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Determining the Stresses in Steel Railroad-Track Rails Due to Freight Movements Using Non-Contact Laser-Speckle

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16. Abstract

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Table of Contents

List of Figures

List of Tables

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Abstract

This research was aimed at developing a procedure to determine the existing stresses in steel rails used in railroad tracks. These stresses are caused by the combination of both thermal restraint and physical/mechanical loads. However, since the track sections are installed at various temperatures and then continuously welded together and secured to wood or concrete ties, the stresses existing in the track at any given time are currently unknown. In fact, not only the magnitude of stress is unknown, but also the basic knowledge about whether the rails are in tension or compression at a given time. Since the stresses due to thermal and physical loading are additive in the elastic range, the existing safety factors of the rail system when subjected to heavy freight movements are also unknown. The research focused on extending the existing technology of laser-speckle strain measurements for concrete surfaces to use on steel rails.

Chapter 1 Introduction

The ability to accurately determine the existing stresses in railroad track rails is extremely valuable when assessing the condition of an existing railway line. This is especially important for routes that pass through Kansas and Nebraska which transport heavily loaded coal-carrying cars from Wyoming's Powder River Basin. However, the ability to obtain this information by using electrical resistance strain gauges is difficult, time consuming, and expensive.

The stresses in a steel rail are caused by the restraint of thermal movements and by physical loads induced by the trains. Initially, sections of steel rail are placed in the track and then welded continuously and secured to wood or concrete ties. These stresses in the track can vary greatly based on the temperature when the track is installed and the subsequent resistance to thermal movements by sub-grade composition and tie spacing. Thus, there is a need to be able to quickly and reliably determine the stresses which occur in the tracks, especially as increasingly heavy freights are being carried.

Traditionally, electrical resistance strain gauges are mounted on the surface of structural members to monitor the strain over time. However these gauges are often expensive and require a great deal of time to mount. Once in place, strain gauges can become dislodged from the surface and are prone to zero-shifting (drift) over time.

While the conventional measurement technique is difficult and time consuming, a non-contact method to measure strain has been developed at Kansas State University (KSU). The technology is called Laser-Speckle Imaging (LSI). The objective of this study was to develop a rapid, non-contact test method for determining the thermal strains in steel rails using LSI, and to compare the results obtained with those of electrical resistance strain gauges.

1.1 Laser-Speckle Imaging Methodology

To determine the accuracy required from the LSI device, results were compared to that of a mechanical hand held gauge typically used to measure the transfer length of pretensioned concrete members. Using a laboratory interferometer as a controlled calibration technique, shown in figure 1.1, the accuracy of an experienced user was about +/- 0.0002 inches. If using the standard 8-inch gauge length, this value corresponds to a strain level of +/- 25 microstrain. Using this information, the design team concluded that the optical system must have an accuracy of at least +/- 25 microstrain (Zhao 2010).

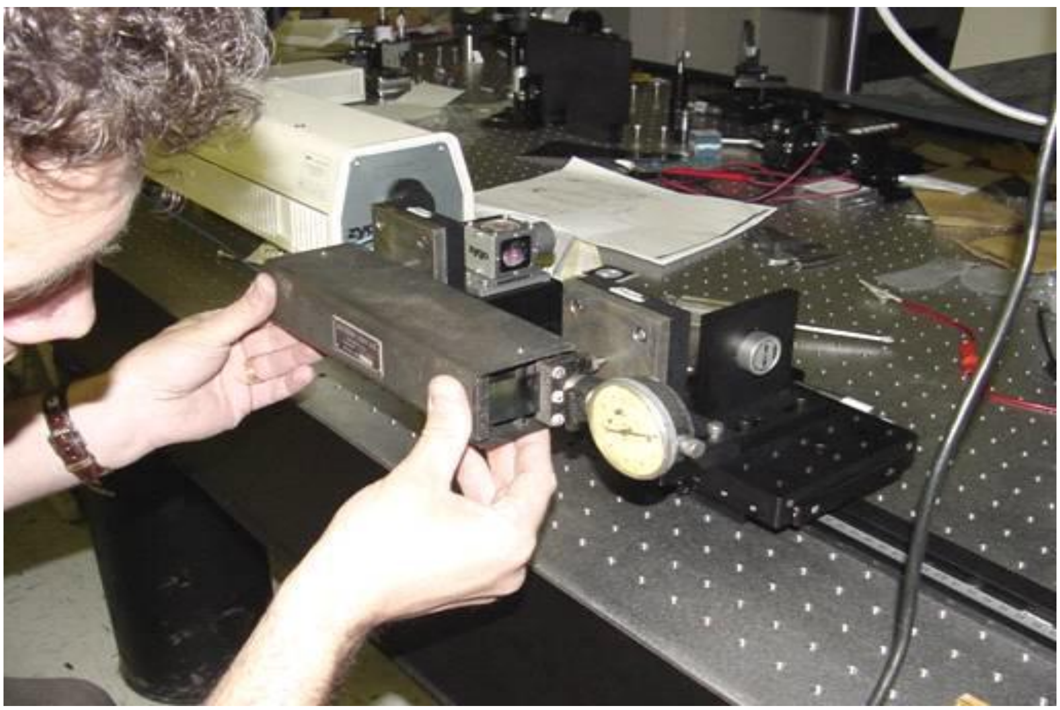

Figure 1.1 Determining the accuracy of a standard mechanical gauge

Optical speckle techniques have evolved into powerful tools for the measurement of surface strain since digital image recording and processing became widely available. When using optical speckle, almost any rough surface can be used, and it has the advantage that minimal surface preparation is needed (Zhao 2010).

Speckle is generated by illuminating a rough surface with a coherent light source, as shown in figure 1.2. The random reflected waves interfere with each other, resulting in the grainy image shown in figure 1.3. The speckle pattern of the member’s surface serves as a “fingerprint” of the unique location (Zhao 2010). As the member undergoes deformation due to stress increases, the speckle pattern will also move. This deformation in the surface can be converted to a change in strain by measuring the speckle pattern movement.

