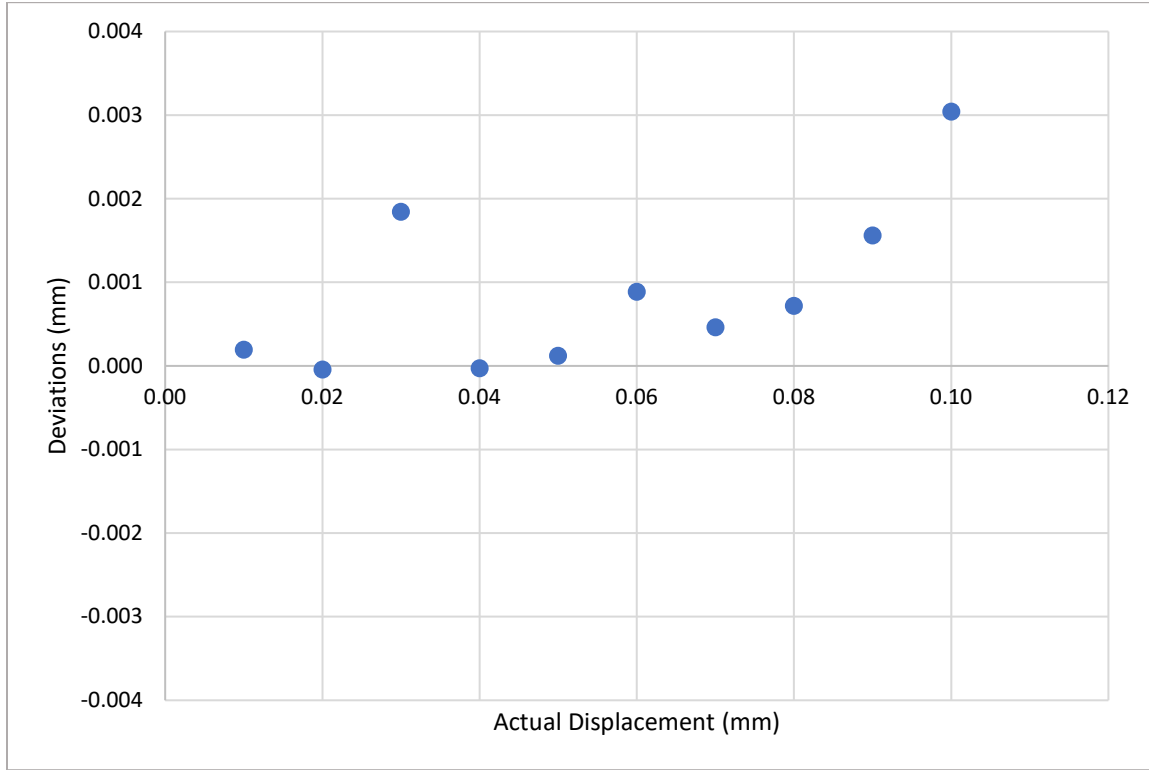


Figure A.2 Deviation Plot for Strain Sensor Data with a Trendline Having Slope=1

As seen in [Figure A.2](#), the maximum bias noted is around +0.003mm. Calculating the total uncertainty in strain sensor measurement as the rms of the bias and scatter (repeatability), yields

$$U_{\Delta L_{G,\text{total}}} = \sqrt{(0.001)^2 + (0.003)^2} = \pm 0.0032\text{mm} \quad (\text{A.51})$$

A.5.6 Uncertainty in Young's Modulus, U_E

The approximate range of the average temperature for the data presented in [Chapter 8, Section 8.3.1](#), was about 70 °F to 190 °F. Young's Modulus was measured for steel rail in the research paper [77]. The measurement results were converted to psi as a function of temperature in degrees Fahrenheit for the use in this dissertation. Looking at the plot in [Figure A.3](#), it can be seen that E varies between about $3.02\text{E}7$ psi and $2.98\text{E}7$ psi for this temperature range.

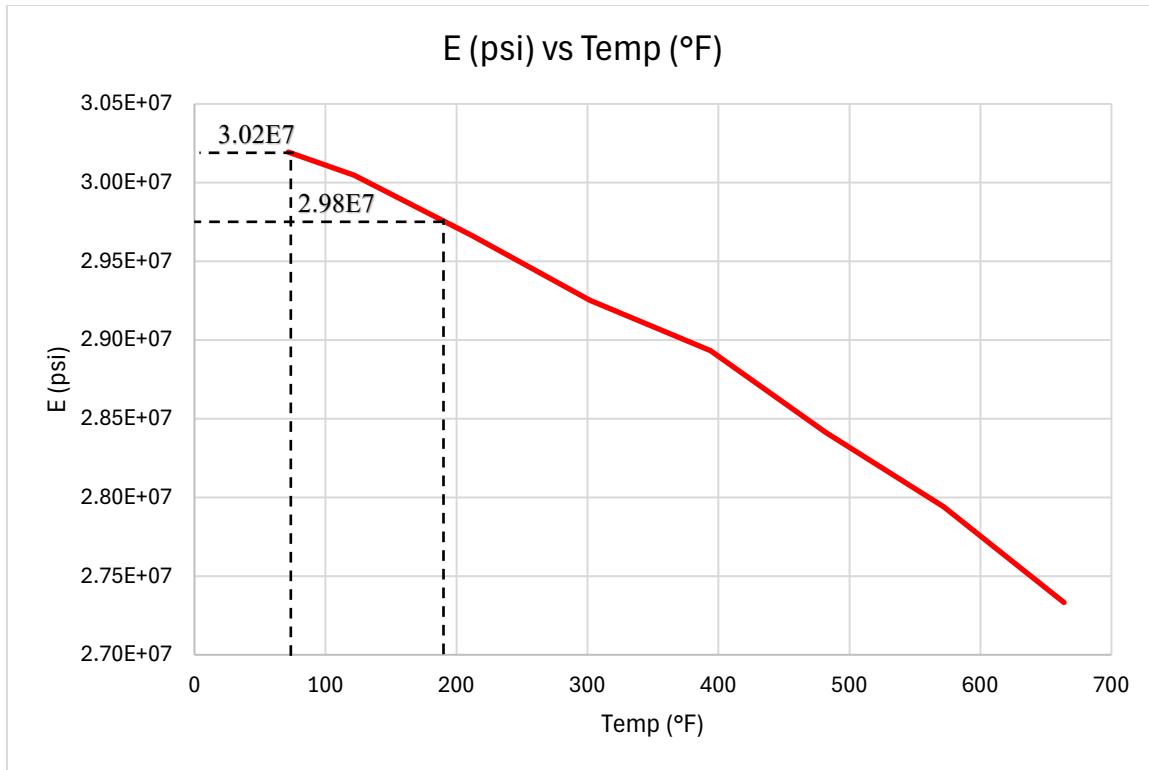


Figure A.3 Young's Modulus vs Temperature (°F) (Plot Data Copied from [77] for Informational Purpose)

With the variation being around $0.4\text{E}7$ psi, a worst-case estimate for the uncertainty in Young's Modulus should be around

$$U_E = \pm 0.02\text{E}7 \text{ psi} \quad (\text{A.52})$$

A.5.7 Uncertainty in Cross-Sectional Area of the Rail, U_A

There was no measurement of rail cross-sectional area performed in the laboratory, and the value was taken from [Figure 4.2](#). Just for the sake of estimating uncertainty in this area for calculations that require its use, an example evaluation will be given here. The height of the rail H_R (7.3125") and base of the rail B_R (6") are marked in [Figure A.4](#), along with an equivalent rectangular slab with the base dimension B_S and the same rail height H_R . This simplified rectangular geometry is used below to estimate the uncertainty in rail cross-sectional area.

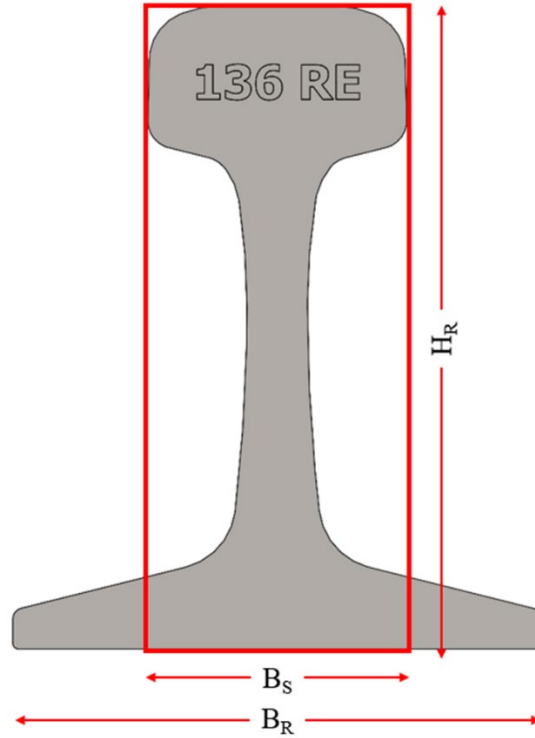


Figure A.4 Rail Dimensions and Equivalent Rectangular Slab

Assuming a digital caliper was used to measure the height and base of the rail with the uncertainty of $\pm 0.002''$ gives the height and base dimensions of the rail and their uncertainties as,

$$H_R = 7.3125'' \pm 0.002'' \quad (\text{A.53})$$

$$B_R = 6'' \pm 0.002'' \quad (\text{A.54})$$

Considering the equivalent rectangular slab and calculating the area of the slab assuming the base of the slab to be

$$B_S = 3'' \quad (\text{A.55})$$

Then the area of the slab is

$$A_S = H_R \times B_S \quad (\text{A.56})$$

Adding a measurement uncertainty of $\pm 0.002''$ for each of the dimensions in equation (A.56), and using the uncertainty relation in equation (A.17) for multiplication for area uncertainty calculations associated with the equivalent rectangular slab, yields

$$U_{A_S}^2 = H_R^2 U_{B_S}^2 + B_S^2 U_{H_R}^2 \quad (A.57)$$

$$U_{A_S} = \sqrt{(3)^2(0.002)^2 + (7.3125)^2(0.002)^2} = \pm 0.016 \text{ in}^2 \quad (A.58)$$

The relative uncertainty in rail cross-sectional area can be estimated using values from equation (A.58), as follows:

$$u_A = \frac{U_{A_S}}{A_S} \quad (A.59)$$

Therefore,

$$U_A = \frac{0.016 \text{ in}^2}{13.32 \text{ in}^2} = \pm 0.12\% \quad (A.60)$$

Looking at the calculated uncertainty value for the area of the rail using some nominal assumptions shows it can be considered negligible.

A.6 Uncertainty Calculations

Now that we have all the individual uncertainties related to the experimental data, we can perform uncertainty analysis using equations (A.31), (A.34) and (A.36).

1. Uncertainty in Change in Length Due to Thermal Expansion Effects

The calculation of uncertainty in the RNT will be evaluated for the same example used in [Chapter 8, Section 8.3.1](#). For the purpose of this dissertation, this example will be considered to be nominally representative of the overall testing results.

Equation (A.31) is written as

$$U_{\Delta L_{G, \text{therm}}}^2 = L_G^2 [T_{\text{ave}} - T_0]^2 U_{\alpha}^2 + L_G^2 \alpha^2 U_{[T_{\text{ave}}]}^2 + L_G^2 \alpha^2 U_{[T_0]}^2 + [T_{\text{ave}} - T_0]^2 \alpha^2 U_{L_G}^2$$

Where the values for individual quantities and uncertainties are

L_G = Gage length, 36", from [Table 8.1](#).