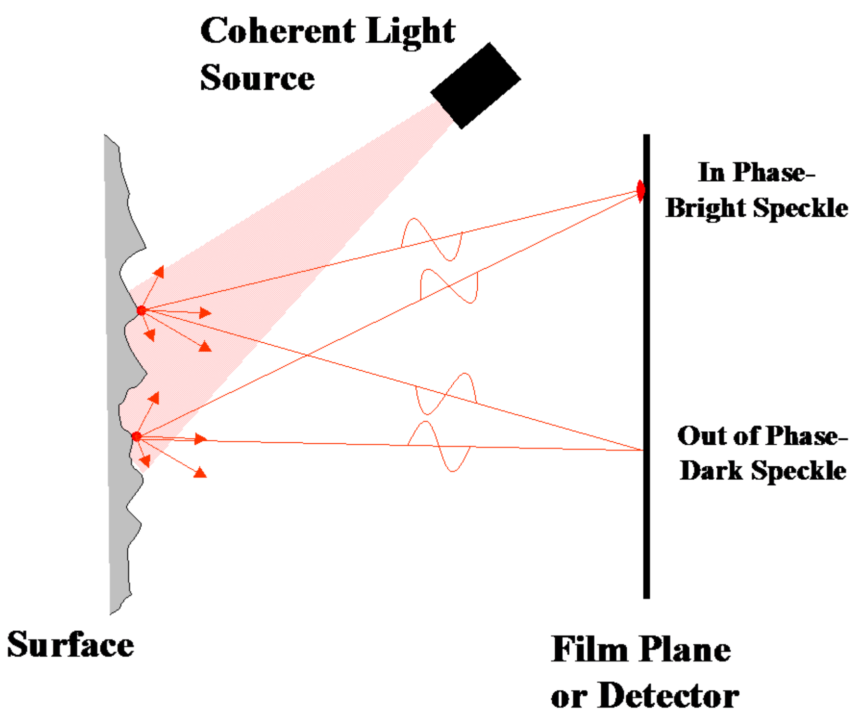

Figure 1.2 Illustration of the laser-speckle concept

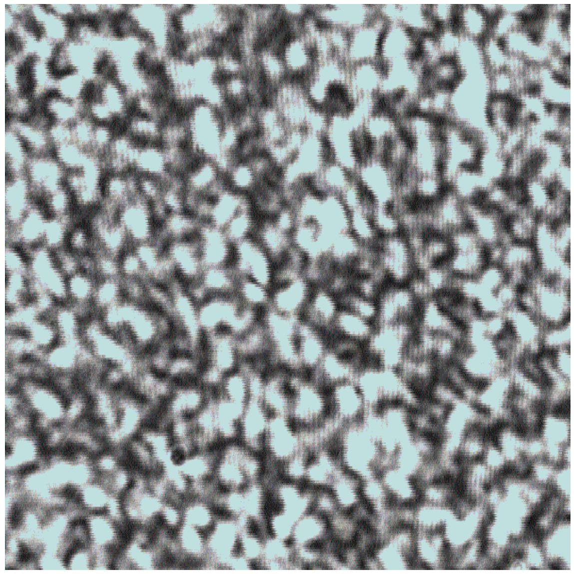

Figure 1.3 Image of speckle pattern generated by concrete surface

To detect the surface strain, the grainy speckle pattern image is recorded before stress is applied to the member and once again after the member undergoes its stress deformation. The deformation or displacement components can then be extracted by comparing the shift of the speckle patterns before and after deformation. This is typically done statistically using a cross-correlation technique to measure the speckle displacement. In particular, phase correlation that mainly relies on the phase information for matching the image pairs is used in the software implement (Zhao 2004).

A prototype of the optical strain sensor was fabricated in a portable light-weight self-contained unit for field testing, as shown in figure 1.4. It has two identical modules attached rigidly to each other in a mirror setup with each module capable of detecting the surface movement independently. This unique modular design provided several preferable features including flexible adjustment of the gauge length, easy upgradeability to automatic operation, robustness and higher accuracy (Zhao 2011).

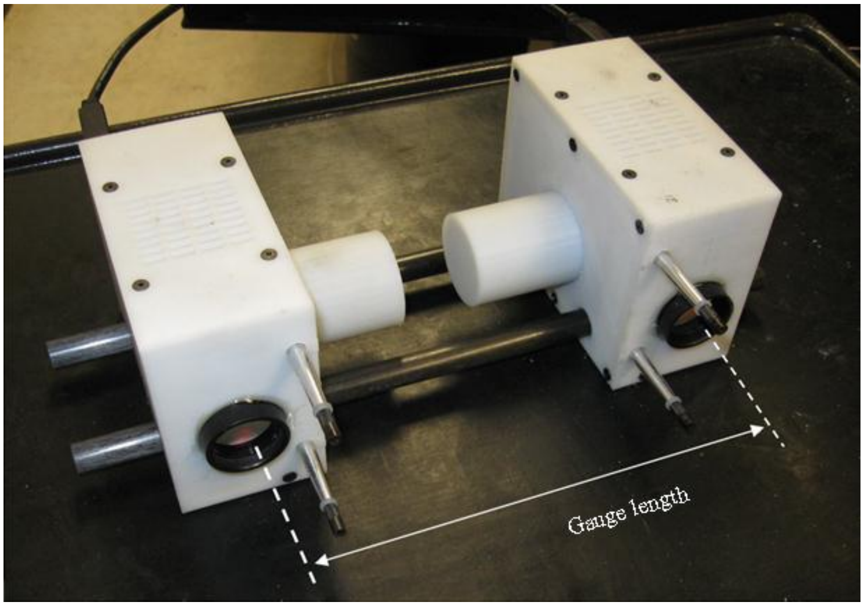

Figure 1.4 Laser-speckle prototype (Zhao 2011)

For the surface strain measurement, the optical strain sensor is first positioned onto the steel rail surface before applying any load. The two cameras in the left and right modules capture a pair of speckle images that are generated by points A and B, respectively. These two speckle images are denoted as A1 and B1 and are referred to as the base readings. The sensor is then removed from the steel surface. When the magnitude of stress in the steel rail is interrogated, the optical sensor is positioned back onto the surface in the exact location that the base readings were taken. The cameras capture another pair of speckle images, which are denoted as A2 and B2. By applying a cross-correlation technique to the pair of speckle images A1 and A2, the displacement ΔA can be extracted. The displacement ΔB can be extracted from image B1 and B2 in a similar fashion. As shown in figure 1.5, the axial surface strain ε, between points A and point B can thus be determined by $\varepsilon = (\Delta B - \Delta A) / L$, where L is the gauge length of 8 inches for the current setup (Zhao 2011).

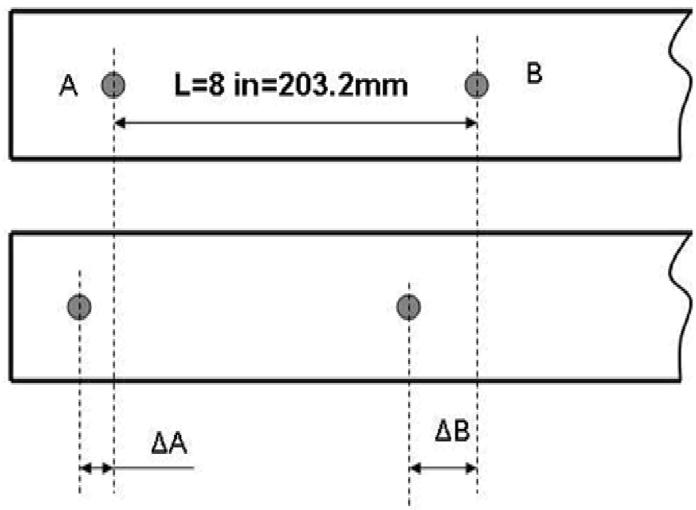

Figure 1.5 Visualization of strain measurement

1.2 Laboratory Verifications of LSI Technique

In order to test the accuracy and sensitivity of the LSI method, a laboratory setup was fabricated and used to conduct comparisons between the optical sensor and a manual gauge. The capability of the optical sensor strain measurement was validated by using a manual motion system, as shown in figure 1.6. Two small concrete blocks were positioned side by side approximately 8 inches apart. The concrete block shown on the left was attached to a manual traverse system and the displacement was measured by a digital dial gauge with a resolution of 0.001 mm (Shars 303-3506) while the concrete block on the right was held stationary. This system was used to create a relatively linear displacement between the two concrete blocks.

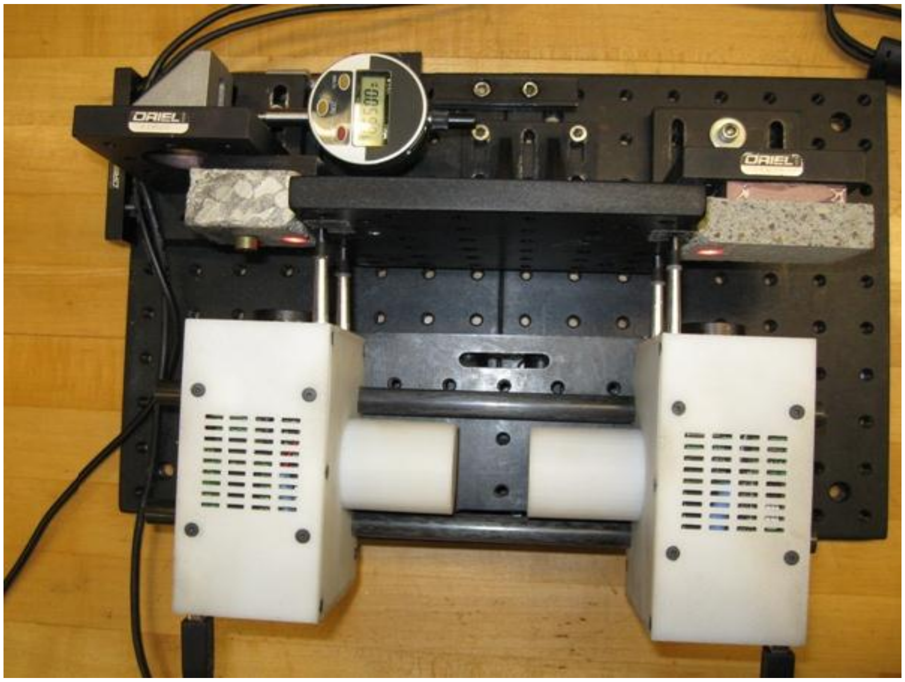

Figure 1.6 Concrete block system used to validate the optical strain measurements (Zhao 2011)

The relative displacement between the two concrete blocks was increased from 0 mm to 2 mm with 0.1 mm increments. Displacements were measured by both the digital dial gauge and the laser-speckle strain sensor. Results from this test are displayed in figure 1.7 and show that the readings from the two devices have excellent correlation (Zhao 2011).

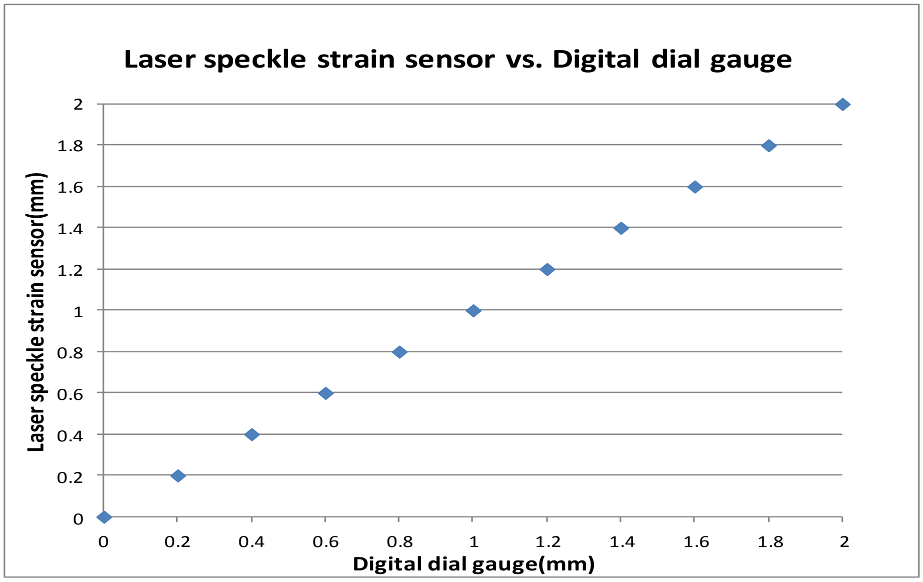

Figure 1.7 Comparison of laser-speckle strain sensor and digital dial gauge (Zhao 2011)

Chapter 2 Application of LSI Device on Steel Rails

Although the Laser-Speckle Imaging device worked excellently in laboratory conditions, many changes needed to be made to make the system more robust for the harsh conditions that the steel rail experiences. Also, the initial laser-speckle software was developed for use on concrete surfaces. This software and camera parameters were modified in this research program so measurements could be taken on steel surfaces. Concrete surfaces offer rough bright textures that vary greatly from the often smooth, dull surface of steel. All of the work needed to alter the laser-speckle program and verify the strain readings on a steel rail was completed on a 66-inch piece of track that was provided to the research team by Union Pacific Railroad (UPR).

2.1 Utilization of the LSI Device on Steel Surfaces

The LSI sensor was initially developed for strain or measurements on concrete surfaces. Due to the nature of the laser-speckle technology, it can work on any rough surface such as wood, fiber glass, steel, etc. The rough surface, regardless of the material type, alters the phase of the incident laser light randomly in the same way and creates similar speckle images, like the pattern shown in figure 1.3. In addition, it is worth noting that the speckle size of the captured speckle image, a main factor that affects the sensor's resolution, is irrelevant to the specimen surface roughness and is completely determined by the configuration of the imaging system. Thus, the measurement resolution of the LSI sensor (+/- 25 microstrain) does not change on different material surfaces.

The LSI sensor is applied to the strain measurements on steel surfaces with adaptation of the software to deal with the image intensity issue. That is, the reflectivity of the (often rusted) steel of the railroad track is much lower than that of the concrete, causing the speckle images captured from the steel track surface to be much darker than those from concrete surfaces. This tends to decrease the contrast of the images and the signal-to-noise ratio. To solve this problem, a feature was added to the software that automatically adjusts the gain and exposure value of the camera to bring the average intensity of the captured image to the same level. This adaptation successfully solves the problem of material reflectivity difference. This makes the LSI sensor function properly in the applications involving different materials, including the steel track surface in this project.

2.2 Loss of Surface Correlation

Once the laser-speckle software had been altered to accommodate steel surfaces, many tests were conducted to see how well the surface profile held up in harsh conditions. In order for the optical sensor to work correctly, the surface profile must remain consistent throughout the testing period. If the surface profile changes, the speckle pattern loses correlation and the "fingerprint" is lost. Changes to the surface profile can be caused by weathering and surface abrasion. When using the optical sensor on steel track, the loss of correlation is a major concern due to the exposure of the elements in the field and the harsh conditions introduced by the trains.

Simple experiments were conducted to view the robustness of the bare steel surface profile. After initial readings were taken on the bare steel surface of the web section of the rail, the steel was rinsed with water and lightly scrubbed with a brush. Once the rail had dried, a set of secondary readings were taken to determine if the surface correlation had been lost. The results of this test were somewhat favorable. Correlation between the initial images and secondary images was evident, however, finding correlation was time consuming and sometimes inaccurate. This indicates that the surface profile had changed enough due to the rinsing and scrubbing to alter the results. If the steel rail was not scrubbed or rinsed with water, it was determined that a three week period was about the maximum amount of time that the speckle pattern could be preserved on the bare steel surface when exposed to the natural elements of snow, wind, and rain.

To mitigate surface changes, paint that contained a speckled pattern was applied to the rail web section as shown in figure 2.1. The speckled pattern contained microscopic reflective particles that bonded to the surface and created an artificial speckle (Zhao 2011). The particles helped maintain the correlation that was needed for the optical strain sensor to function properly.

Figure 2.1 Steel rail with paint to protect surface correlation

With the paint applied to the steel rail surface, the strain sensor was able to obtain a correlation between the speckle image pairs and extract the surface strain information needed. Various tests were conducted to ensure the durability of the paint on the steel surface. A layer of paint was applied to one side of the steel rail. Once the paint had been given time to dry, initial readings were taken on the rail using the optical strain sensor as shown in figure 2.2.

Figure 2.2 Taking base readings using the hand held method

After the reference readings had been taken, the painted surface was scrubbed with a towel and a rough brush. This procedure simulated the harsh environment in the field that the rails are subjected to. The rail was also rinsed with water and left outside during a three month period in the winter months, as shown in figure 2.3. This tested the durability of the paint by naturally weathering the surface. After each of these tests, the painted surface was checked to see if surface correlation had been lost by taking another set of readings using the optical strain sensor. These new readings compared the images taken during the reference readings to the new images during the time of testing. It was determined that the microscopic particles remained in the paint and stood up to the abrasion and weathering tests. Correlation was found after each and every test the rail was put through. This evidence proved that correlation could be found over a longer period of time than if readings were taken on the bare steel surface.