T_{ave} = Average temperature of the rail under strain sensor, 128.2 °F, from equation (8.25)

T_0 = Ambient temperature, 68.2 °F, from equation (8.13)

U_α = Uncertainty in coefficient of thermal expansion, $\pm 0.14E-6$ °F⁻¹, from equation (A.37)

α = Coefficient of thermal expansion, $6.5E-6$ °F⁻¹, from [Table 8.1](#).

$U_{T_{ave}}$ = Uncertainty in average temperature of the rail under strain sensor, ± 2.19 °F, from equation (A.42)

U_{T_0} = Uncertainty in ambient temperature, ± 2.19 °F, from equation (A.43)

U_{L_G} = Uncertainty in gage length of the strain sensor, ± 0.088 " from equation (A.48)

Substituting all the above values in equation (A.31),

$$U_{\Delta L_{G,therm}}^2 = (36in)^2 [128.2F - 68.2F]^2 (0.14 \times 10^{-6} F^{-1})^2 + (36in)^2 (6.5 \times 10^{-6} F^{-1})^2 (2.19F)^2 \\ + (36in)^2 (6.5 \times 10^{-6} F^{-1})^2 (2.19F)^2 + [128.2F - 68.2F]^2 (6.5 \times 10^{-6} F^{-1})^2 (0.088in)^2 \quad (A.61)$$

Evaluating equation (A.61) yields

$$U_{\Delta L_{G,therm}}^2 = 6.18 \times 10^{-7} in^2 \quad (A.62)$$

$$U_{\Delta L_{G,therm}} = 0.000786 in \quad (A.63)$$

2. Uncertainty in Mechanical Displacement (Thermal Displacement Removed)

For this equation (A.34) will be used.

$$U_{\Delta L_{G,mech}}^2 = U_{\Delta L_{G,total}}^2 + U_{\Delta L_{G,therm}}^2$$

$U_{\Delta L_{G,total}}$ = Uncertainty in total displacement calculated by the strain sensor, 0.0032mm or 0.000126 in., from equation (A.51).

$$\text{Hence, } U_{\Delta L_{G,total}}^2 = 1.59E-8 in^2 \quad (A.64)$$

$U_{\Delta L_{G,therm}}^2$ = Uncertainty in change in length due to temperature effects, $6.18E-7 \text{ in}^2$, from equation (A.62). Substituting values from equations (A.64) and (A.62) in equation (A.34) to calculate $U_{\Delta L_{G,mech}}$ yields

$$U_{\Delta L_{G,mech}}^2 = (1.59 \times 10^{-8} \text{ in}^2) + (6.18 \times 10^{-7} \text{ in}^2) = 6.34 \times 10^{-7} \text{ in}^2 \quad (\text{A.65})$$

$$U_{\Delta L_{G,mech}} = 0.000796 \text{ in} \quad (\text{A.66})$$

3. Uncertainty in Rail Neutral Temperature

This is calculated using equation (A.36),

$$U_{T_{RN}}^2 = \left(\frac{1}{\alpha L_G} \right)^2 U_{\Delta L_{G,mech}}^2 + \left(\frac{\Delta L_{G,mech}}{\alpha^2 L_G} \right)^2 U_{\alpha}^2 + U_{T_0}^2$$

To calculate uncertainty in rail neutral temperature requires values for individual terms used in equation (A.36) from [Table 8.1](#) and equations (A.65), (8.34), (A.37), (A.43).

$$U_{T_{RN}}^2 = \left(\frac{1}{6.5 \times 10^{-6} \text{ F}^{-1} \times 36 \text{ in}} \right)^2 (6.34 \times 10^{-7} \text{ in}^2) + \left(\frac{0.0079 \text{ in}}{(6.5 \times 10^{-6} \text{ F}^{-1})^2 \times 36 \text{ in}} \right)^2 (0.14 \times 10^{-6} \text{ F}^{-1})^2 + (2.19 \text{ F})^2$$

$$U_{T_{RN}}^2 = 16.90 \text{ F}^2 \quad (\text{A.67})$$

$$U_{T_{RN}} = \pm 4.11 \text{ }^{\circ}\text{F} \quad (\text{A.68})$$

Thus, it can be concluded that the uncertainty in the calculated RNT will be approximately $\pm 4.11 \text{ }^{\circ}\text{F}$.

The uncertainty in rail neutral temperature of $\pm 4.11 \text{ }^{\circ}\text{F}$ shown in equation (A.68) was based on extreme temperature variations, and their possible effect on the CTE. However, a more extreme case of uncertainty variation in CTE is based on the values used in the plots shown in [Figures 8.21](#), [8.22](#) and [8.23](#). The values of CTE used were around $6.0E-6$ to $7.0E-6$ giving the uncertainty range,

$$U_{\alpha} = \pm 0.5E-6 \text{ }^{\circ}\text{F}^{-1} \quad (\text{A.69})$$

Using this more extreme case of uncertainty variation in CTE (equation A.69) and calculating the uncertainty in rail neutral temperature yields

$$U_{\text{TRN}} = \pm 6.54 \text{ }^{\circ}\text{F} \quad (\text{A.70})$$

The results in the equations (A.68) and (A.70) clearly show that the CTE is a significant contributor to the determination of the RNT. However, its exact value is yet unknown.

Appendix B – Dual Deflection Measurements on the Non-Heater

Side of the Rail

This Appendix Continues the discussion on the topic in [Section 8.3.2](#) from [Chapter 8](#).

All the apparent RNT errors were calculated using 3rd order polynomial functions for the IR Spot sensor temperature measurements. However, as mentioned in the main body of the dissertation, another method of evaluating the average rail temperature within the gauge length region is to use “box averaging”. This method is being used to calculate the average temperature of the rail frontal area (and/or the average temperature of the web area) where the displacement readings are taken. [Figures B.1](#) and [B.2](#) show schematic diagrams of the long rail section on testbed with the red dotted box marked over the sensor gage length area for left displacement region and center displacement region measurements. These areas can be isolated in the FLIR Thermal Studio Software using markers placed over the rail to enable calculation of the box average temperature for each particular test.

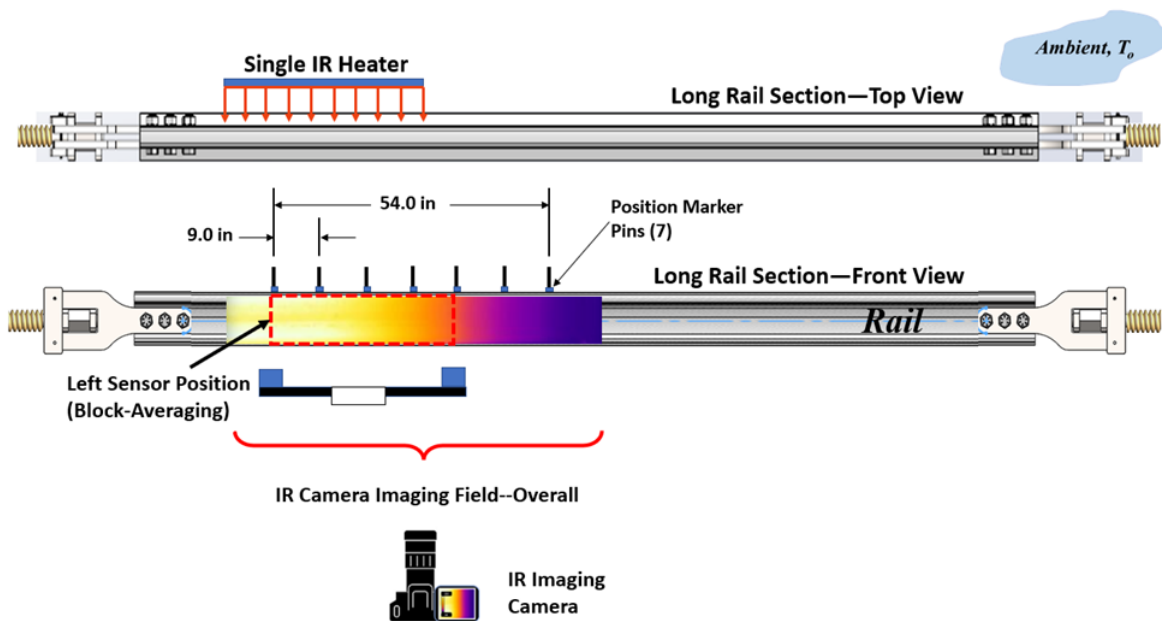


Figure B.1 IR Temperature Block Averaging—Left Sensor Field

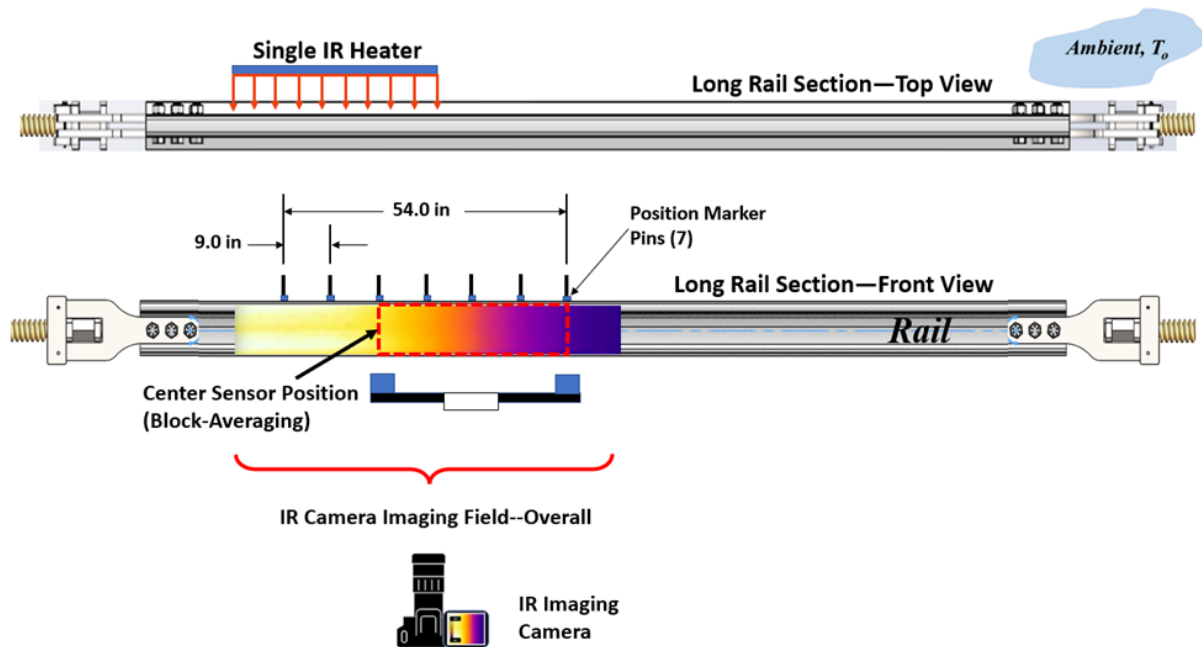


Figure B.2 IR Temperature Block Averaging—Center Sensor Field

[Figures B.3](#) and [B.4](#) shows the actual IR Imaging camera picture with a box drawn in the web area and the overall frontal area regions.