Figure 2.3 Steel rail exposed to extreme weather conditions

After roughly a three month period, the laser-speckle began to lose correlation on the painted surface. The natural weathering process changed the surface texture enough so the LSI device didn't recognize the original surface images. Surface correlation could likely be preserved for longer periods of time if the location of the rail where readings are being taken were covered and protected.

2.3 Verification of Painted Surface

Although the paint helped preserve the surface correlation, it was uncertain whether or not the paint was experiencing the same strain that the steel surface was. If the paint and steel surface did not have a perfect bond, strain readings from the painted surface would not give the correct results. Knowing this, thermal strains were monitored on the steel rail donated to Kansas State University. One side of the rail was covered with paint while the other side was not. The LSI device was used to take reference readings on both sides of the rail at room temperature. Twenty readings were taken along the length of the rail to view any discrepancies between the two surfaces. The rail was then placed outside during the winter months to view the change in strain the rail experienced. Because this was just a procedure to test the comparison between the paint and steel surface, the temperature of the rail was not monitored at this point.

Over the course of a three week period, the thermal strains were monitored on the two surfaces. Due to the extremely cold weather during the time of testing, the steel rail experienced high thermal strains. A few examples of the strain measurements can be seen below in the following figures.

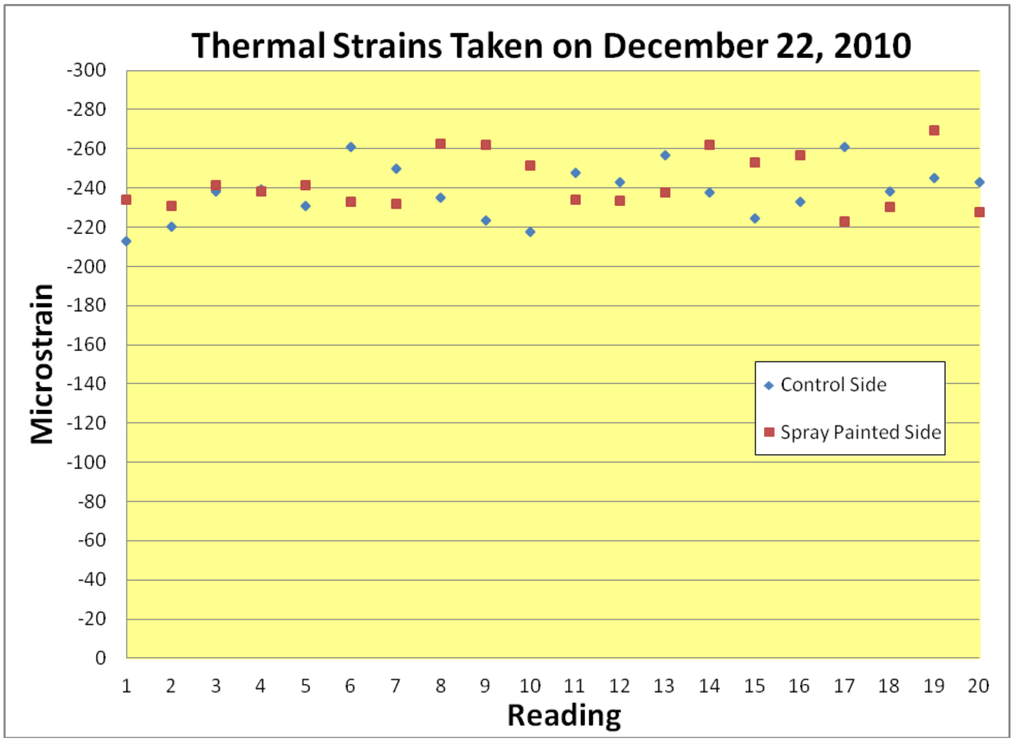

Figure 2.4 Steel rail thermal strains taken on December 22, 2010

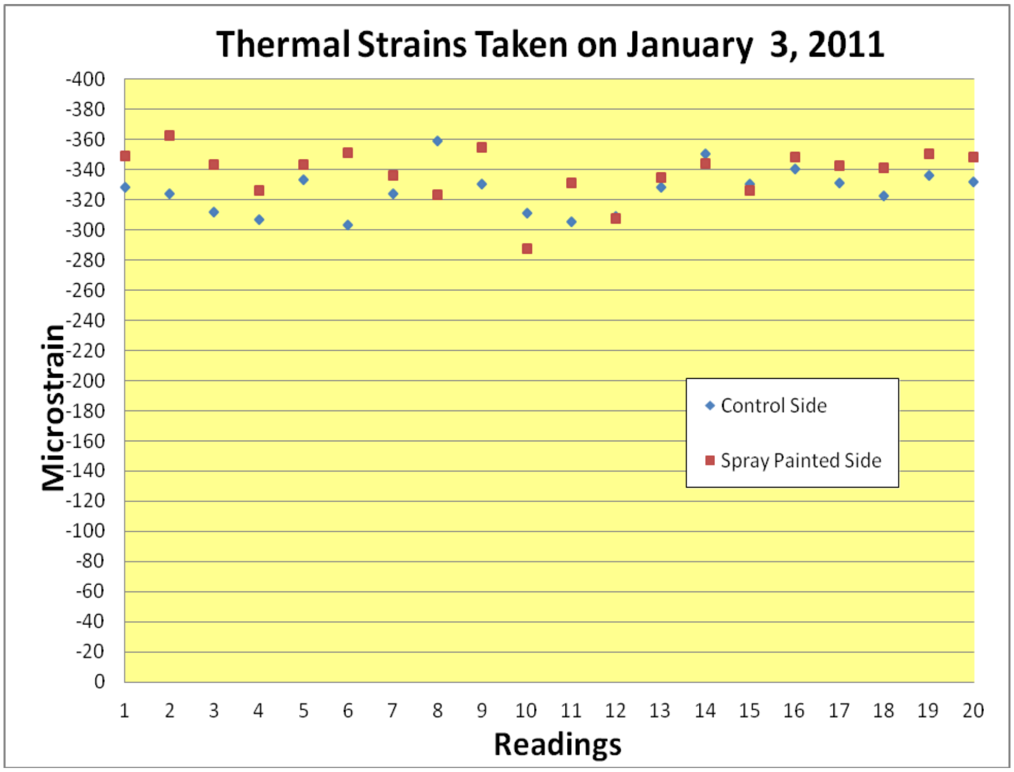

Figure 2.5 Steel rail thermal strains taken on January 3, 2011

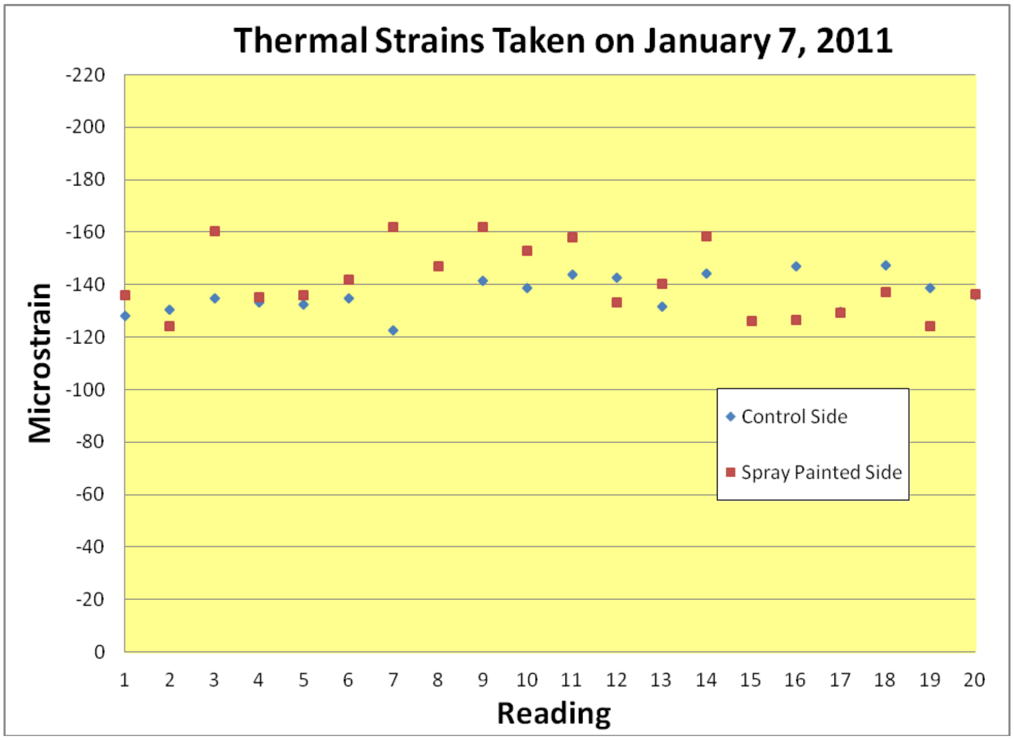

Figure 2.6 Steel rail thermal strain taken on January 7, 2011

From the graphs of these thermal strains, it was determined that the painted surface correlated very well to the bare steel surface. This proves that the two surfaces do not act independently from each other. The painted surface experiences the same strain as the bare steel surface. Once this information was known, further tests were conducted to advance the strain measuring technique on the steel rail.

2.4 Optical Strain Sensor Rail Mounts

In order to take strain measurements using the LSI device, readings must be taken at approximately the same location as the one where reference readings are taken. Otherwise, the images will not correlate to one another and no data can be gathered. The measurement range of the LSI device is ±2mm, which means if readings are being taken within 2 mm of the reference images, successful correlation can be obtained. If the misalignment of the sensor exceeds ±2mm, the correlation condition is violated and a false or inaccurate reading will occur.

To ensure readings are being taken at the same locations every time, a number of techniques were developed to accurately use the strain sensor. The first and easiest method to take readings involves a hand held procedure. Three offset screws that project from the laser module were used to pin-point the location of readings. The offsets can be seen below in figure 2.7.

Using these offsets requires the user to accurately label points on the steel rail web surface to ensure that the laser module is reading from the exact same location as the previous readings. Examples of surface labeling can be seen in figure 2.8. Although this method is quick and easy, human errors do occur due to the inaccuracy of marking and labeling the steel rail and the unsteadiness of the human hand.

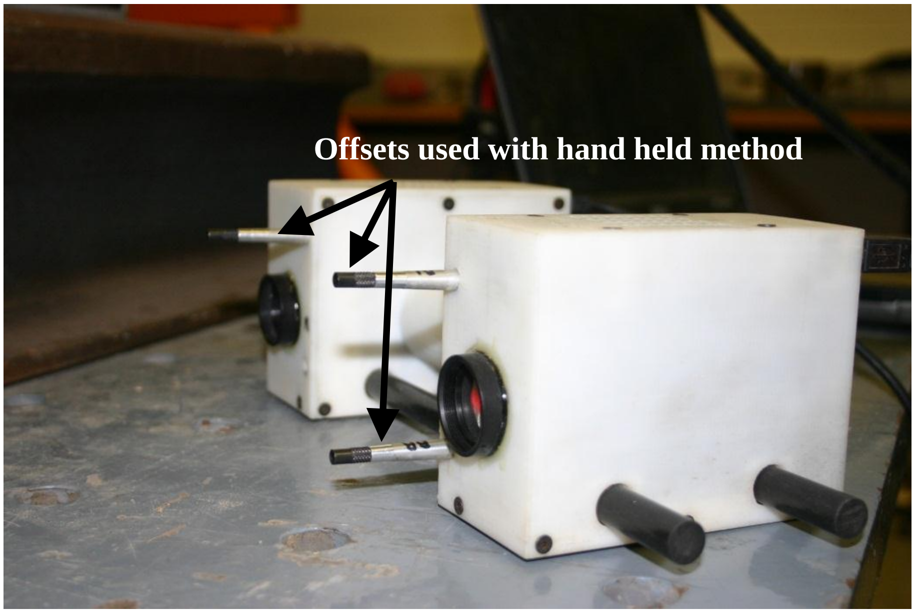

Figure 2.7 Laser module offsets used with hand held method

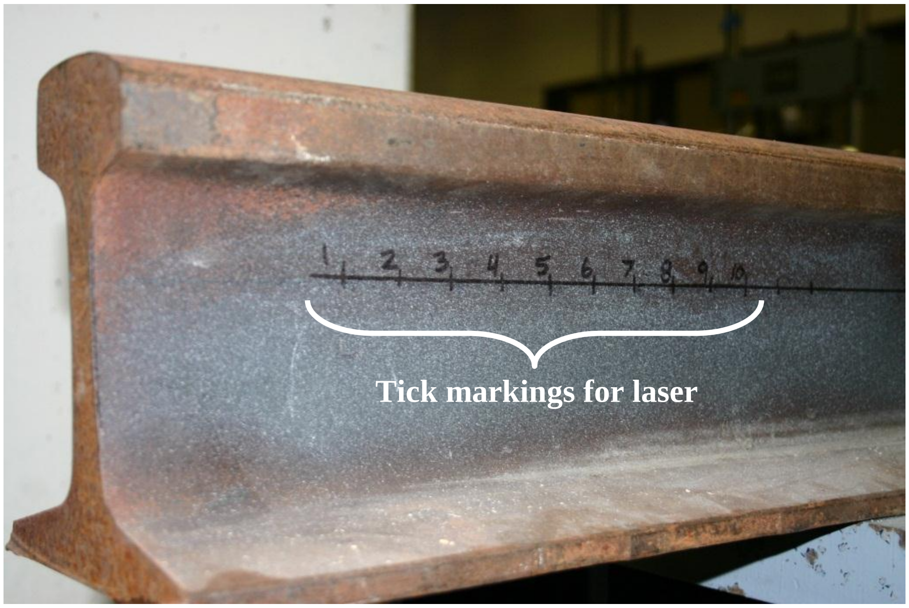

Figure 2.8 Surface labeling on rail web for hand held method

After the research team determined that more accurate data could be obtained by means other than the hand held method, a cart was made that could travel down the length of the steel rail. The laser module was able to clamp onto the cart and was prevented from moving. The main idea behind the cart was to provide a quick way to traverse the steel rail while taking readings. This procedure would eliminate the slow process of taking readings using the hand held method. The cart and laser module assembly are shown below in figure 2.9.