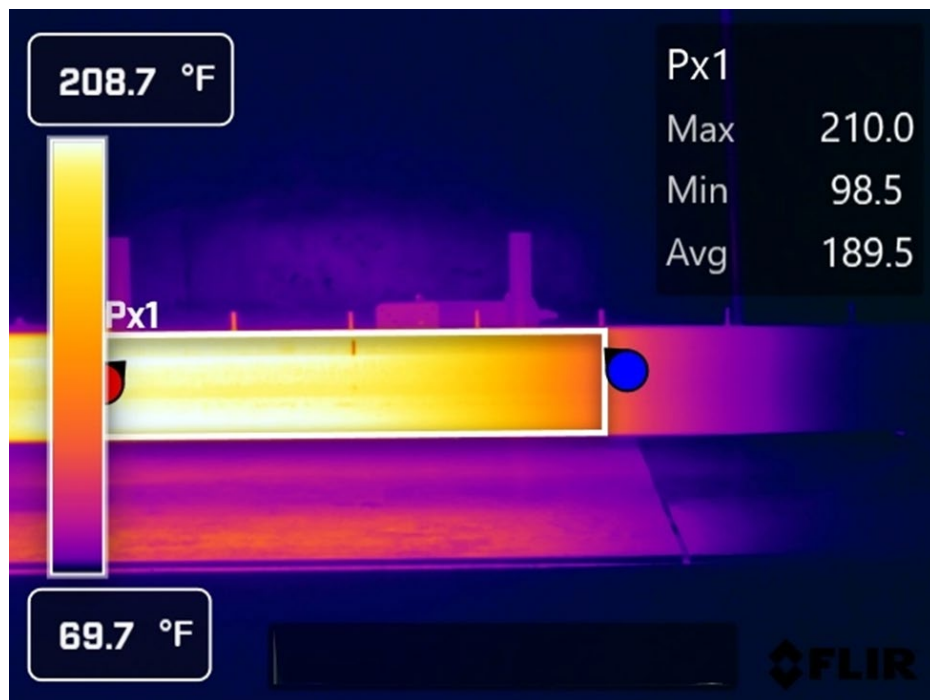


Figure B.3 IR Imaging Camera Picture of Long Rail Section with Highlighted Full Profile

Area for Box Averaging

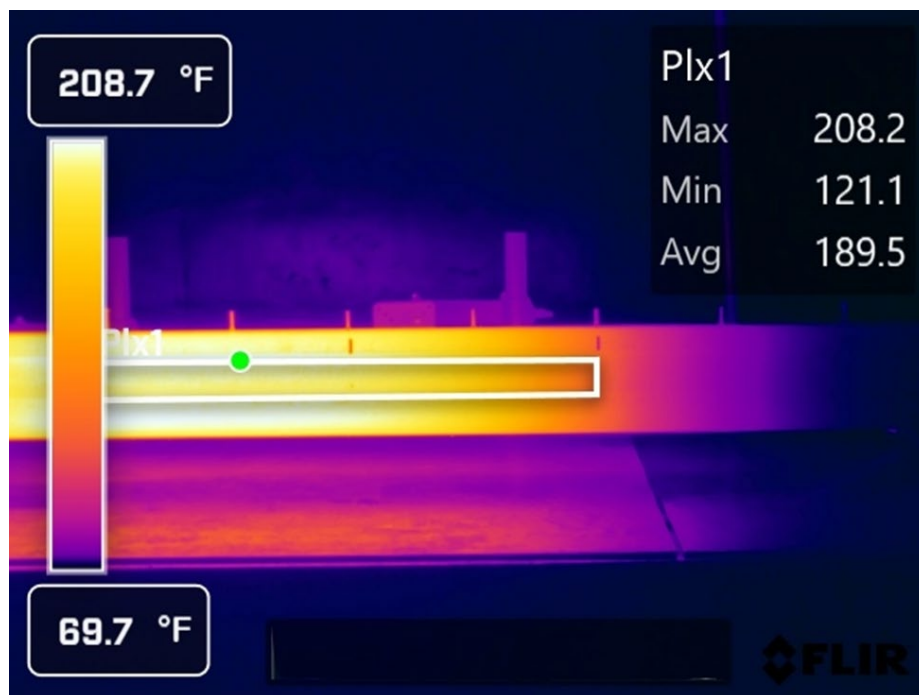


Figure B.4 IR Imaging Camera Picture of Long Rail Section with Highlighted Web Only

Profile Area for Box Averaging

The method described above allows calculation of the average temperature of the whole region under consideration, rather than relying on curve fits to only limited spots where discrete temperature measurements were made. Once the box average is taken for the temperature measurements using the FLIR Thermal Studio software, the same procedures can be used to calculate the apparent RNT error. This alternative approach will help decide the best method for assessing the average rail temperature during testing of the new strain sensor. This will also help determine the easiest and most accurate method that can be used to perform field testing of the new strain sensor.

Appendix C – Testbed Bending

Something unusual was observed while loading the steel rail test sections on the testbed. The testbed has dual motor system that is connected to a sliding frame on a guide rail mounted on the floor. This sliding frame allows the tension rods to pull the steel rail section connected via clevises. [Figure C.1](#) shows the testbed frame and the sliding frame on the guide rail on the floor. The load cells are pushed against the moving frame to register the actual tension in the rods; in turn, measuring the load in the steel rail section.

However, while loading the steel rail section, it was noticed that the moving frame was getting lifted off the sliding guide rail when the tension was increased. This could be the result of multiple things: the frame not being perfectly aligned with the testbed, too much tension in the rods compared to the weight of the frame, bending of the frame itself, or settling of the mechanical system components while the tension was being applied. In any case, it became necessary to investigate if the lifting of the moving frame was affecting some of the results being recorded for the project.



Figure C.1 Wooden Stick Connected to Testbed on One End and a Dial Gage on the Other

A small test was performed using a dial gage connected to the testbed frame and the moving frame to measure the displacement between the surfaces for each load increment. If the frame is moving upwards/getting lifted or bent, the displacement will be different for each increment of the load setting. In this test, wooden sticks were bolted together to make one long enough to reach from one end of the testbed to the other end. This allowed measurement of the reduction in the testbed spacing. If the frame bends, the distance between the two ends of the testbed should decrease. This arrangement can be seen in [Figure C.1](#). The wooden stick was fixed on one side of the testbed as shown in [Figure C.2](#). A gap was provided on the other end for positioning of a dial gage so as to measure the change in gap dimension as the steel railroad rail was subjected to tension. [Figure C.3](#) shows the dial gage placed between a steel angle plate mounted on the wooden stick and the frame of the testbed.

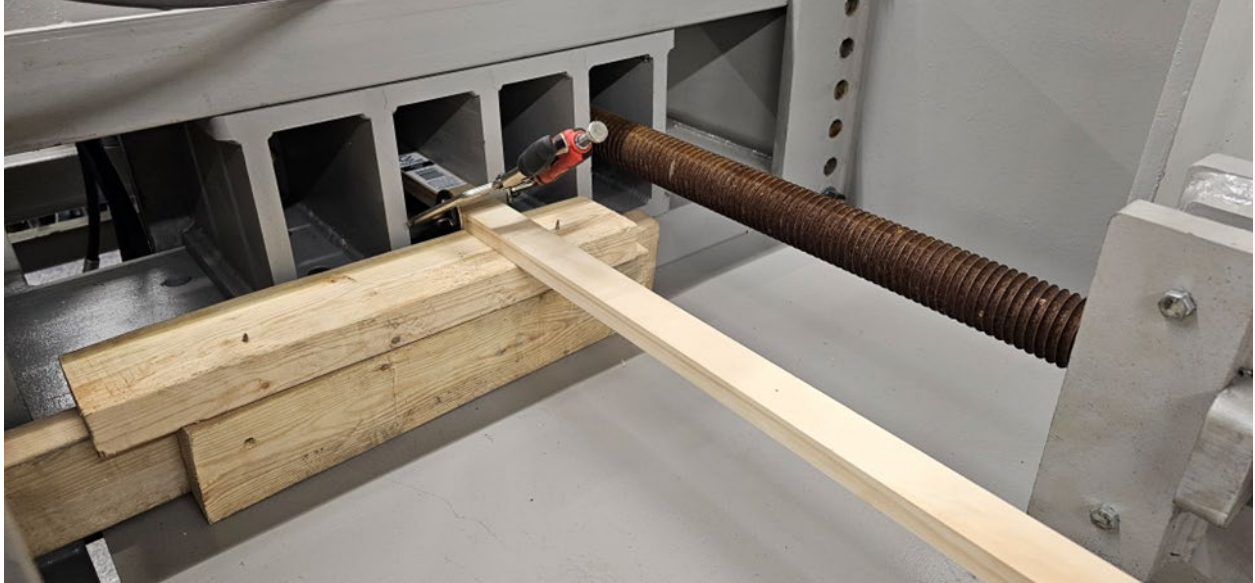


Figure C.2 Fixed Wooden Stick on One End of the Testbed



Figure C.3 Dial Gage Connection with Wooden Stick for Deflection Measurement

Unfortunately, the results from this preliminary testing were inconclusive, in that they suggested that as the load was increased the bending of the frame (and gap spacing) appeared to increase instead of decrease (as was expected). Future testing to further investigate the bending of the frame is planned; however, this bending effect should not influence the direct measurement of the applied rail loading since it takes place through the system load cells.

Appendix D – Equipment Used

1. k-type thermocouples:

Standard Grade: Range is -270°C to +1260°C (-454°F to +2300°F)

Error: Standard: $\pm 2.2^{\circ}\text{C}$ or $\pm 0.75\%$ of reading and Special Limits of Error: $\pm 1.1^{\circ}\text{C}$ or 0.4% of reading.

2. BK Precision Test Bench 390A Meter:

Accuracy:

$\pm(0.8\% \text{rdg} + 2^{\circ}\text{C})$ for -50°C to $+400^{\circ}\text{C}$

$\pm(1\% \text{rdg} + 2^{\circ}\text{C})$ for $+400^{\circ}\text{C}$ to $+1300^{\circ}\text{C}$

3. FLIR IR Spot (Handheld) Sensor (Model# TG56-2):

Range: -30°C to $+1300^{\circ}\text{C}$ (-22°F to $+2372^{\circ}\text{F}$)

Measurement Resolution: $0.1^{\circ}\text{F}/^{\circ}\text{C}$.

Spot Ratio: 30:1 distance to spot ratio.

Basic Accuracy for 0°C to $+100^{\circ}\text{C}$ ($+32^{\circ}\text{F}$ to $+212^{\circ}\text{F}$): $\pm 1^{\circ}\text{C}$ ($\pm 1.8^{\circ}\text{F}$).

Emissivity: 0.01 to 1.00 (can be changed).

4. Milwaukee Spot (Handheld) Sensor (Model# Laser Temp-Gun):

Range: -22°F to +662°F (-30°C to +350°C)

Spot Ratio: 10:1 distance to spot ratio (measures 1 foot spot from 10 foot away)

Display Resolution: 0.1 °F/°C.

Basic accuracy: 1.5%

Repeatability: 0.50%

Emissivity: 0.95 (fixed)

5. IR Imaging Camera (Model# T865):

5 MP with built-in LED photo/video lamp

Range:

-20°C to +120°C (-4°F to +248°F)

0°C to +650°C (+32°F to +1202°F)

+300°C to +2000°C (+572°F to +3632°F)

Accuracy:

±1°C (±1.8°F): +5°C to +100°C (+41°F to +212°F)

±1%: +100°C to +120°C (+212°F to +248°F)

±2°C (±3.6°F): -40°C to +100°C (-40°F to +212°F)

±2%: +100°C to +650°C (+212°F to +1202°F), +300°C to +2000°C (+572°F to +3632°F)

±3%: +1800°C to +2000°C (+3272°F to +3632°F) with 42° lens

Emissivity: 0.01 to 1.00 (can be changed).

6. IR Imaging Camera (Model# ThermaCam S65):

Range:

-40°C to +120°C (-40°F to +248°F)-Range 1

0°C to +500°C (+32°F to +932°F)-Range 2

Up to +1500°C (+2732°F)-Optional

Up to +2000°C (+3632°F)-Optional

Accuracy: $\pm 2^{\circ}\text{C}$ or $\pm 2\%$

Emissivity: 0.1 to 1.0 (can be changed).