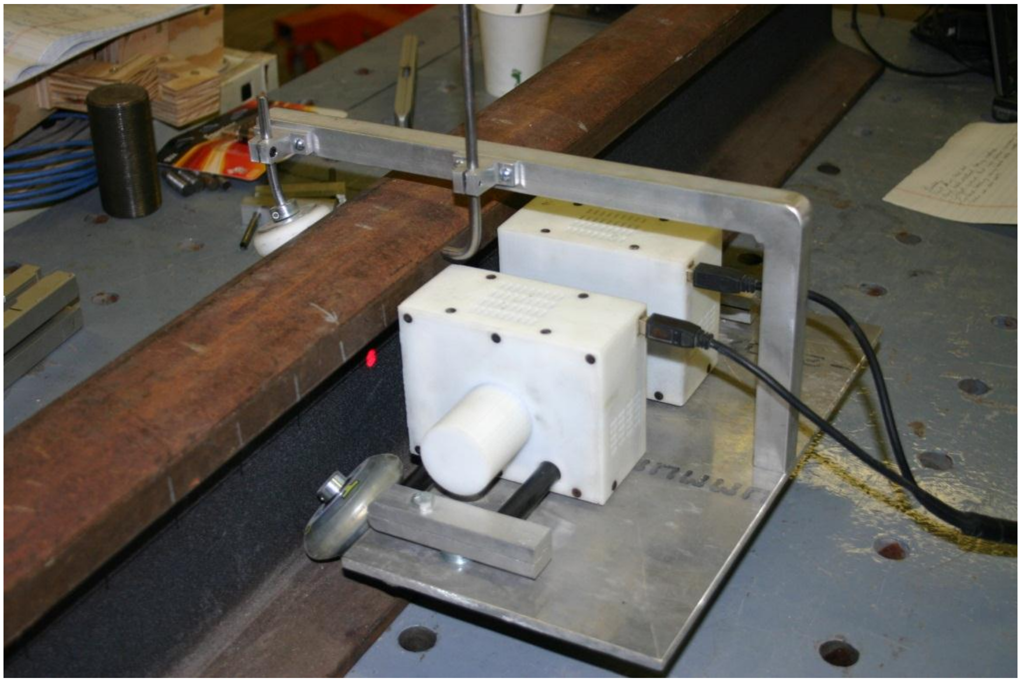

Figure 2.9 Laser cart used on steel rail

Initial tests using the cart assembly were unsuccessful. It was very difficult to get the cart to ride smoothly on the rail and there was too much instability in the system. The laser-speckle device requires accuracy in all three axes to obtain desirable results, and the cart proved to be unsteady in every direction. Later alterations were made to the cart to try and make it ride tightly along the steel rail, but the many radii located on the steel rail cross section caused problems with the wheel location of the cart. After having many unsuccessful trial runs, it was determined that the steel rail cart was not the solution to the problem.

Another method that was used to take readings involved mounting an aluminum bracket to the side of the steel rail as shown in figure 2.10. The bracket was mounted to the steel rail using a very strong epoxy. This method proved to be very effective in recording accurate data over time. The laser device was guaranteed to take readings in exactly the same location every time due to the rigidity of the aluminum bracket. This produced highly desirable results.

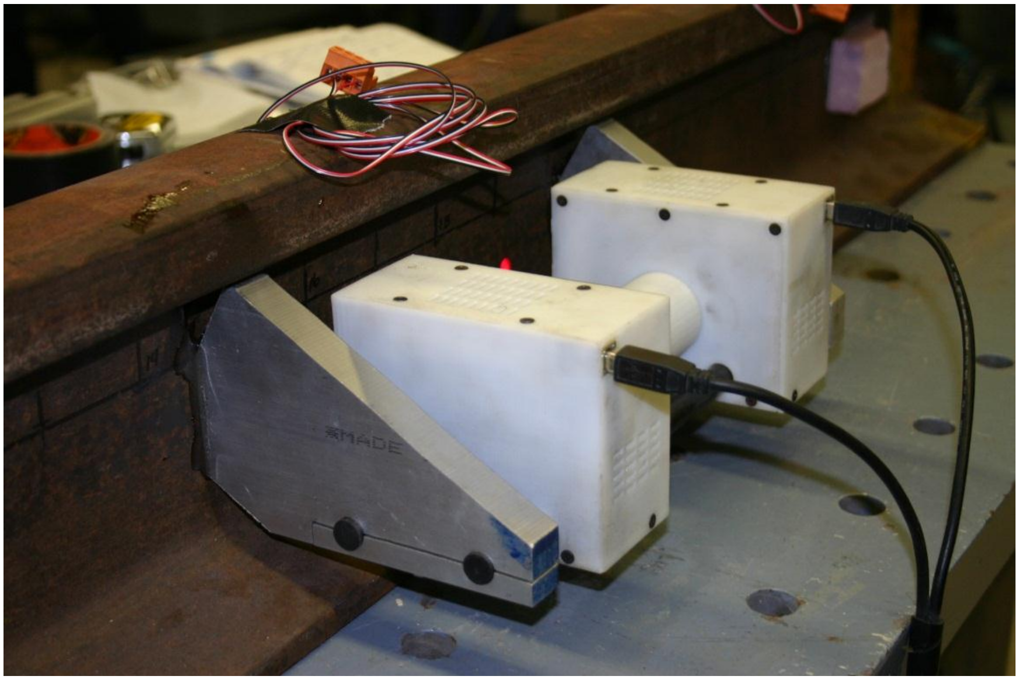

Figure 2.10 Laser-speckle device in aluminum bracket

The aluminum bracket allowed the laser to be removed after readings were taken and then reconnected any time data was needed. Although the aluminum bracket provided very accurate readings, having the bracket permanently mounted to a steel rail in the field would be undesirable. Not only would the bracket be susceptible to falling off, but it may be a hindrance to maintenance vehicles that travel down the track. If the bracket fell off in the field, no future readings could be taken.

After conducting tests on many steel rail mount systems, the research team concluded that the most successful means of taking measurements in our laboratory was the hand held method. Although taking readings by holding the laser isn't the most accurate method, correlation can be found easily over time without the need to mount brackets. Also, using the laser device on a rolling cart system proves to be very difficult due to the rounded surface of a steel rail.

It must be noted that in the laboratory attempts, the rolling cart was only mounted to one rail. In actual track applications, it is plausible that a wide cart which rested on both steel rails could provide the stability necessary for repeatable measurements.

From the laboratory tests, it was determined that an error of +/- 40 microstrain was experienced by using the hand held method. The research team concluded that an error of 40 microstrain was acceptable because many of the thermally-induced stresses that the steel rails experience are on the order of several hundred microstrain.

2.5 Testing Procedures

The next step in the validation procedure was to compare surface strain measurements between the LSI technique and electrical resistance strain gauges. In order to accomplish this, strain gauges were mounted in three locations on the piece of steel rail track measuring 66 inches in length. The strain gauges were mounted to the steel rail as shown in figure 2.11.

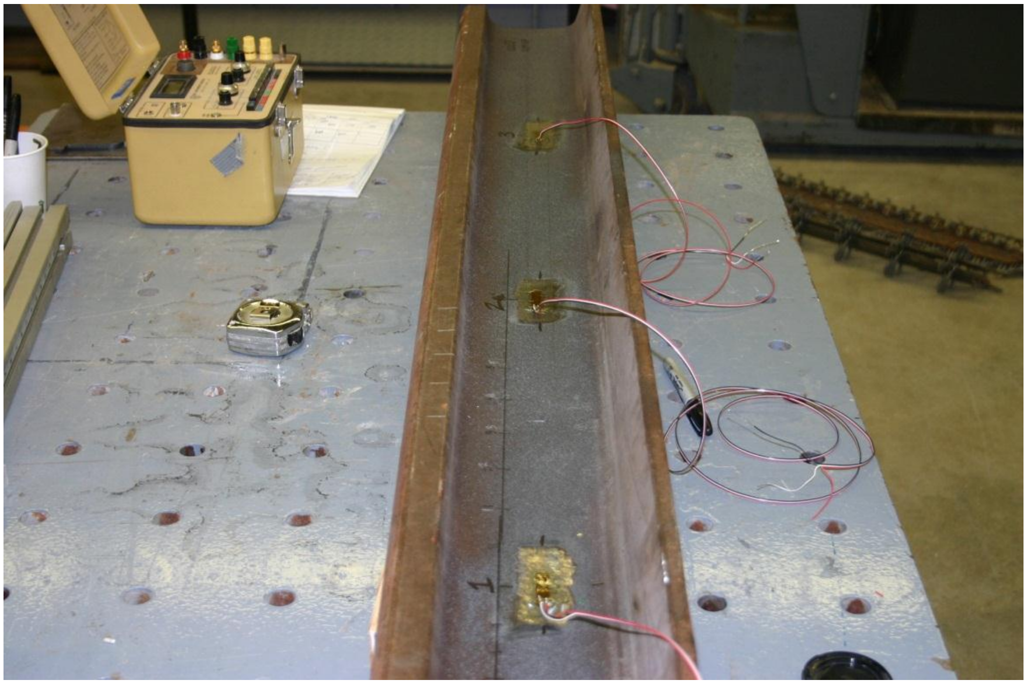

Figure 2.11 Strain gauges mounted to steel rail

After the gauges were mounted to the rail, they were covered with epoxy as shown in figure 2.12 to eliminate the risk being ripped off the surface due to handling mistakes.

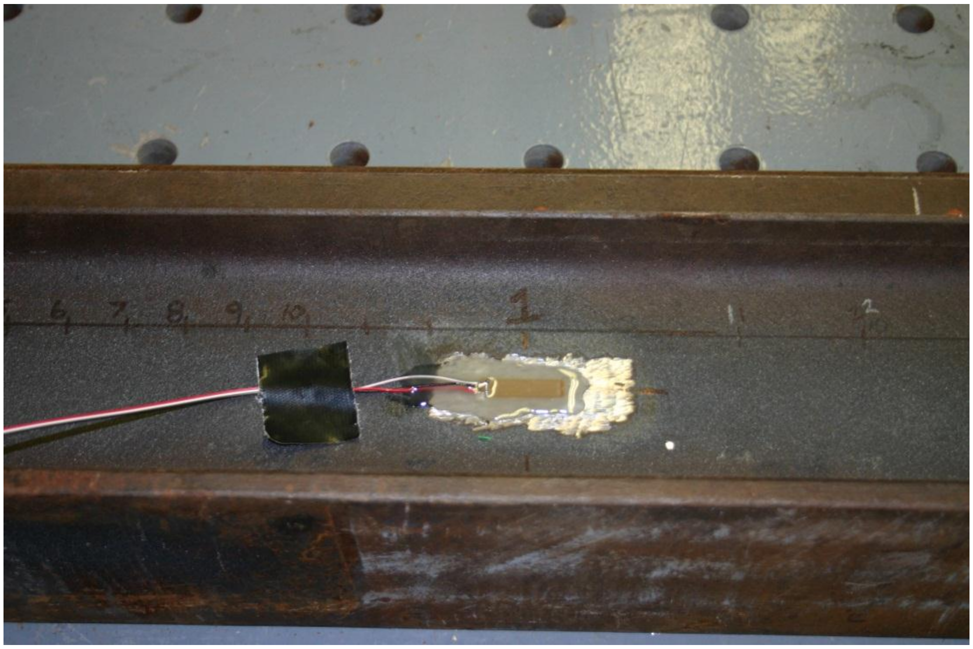

Figure 2.12 Strain gauge protected with epoxy

These gauges were used to view the accuracy of the data gathered by the LSI device when determining thermal strain. The steel rail was placed in room temperature conditions and the three strain gauges were zeroed using a P-3500 Strain Indicator, as shown in figure 2.13.

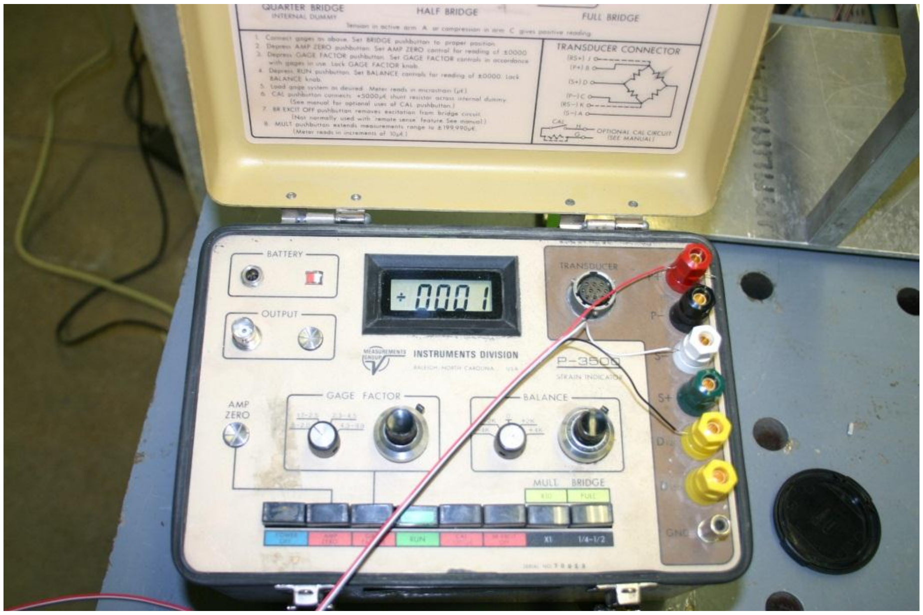

Figure 2.13 P-3500 Strain Indicator used to read strain gauge values

Also, a set of 10 initial readings were taken at the location of each strain gauge using the laser-speckle device. Ten readings were taken at each point so the average strain could be determined. This reduced any errors in the measurement process. To eliminate any discrepancies in the strain readings of the strain gauges and laser-speckle, base readings were taken at points that spanned the strain gauges as shown in figure 2.14.

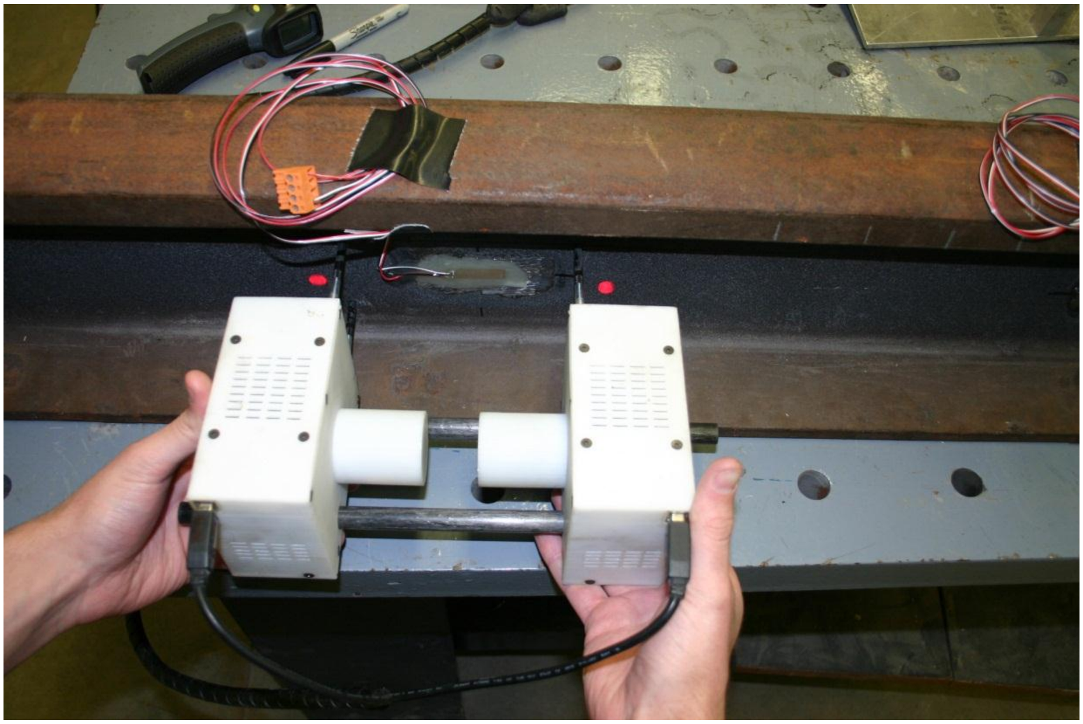

Figure 2.14 Taking readings with laser spanning strain gauge

By taking a set of base readings using the strain gauges and laser-speckle at room temperature, any strains the steel rail experienced due to thermal effects could be determined. The strains due to temperature change were determined from the following equation:

$$\varepsilon_T = \alpha\, \Delta T \tag{2.1}$$

where α is the coefficient of thermal expansion of the rail (assumed to be 6.4 x 10^{-6} / °F), ΔT is the change in temperature the steel rail in degrees Fahrenheit.