7. Digital Dial Gage (Model# Mitutoyo 543-792-lug back):

Range: 0.5"/12.7mm

Accuracy: 0.0001"

Resolution: 0.00005"/0.001mm

8. IR Heater (Small):

120V, 1500W, 12.5 Amps, approximately 5200 Btu/h

9. IR Heater (Large):

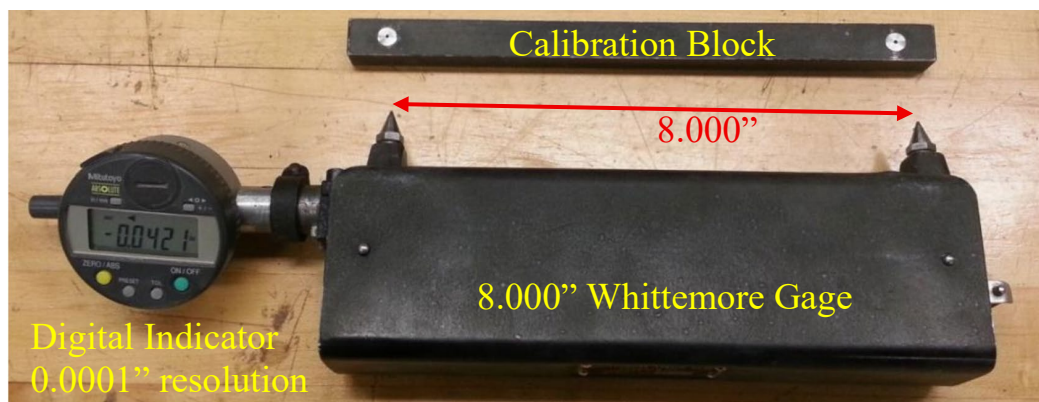
208V, 4000W, 19.2 Amps, approximately 13650 Btu/h

10. Dot-Peen Machine (model E-Mark™ by SIC-Marking)

11. Whittemore Gage:

8" Gage Length

Digital Indicator with 0.0001" Resolution



Appendix E – Measurement of the Coefficient of Thermal Expansion (CTE)

This Appendix presents independent measurements of the “Coefficient of Thermal Expansion (CTE)” of steel railway rail. One way to achieve this is to complete initiate pure thermal strain on the steel rail and measure its elongation characteristics when subjected to a known temperature change. The CTE has a very high impact on accurate thermal assessment of the steel rail, and therefore also in measuring the RNT. Just to ensure consistency and accuracy of the measured CTE, there were two separate tests performed for its estimation. One test was performed at the Technology Development Institute (TDI), and the other one at the Non-Contact Precision Measurement (NCPM) laboratory in the MNE Department at Kansas State University. A commonly used value for railway rail CTE is $6.5\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ [16,18]. This value has been consistently reported in the published literature and has been used for decades (since the 1930’s). However, it is likely that over this long period of time the composition has changed and so it is vital that the correct CTE value be used in any experimental procedure that attempts to measure the RNT (such as the new one presented in this dissertation).

Steel railway rail is typically made from high-carbon steel (type 1084 or higher grade). The chemical composition for this alloy of steel rail is given in [Chapter 4, Section 4.2](#). Due to proprietary reasons, it was not possible to get the exact composition from the rail manufacturer; however, there are other steel manufacturers that produce 1084 grade steel which can give an idea of the material characteristics and CTE for this grade of steel. One of the manufacturers that produces this type of steel, with similar chemical composition, suggests that the CTE value is around $6.67\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ [32]. Another reference suggests that the longitudinal coefficient of thermal expansion of carbon steel is around $7.39\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ for the temperature range from 86°F(25°C) to

482°F(250°C), and that the tangential and radial components can range from $7.11\text{E-}6\text{ }^{\circ}\text{F}^{-1}$ to $7.61\text{E-}6\text{ }^{\circ}\text{F}^{-1}$; meaning that it can be anisotropic)[54]. One other reference suggests that the CTE is temperature dependent and can creep up in value from 32°F (0°C) to 572°F (300°C), and then plummet until 1292°F (700°C), after which it stays constant until 1832°F (1000°C)[55]. The available research suggests that the CTE is not a fixed value, depends on the steel composition, and that it is also temperature dependent. To confirm these results, tests were performed on sections of steel rail used in the current research.

E.1 Thermal Strain Test at TDI

To assess the coefficient of thermal expansion of steel rail, a 5' (60 inch) rail section was set up on a non-conductive surface with bricks blocking both sides of the rail to avoid end heat loss. The setup is shown in [Figure E.1](#) where the rail section is supported on wooden blocks. The rail section was heated with a 4000-watt IR heater sunning at full power, connected directly to a 120V wall outlet.

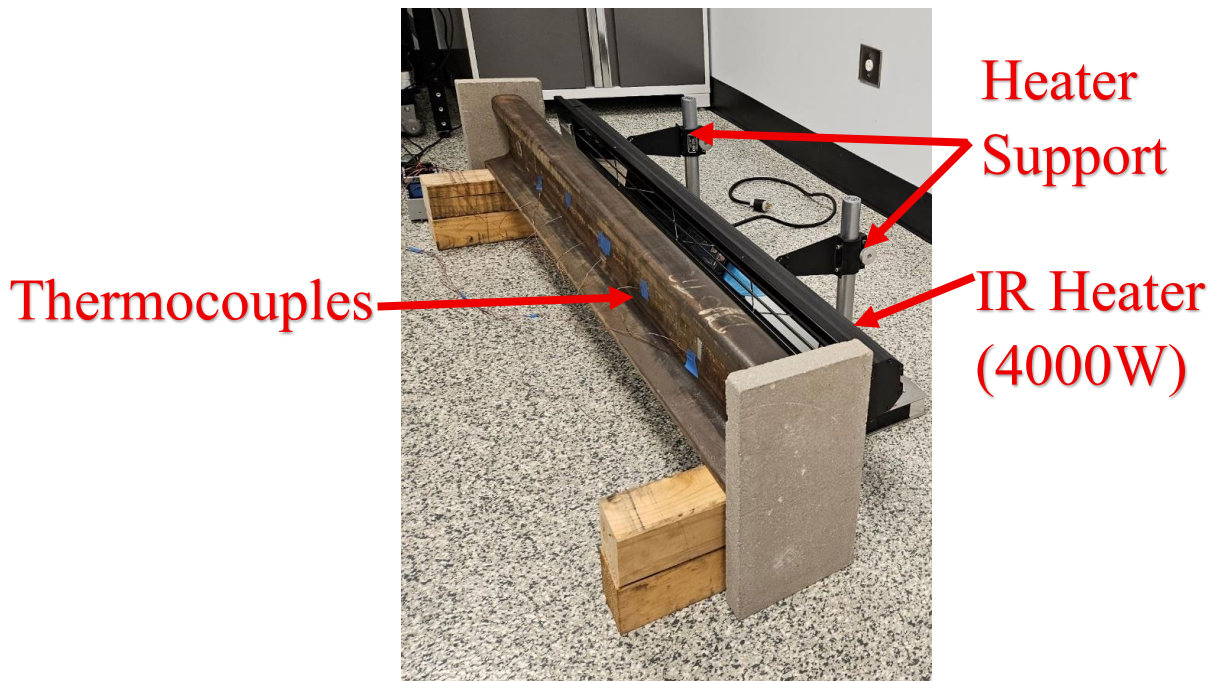


Figure E.1 Supports for Rail and IR Heater

To measure the temperature of the rail section while it heated up and while it was cooling, thermocouples were attached to the web of the rail as shown by the photograph in [Figure E.1](#) and in the schematic diagram shown in [Figure E.2](#). Thermocouples were used to provide direct contact, and presumably more accurate, assessment of steel rail temperature needed for accurate CTE estimation.

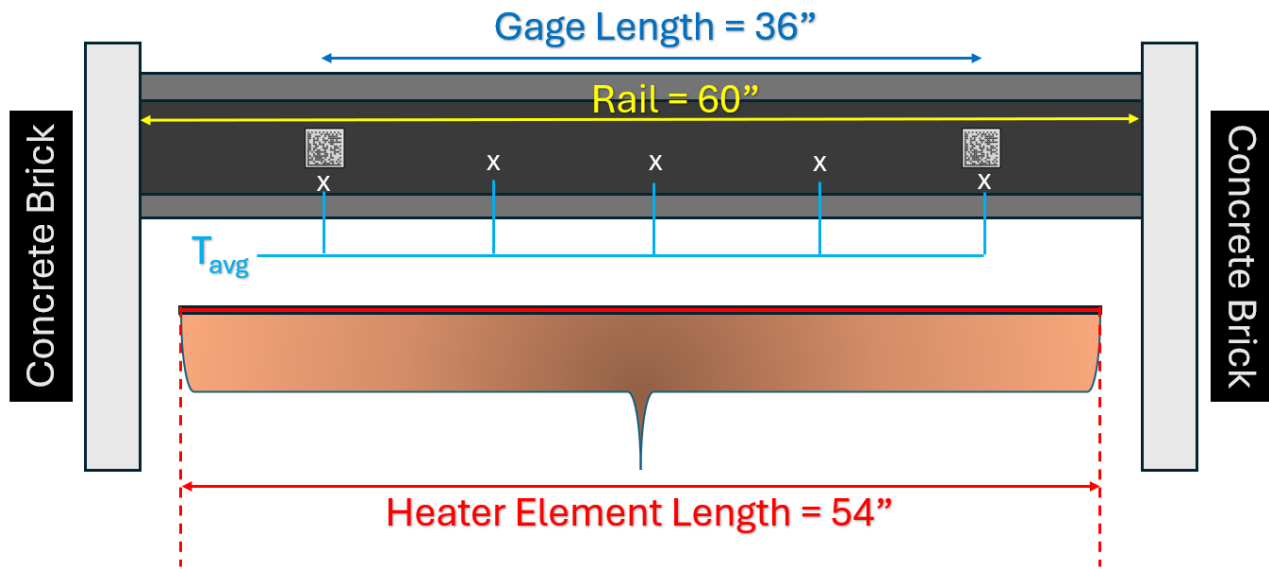


Figure E.2 Schematic Image for Supports for Rail and IR Heater

The average temperature associated with five thermocouples attached to the web was used to obtain the effective temperature of the rail while it cooled. The new strain sensor was used to measure the thermal strain induced by heating the rail and subsequently letting it cool. A reference image was taken before the heating started, and then the IR heater was turned off once the temperature reached about 115°F. After the heater was turned off, displacement measurements were taken using the new strain sensor as shown in [Figure E.3](#).

New Strain
Sensor

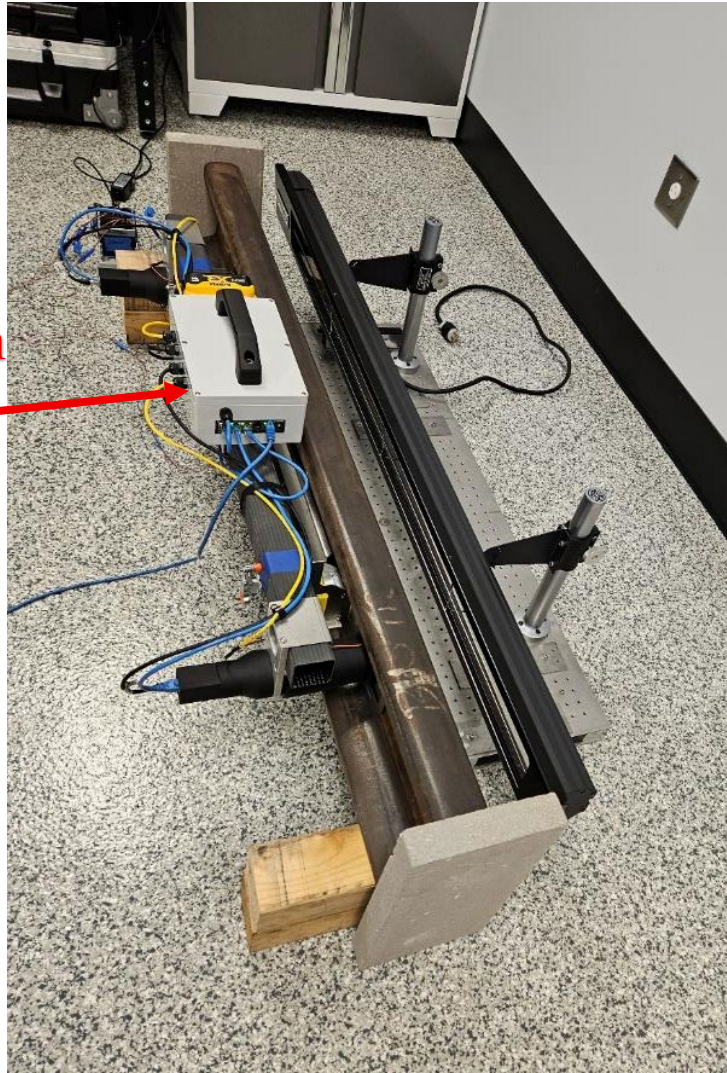


Figure E.3 Strain Sensor Mounted on Rail

Multiple measurements were taken while the temperature of the rail approached the ambient temperature from its initial heated condition. A plot was created for displacement measured by the new strain sensor versus the temperature elevation above the ambient temperature (ΔT). [Figure E.4](#) shows the slope/sensitivity of the plotted data and an R^2 value which is very close to 1 (indicating a high degree of linearity for the data).

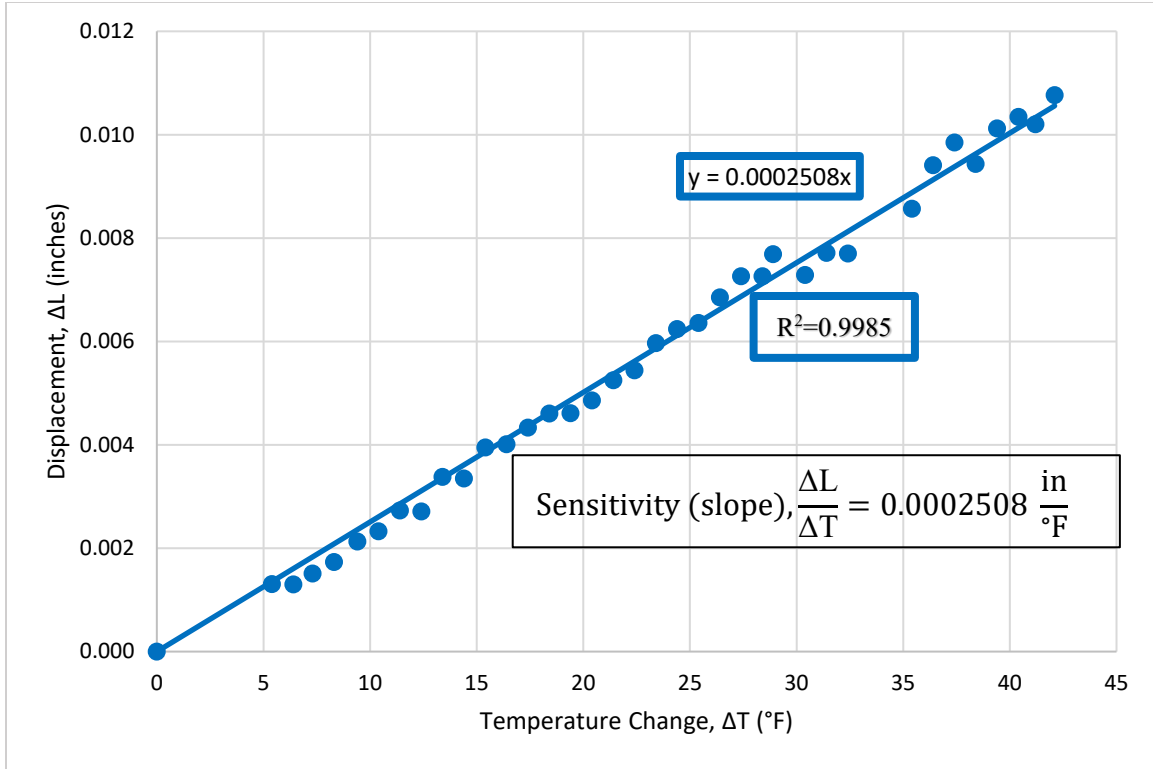


Figure E.4 Displacement vs. Temperature Change Using New Strain Sensor

From [Figure E.4](#), and using the determined sensitivity (slope of the trendline), the value of CTE can be estimated as follows:

$$\alpha = \text{CTE} = \frac{\Delta L}{L * \Delta T} \quad (\text{E.1})$$

The sensitivity $\frac{\Delta L}{\Delta T}$ from [Figure E.4](#) is

$$\frac{\Delta L}{\Delta T} = 0.0002508 \frac{\text{in}}{^\circ\text{F}} .$$

The resulting CTE is thus

$$\text{CTE} = \frac{\Delta L}{L * \Delta T} = \frac{0.0002508}{36}$$

yielding,

$$\text{CTE} = 6.97 \times 10^{-6} \text{ } ^\circ\text{F}^{-1}$$

E.2 Thermal Strain Test at NCPM Lab

Because of the importance of having an accurate value of CTE in assessing thermal strain, an additional CTE measurement method was employed in an attempt to provide an independent corroborative value of the CTE for the rail used in the current research.

The measurement was conducted by using the mechanical Whittemore gage (gage length 8.000in), shown in [Figure E.5](#), to measure strain (thermal displacement) on the head of a small section of steel rail.

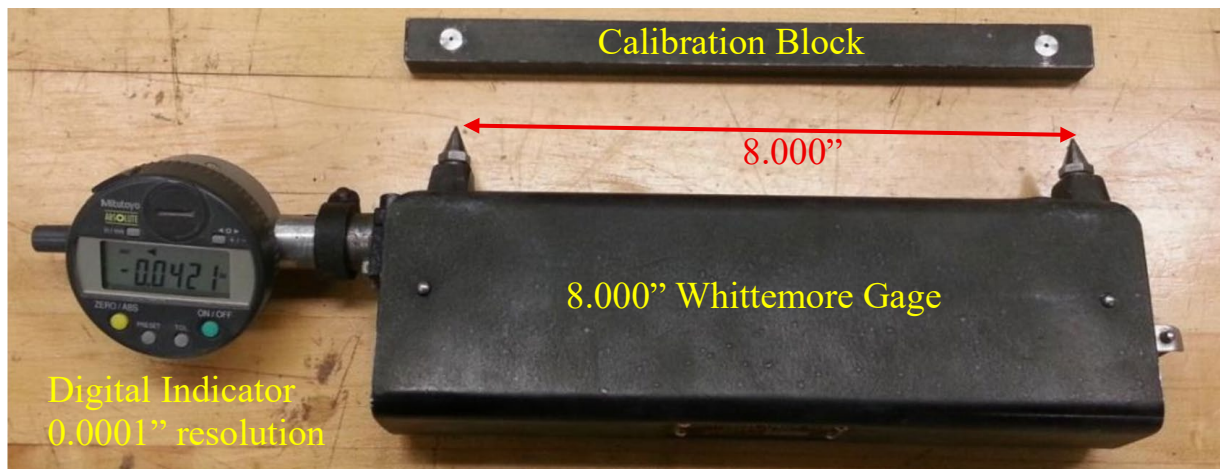


Figure E.5 8.000inch Whittemore Gage

A small rail section of 17.5" was cut and set up as shown in [Figure E.6](#). This very simple but effective setup included a line support for rail on couple bricks and two brick slabs to obstruct the heat loss from the ends to the surroundings. Since the rail section is small, the previously used 1500 Watt IR Heater was sufficient for heating the rail. Three thermocouples were used to measure the temperature of the rail section on the head of the rail. They were mounted (taped) on the left, center and right positions, as shown in the [Figure E.6](#).

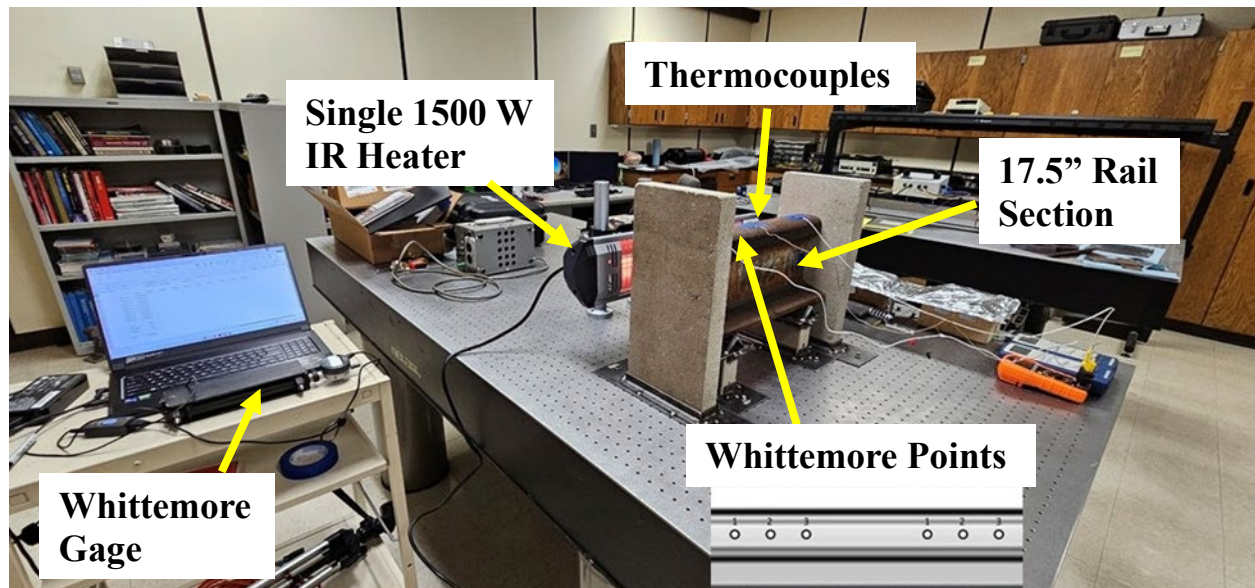


Figure E.6 Small Rail Section Setup to Assess CTE Using Whittemore Gage

As seen in the [Figure E.6](#), there are three sets of Whittemore points to provide three separate locations for strain measurement on the rail. Three sets of strain readings for each set of points were taken to improve accuracy, resulting in a total of 9 Whittemore readings for an average surface displacement at each temperature. Following a set of reference readings, the small IR heater was turned on, and the rail section was heated around 40°F above ambient. The heater was then turned off, and the rail was allowed to sit for about 10 minutes before the strain readings were taken, to give enough time for thermal distribution to happen with the rail section. Subsequently, 9 readings were taken on a total of three sets of points (similar to what was done for the reference readings) for four separate temperature levels while the rail was cooling. For each set of displacement measurements, thermocouples were used to record temperatures at three separate locations on the head of the rail to provide an estimate of the average rail temperature.

[Figure E.7](#) shows a plot of the displacement results versus temperature change. Similar to what was done in [Section E.1](#), a sensitivity was calculated as the slope of the trendline shown, and this was used to estimate the CTE.

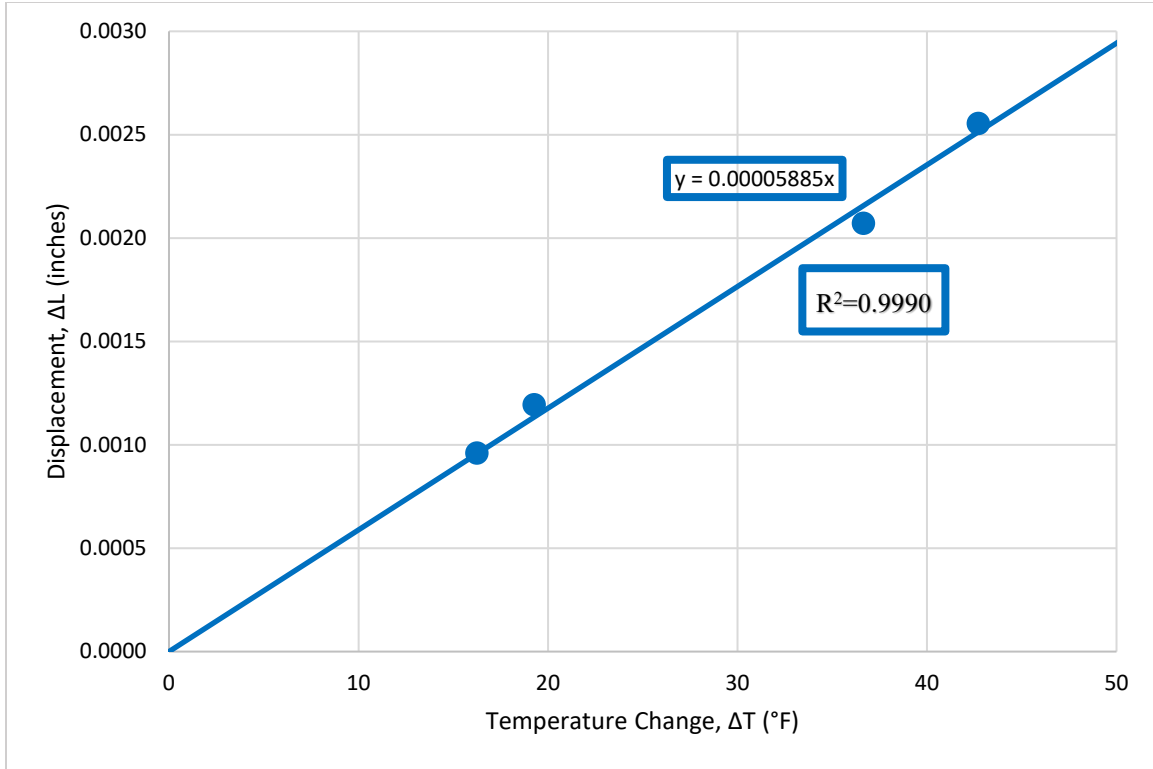


Figure E.7 Displacement vs. Temperature Change for Whittemore Gage Reading

Following the same procedure used in [Section E.1](#), the CTE is determined using equation E.1,

$$\alpha = \text{CTE} = \frac{\Delta L}{L * \Delta T}$$

From the slope of the trendline in [Figure E.7](#),

$$\frac{\Delta L}{\Delta T} = 0.00005885 \frac{\text{in}}{^{\circ}\text{F}}$$

Which yields the following estimate of the CTE

$$\text{CTE} = \frac{\Delta L}{L * \Delta T} = \frac{0.00005885}{8}$$

$$\text{CTE} = 7.36 \times 10^{-6} \text{ } ^{\circ}\text{F}^{-1}$$

As can be seen from [Figure E.7](#), all the measured points have very minimal deviation from the linear trendline having R^2 of 0.999. This strong linearity is also shown in the deviation plot given in [Figure E.8](#).

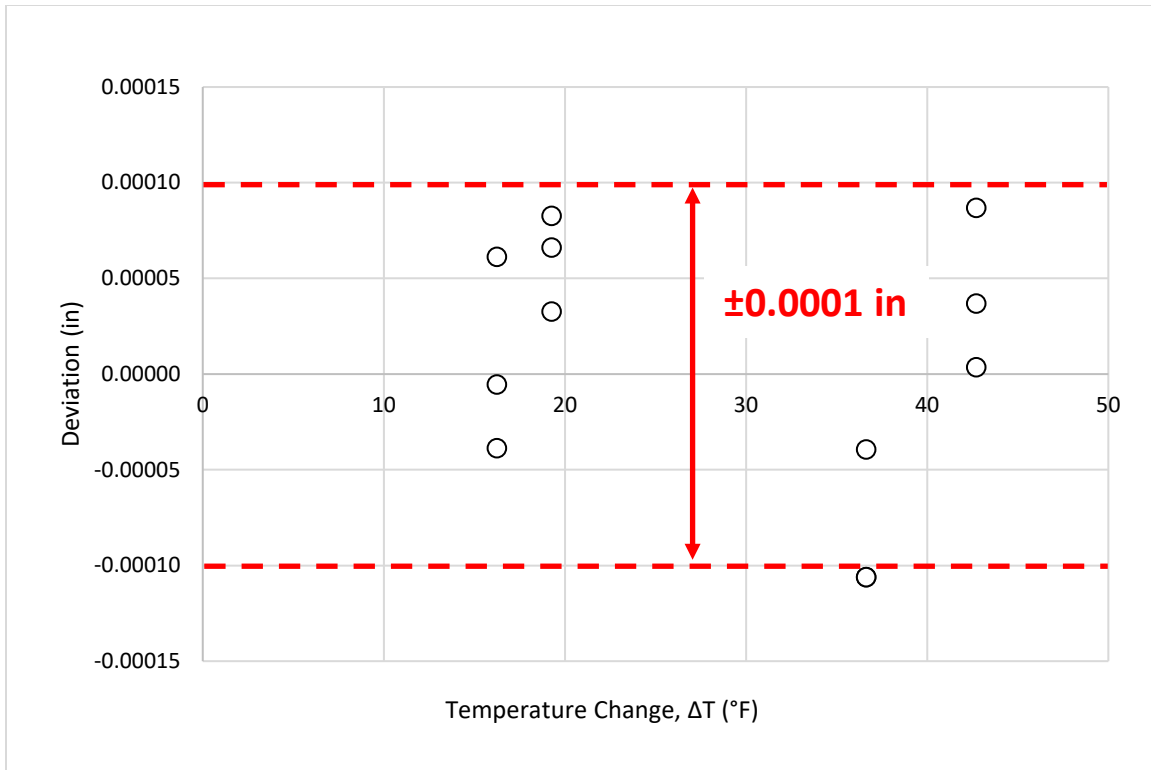


Figure E.8 Deviation Plot for Whittemore Gage Readings

The high degree of linearity indicated by the results plotted in [Figure E.7](#) and [Figure E.8](#), suggests that the CTE value calculated from the measured slope (sensitivity) should be reasonable.

E.3 Summary of CTE Assessment Results

In summary, the measurements of the CTE obtained in this Appendix suggest that the average CTE value of $6.5\text{E-}6 \text{ }^{\circ}\text{F}^{-1}$ [16] used for some decades may need to be modified, to obtain the best measurement of RNT for the rail currently under test. The reason for this could be that the rail manufacturing, including chemical composition of the rail, may have changed since the 1930's. Additionally, the testing methods performed in 1930's versus the availability and types of the testing methods used today, may contribute to the evaluation of a different value of CTE.

Appendix F – Sensitivity Comparison with The Mechanical Whittemore Gage

As discussed in the introduction, an alternative manual contact strain measurement system with good proven accuracy is a mechanical gage (e.g., a Whittemore gage). Depending on the user and their training experience, the accuracy of the Whittemore gage can reach up to about $\pm 25\text{-}50\mu\epsilon$ [1,3]. This section compares the uncertainty and sensitivity of the new non-contact sensor with manual Whittemore gage measurements. Testing was performed on a steel plate with machined Whittemore gage points. [Figure F.1](#) shows the Whittemore gage used for these tests; having 0.0001in. resolution and 8.000in. gage length.

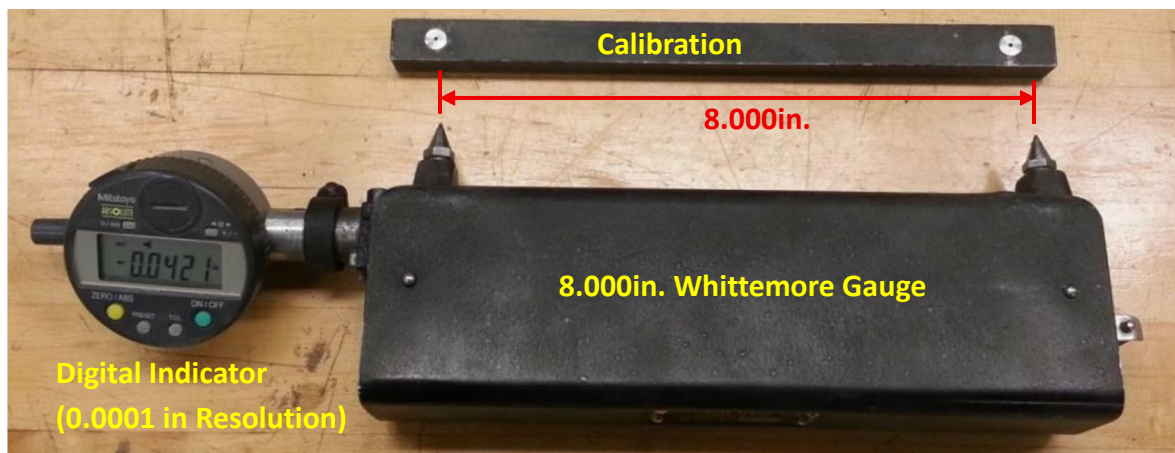


Figure F.1 Mechanical Whittemore Strain Measurement Gage

Three separate set of indents/points were machined on two steel plates, as shown in [Figure F.2](#). These points were separated by approximately 8.00in, with one plate stationary and one plate mounted on a movable micrometer stage. The micrometer stage was used to perform precisely known displacements, and the digital dial gage was used to record the actual (calibrated) displacements.

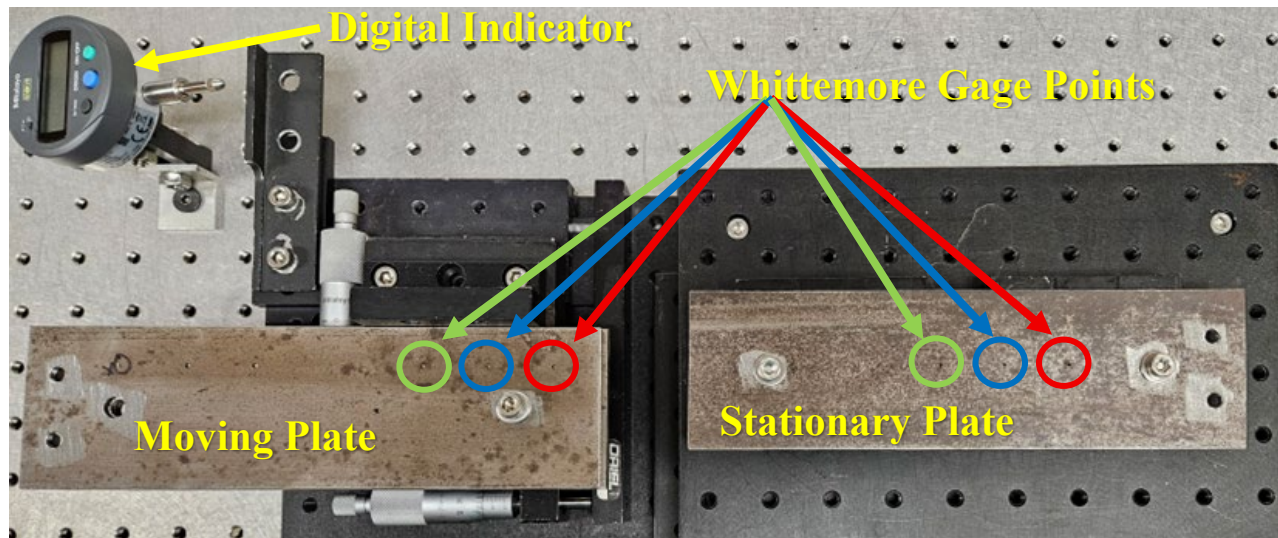


Figure F.2 Machined Whittemore Gage Points (Circled) for Strain Measurement

Whittemore gage displacement was precisely recorded using a remote data cable trigger (button) switch connected from the digital display of the gage to a laptop via USB. By a click of the trigger button, the precise displacement to 4 decimal places was recorded on the laptop directly into an excel sheet.

A reference (baseline) measurement was first recorded, and the micrometer stage was subsequently displaced in increments of approximately 0.01mm, over a displacement range of about 0.10mm. All the readings taken for each displacement were then correlated with the reference (baseline) taken when the dial gauge was at 0.000mm, to yield a net displacement from the reference (baseline) position. For improved measurement accuracy, 3 readings were taken for each set of points for each displacement; providing a total of 9 readings for each displacement measurement. [Figure F.3](#) shows a plot of these averaged measurements (orange circles), along with a trendline. This plot also shows a comparison between the Whittemore gage displacement results and calibration results for the new strain sensor (blue squares).

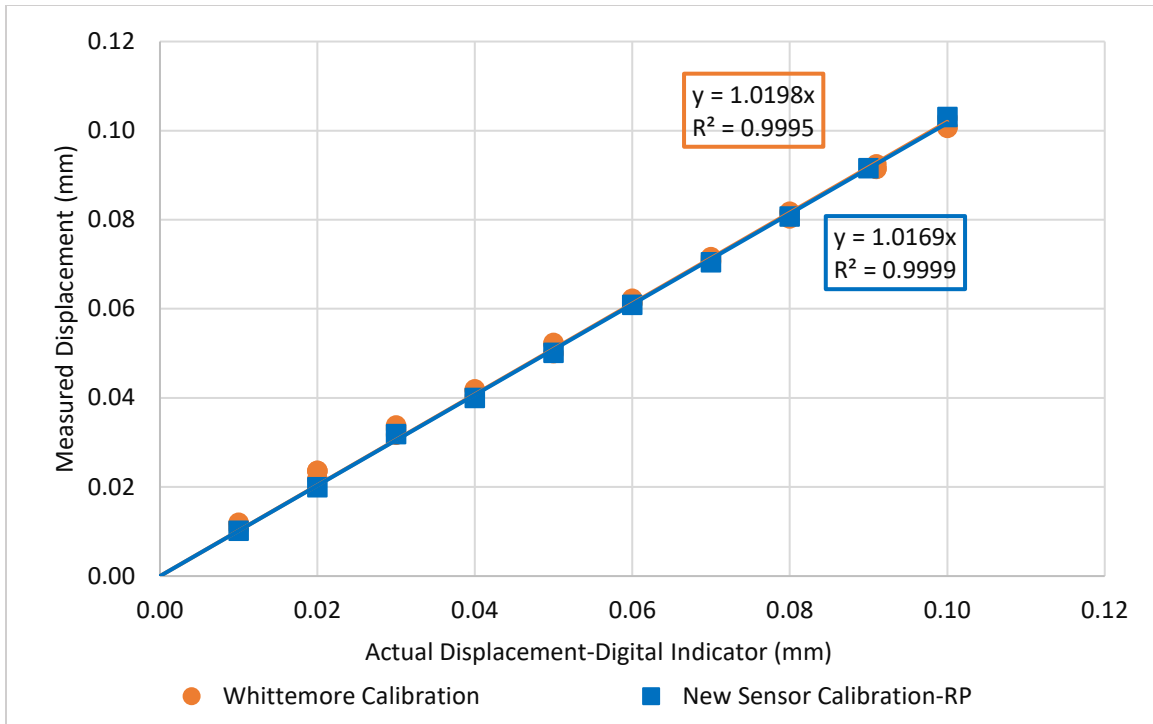


Figure F.3 Whittemore Gage and New Strain Sensor Displacement Data Comparison

The trendlines are linear, and all the measurements are within a small deviation from this line. This is displayed in a deviation plot for comparison purposes, as shown in [Figure F.4](#).

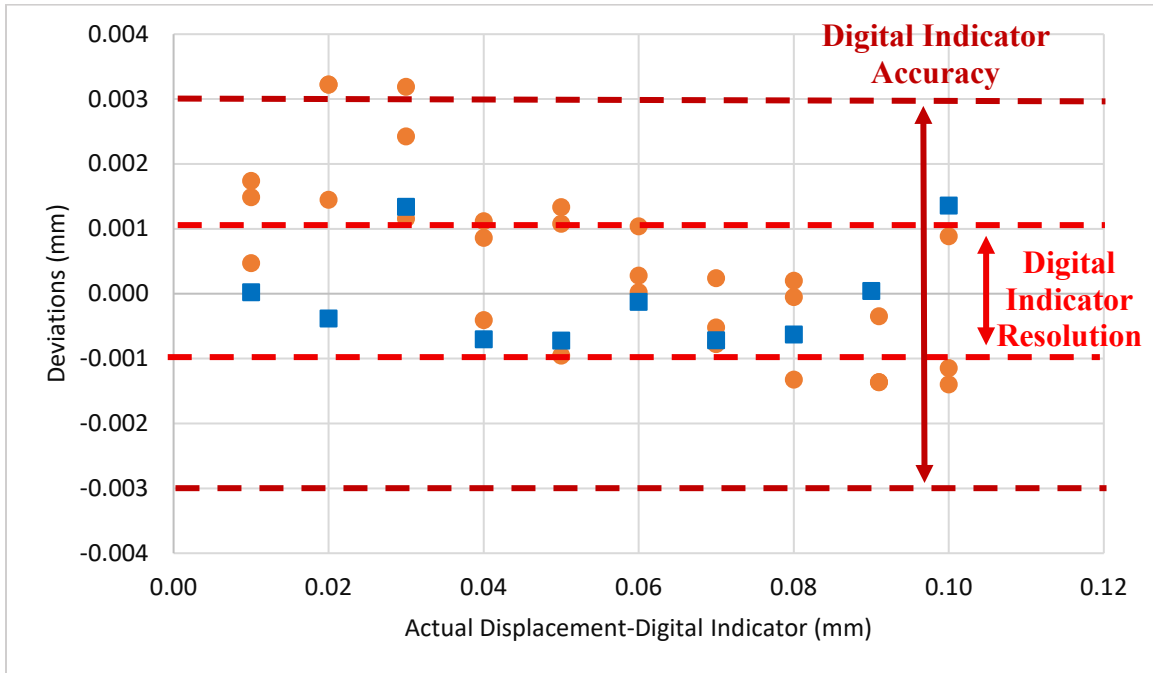


Figure F.4 Deviation Plot for Whittemore Gage and New Strain Sensor Displacements

Most of the deviations for new strain sensor fall within about $\pm 0.001\text{mm}$ whereas the deviations for Whittemore gage measurements are more spread out and fall within the range of about $\pm 0.003\text{mm}$. This shows that the uncertainty of the new strain sensor is considerably better than the manual mechanical gage uncertainty.

Appendix G – IR Heater Radiation Dispersion Effects

In establishing the IR heater power requirements for inducing known thermal loading of the rail under test, it was very important to identify the distance necessary to achieve appropriate heating of the rail test sections. This was to ensure that the heater was heating only the area under consideration with minimal heat loss to the surroundings. Also, the efficiency of the heating process would greatly affect the time required for heating the rail. To perform these tests, the small 1500W IR heater (used in previous thermal testing) was set up adjacent to a brick wall slab that was used as a target for the IR radiation, as shown in [Figure G.1](#). The slab was moved from 12” to up to 30” and the heater was kept on for about two minutes at each distance. These tests confirmed that the heat loss (dispersion of the IR radiation) increases as the distance of the wall from the heater increases.

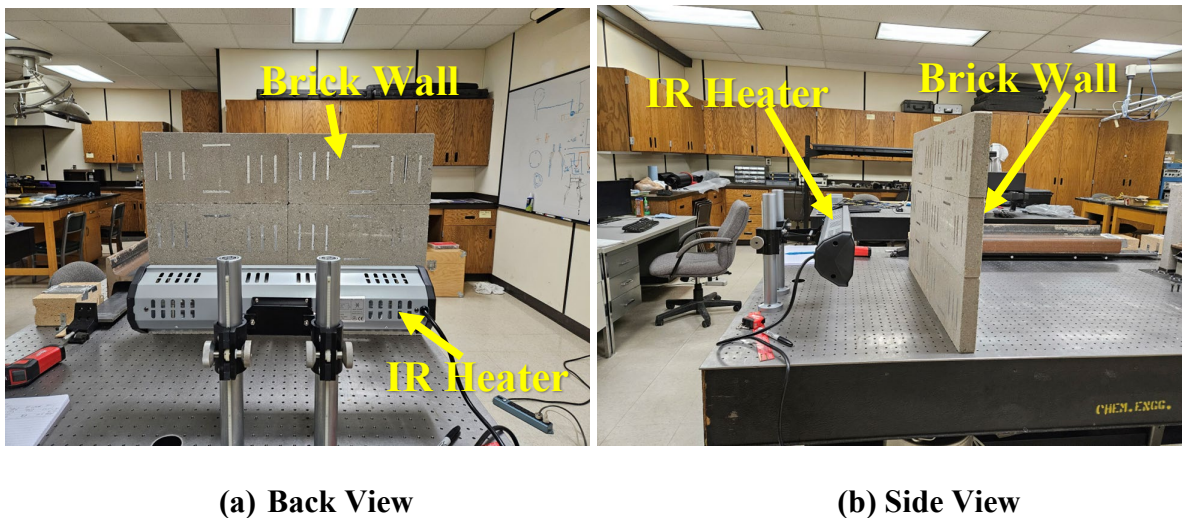


Figure G.1 Commercial 1500W IR Heater and Brick Wall Target

[Figures G.2](#) and [G.3](#) show the heated zone on the brick wall for 12” and 18” distances, respectively. These images were captured by the FLIR IR Imaging camera, similar to the one used for rail temperature measurements earlier in this dissertation described in [Chapter 7](#) and [Chapter 8](#). Aluminum strips on the brick wall was used as markers to measure the diameter and height of

the heated area on the brick wall. The heating (temperature rise) of the slab will depend on the distribution of intensity absorbed into its surface, and the exposure time. The IR intensity impinging on the slab surface will vary roughly inversely with the distance from the heater. It will also spread laterally (vertically and somewhat horizontally) as the distance from the source increases. For this test, the IR heating was applied for the same duration of time (approximately 2 minutes). The reason for keeping IR heater ON for couple minutes is that the brick wall takes time to heat up as it absorbs the IR radiation. Also, the brick wall was allowed to cool down naturally at ambient temperature before next series of tests were performed. This indicates that the IR heater disperses radiation with the same diffusing pattern. Hence, the farther away the wall is, the less radiation intensity it receives which is identified in [Figures G.2](#) and [G.3](#).

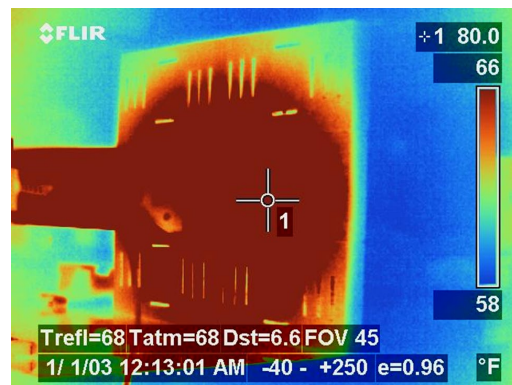


Figure G.2 Commercial Heater and Brick slab - 12” apart

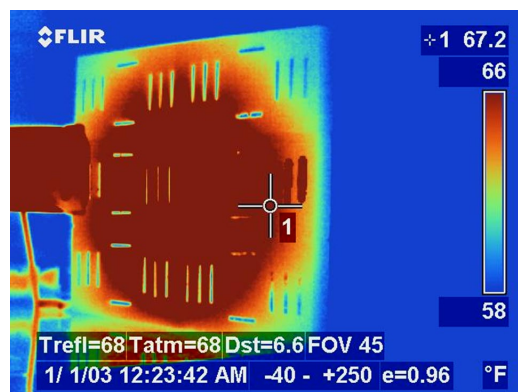


Figure G.3 Commercial Heater and Brick Wall - 18” apart

As shown in [Figures G.2](#) and [G.3](#), the heated zone (red circular zone) roughly indicates the diameter of the absorbed IR heater radiation. The heated zone is roughly circular due to the fact that the IR heater uses reflectors for better heat dispersion out the front face of the heater. The IR heater includes a long approximately parabolic reflecting panel behind the heater, and end panel reflectors to better direct the IR radiation that might otherwise disperse out each end. These are indicated in [Figure G.4](#). The IR radiation actually tends to spread in all directions, although not quite equally due to the rectangular shape of the heater. For the 12" distance, the diameter of the red circular heated zone was approximately 31" x 20" whereas the diameter of the of the red circular zone for 18" distance was approximately 25" x 20". This indicates that the width of the heater zone did not change much but the height was changing significantly with distance. The width of the heater zone did not get affected too much because the IR heater is longer in comparison to its height. Additionally, the height of the heated zone changes because the reflective panels around the IR heater element are longer in length in horizontal direction than in the vertical direction as shown in [Figure G.4](#).

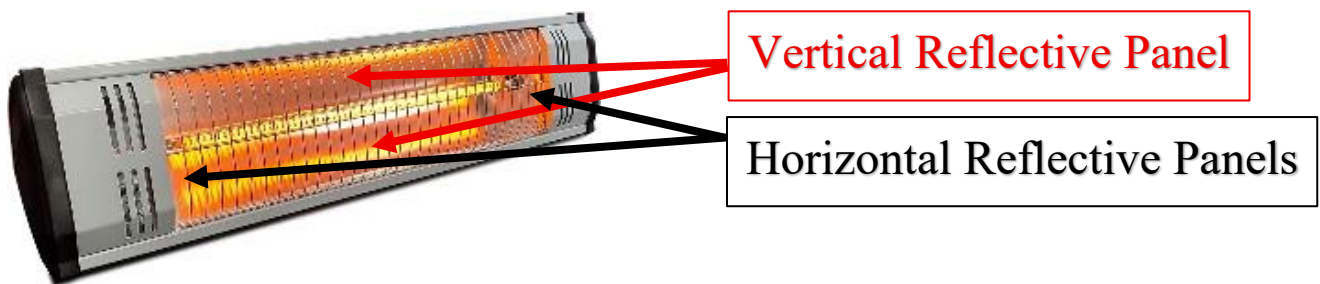


Figure G.4 Commercial 1500W Heater Vertical vs Horizontal Reflective Panels

To investigate improving the focus of the IR heater radiation and reduce IR dispersion heat loss, a test was conducted using aluminum blades (sheets) attached to the top and bottom of the IR heater, as shown in the [Figure G.5](#).



Figure G.5 Commercial Heater with Aluminum Blades for Radiation Convergence

The same heater-to-slab spacings were used to perform testing of the heated zone on the brick wall. [Figures G.6](#) and [G.7](#) show the imaged region of absorbed radiation on the brick wall with the addition of the aluminum blades. There was a huge reduction in dispersion of the IR radiation (apparent heat loss). The region of absorbed IR heater radiation was concentrated on a smaller area in the vertical direction due to the reflective sheets of aluminum guiding (or focusing) the radiation from the IR heater in a more collimated manner.

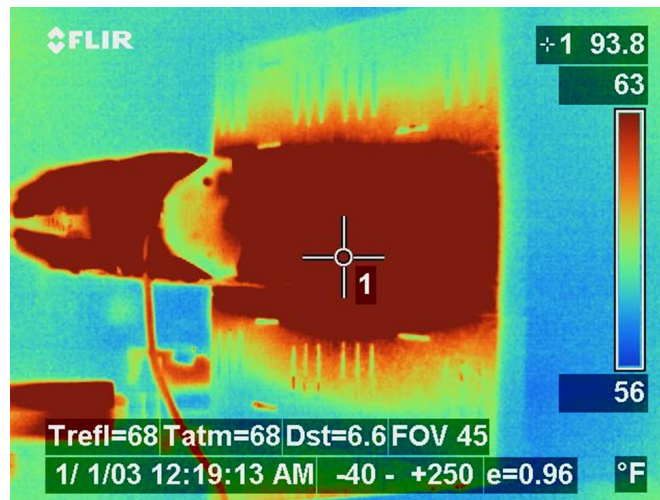


Figure G.6 Commercial Heater and Brick Wall - 12" Apart with Aluminum Blades

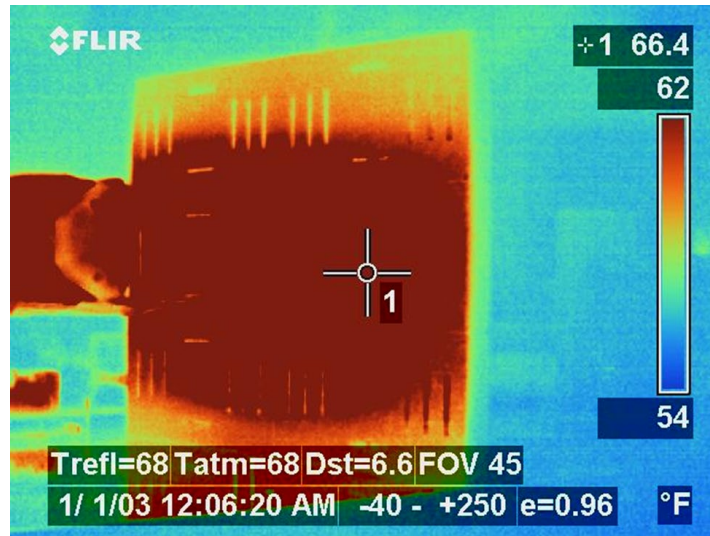


Figure G.7 Commercial Heater and Brick Wall - 18" Apart with Aluminum Blades

[Figures G.8](#) and [G.9](#) show side by side comparisons of the brick wall absorbed radiation zone for 12" distance, 30 seconds and 60 seconds after turning off the heater, respectively. With the blades, the radiation is able to better focus on the wall (and be absorbed) than without the blades.

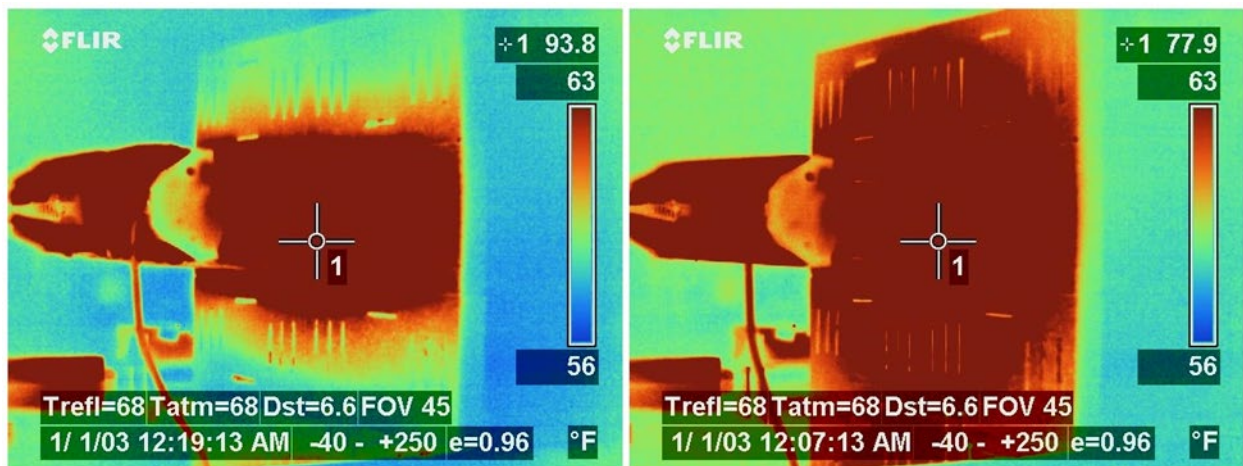


**Figure G.8 IR Heater Radiation Zone Comparison – with and without Aluminum Blades
(30 Seconds After Heater was Turned Off)**

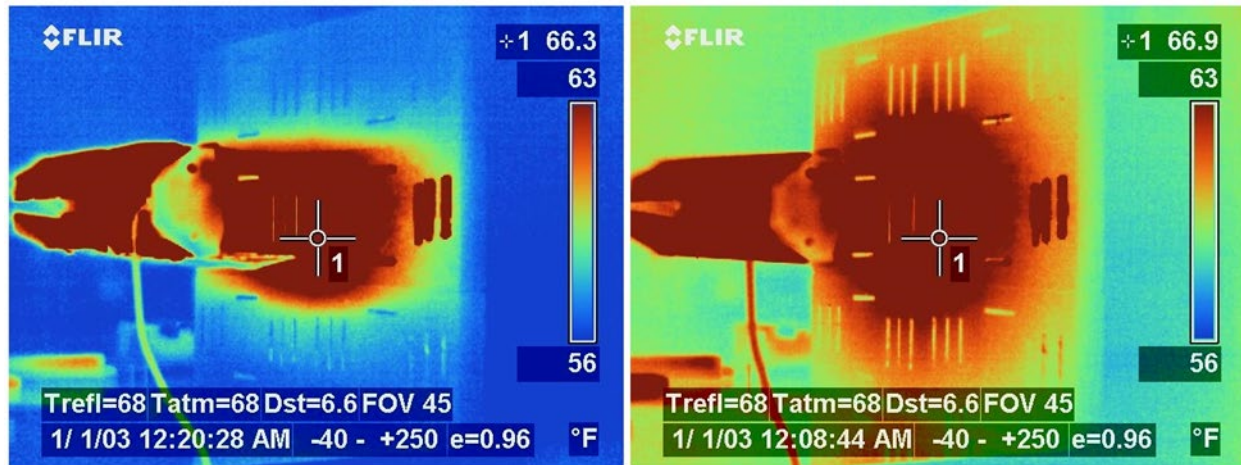


**Figure G.9 IR Heater Radiation Zone Comparison – with and without Aluminum Blades
(60 Seconds After Heater was Turned Off)**