The change in temperature (ΔT) of the steel rail was determined using an infrared thermometer, as shown in figure 2.15.

Note the two LSI modules are connected together with two carbon rods, as shown in figure 2.15, which have a coefficient of thermal expansion of approximately 0.7 x 10^{-6} / °F. Thus, the LSI device itself will expand and contract with changing temperatures. Hence, in order to determine the strain in the rail due to temperature change, the apparent strain caused by thermal shift of the LSI device must be taken into account. This is most easily done by using an adjusted coefficient of thermal expansion of the steel of 5.7 x 10^{-6} / °F (6.4 x 10^{-6} / °F – 0.7 x 10^{-6} / °F).

Figure 2.15 Infrared thermometer used to measure temperature of steel rail

Although monitoring the thermal strains in this fashion is helpful in showing that the laser-speckle device has comparable results to that of strain gauges, the system is free to expand and contract. When the steel track is laid on the track in the field, steel sections are continuously welded together and secured to ties. This rigid system doesn't allow the steel rail to contract and expand as it naturally would if both ends were free to move. To address this problem, a section of steel track that was fixed in place was used to monitor the thermal strains. The section of track that was used was at the Union Pacific Depot shown in figure 2.16 in Manhattan, KS.

Figure 2.16 Union Pacific Depot used for steel rail measurements

The thermal strains of this section of track were monitored by taking strain readings using the laser-speckle device and determining the temperature of the rail over the course of a ten day period. The track section was broken up into four sections. At each section, ten strain measurements were taken every two inches along the length of the rail. This procedure was done so the average of the ten strain measurements could be determined.

Because the Union Pacific Depot is owned by the city of Manhattan, the surface of the steel was not allowed to be painted and strain gauges could not be mounted. Since the web section of the rail could not be painted, the bare steel surface had to be used to take readings on.

This caused the rail to be susceptible to surface changes caused by weathering. Due to this fact, extensive measurements could not be taken over the course of several months.

Chapter 3 Results

3.1 Results from tests at KSU

Surface strain measurements due to thermal effects were obtained on the 66 inch long un-restrained rail using both electrical resistance strain gauges and the Laser Speckle Imaging device. Initial strain readings were taken when the temperature of the rail was 79˚F. Every time readings were taken afterwards, the temperature of the rail was measured with the infrared thermometer and the temperature difference was recorded.

The results from these measurements are shown in table 3.1 and are also plotted in figures 3.1 through 3.8. From these figures, it can be seen that the strain measurements obtained from the LSI device correlate very well with the strain gauge values and with the theoretical computations. The labels on the horizontal axis correspond to the three strain gauge locations. At each location, a strain gauge value was obtained and laser-speckle readings were taken.

It can also be noted from the figures that the laser-speckle device never deviated by more than 25 microstrain from the theoretical thermal strain. This accuracy is very acceptable due to the fact that the rail strains can typically be in the range of several hundred microstrain. In these figures, the theoretical thermal strain is shown by the solid black line that passes horizontally across the graph. The theoretical strain was determined by the equation:

$$\varepsilon_T = \alpha \, \Delta T \qquad (3.1)$$

where α is the adjusted coefficient of thermal expansion for the steel rail (5.7×10^{-6} / °F) and ΔT is the change in temperature of the steel rail steels.

Table 3.1 Results from temperature change experiment on un-restrained rail

		Apparent Strain				Thermal	%
Reading	ΔT (°F)	Location 1	Location 2	Location 3	Average	Strain	Difference
1	-59	-366	-331	-328	-341.7	-336.3	1.6%
2	-41	-210	-222	-225	-219.0	-233.7	-6.3%
3	-53	-318	-329	-312	-319.7	-302.1	5.8%
4	13	69	67	65	67.0	74.1	-9.6%
5	-62	-328	-359	-367	-351.3	-353.4	-0.6%
6	-15	-83	-111	-113	-102.3	-85.5	19.7%
7	-29	-150	-189	-174	-171.0	-165.3	3.4%
8	-48	-295	-295	-300	-296.7	-273.6	8.4%
						Average =	**2.8%**

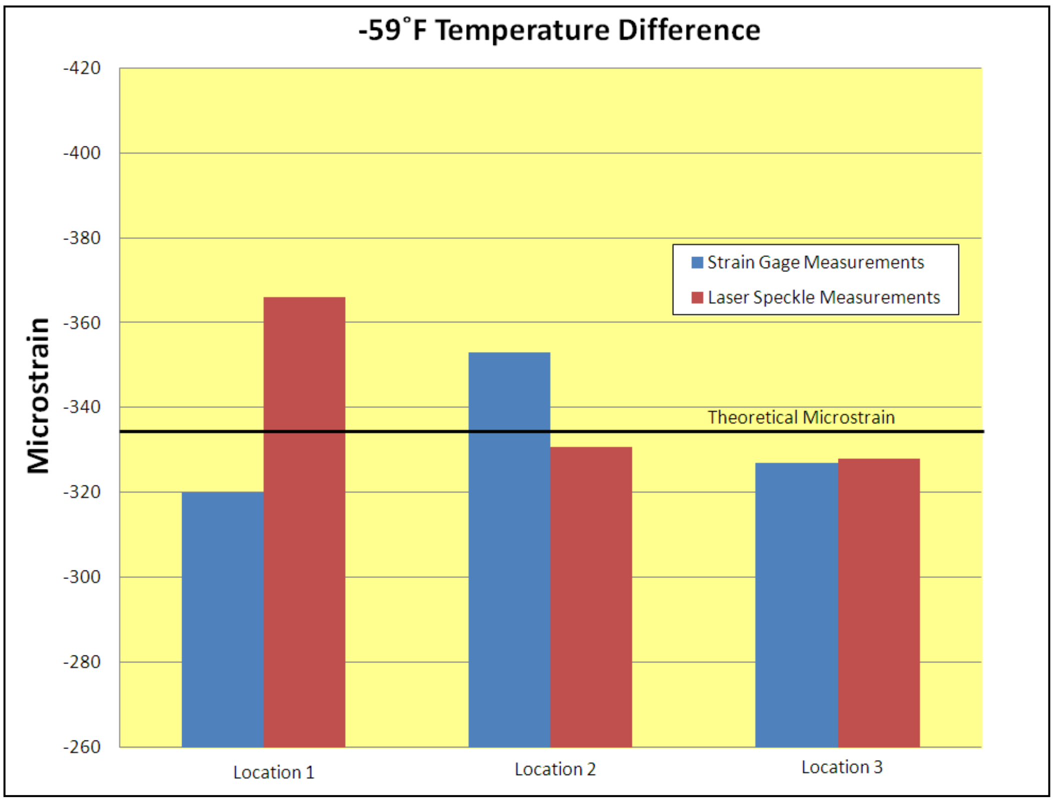

Figure 3.1 Strain measurements with a -59˚F temperature difference

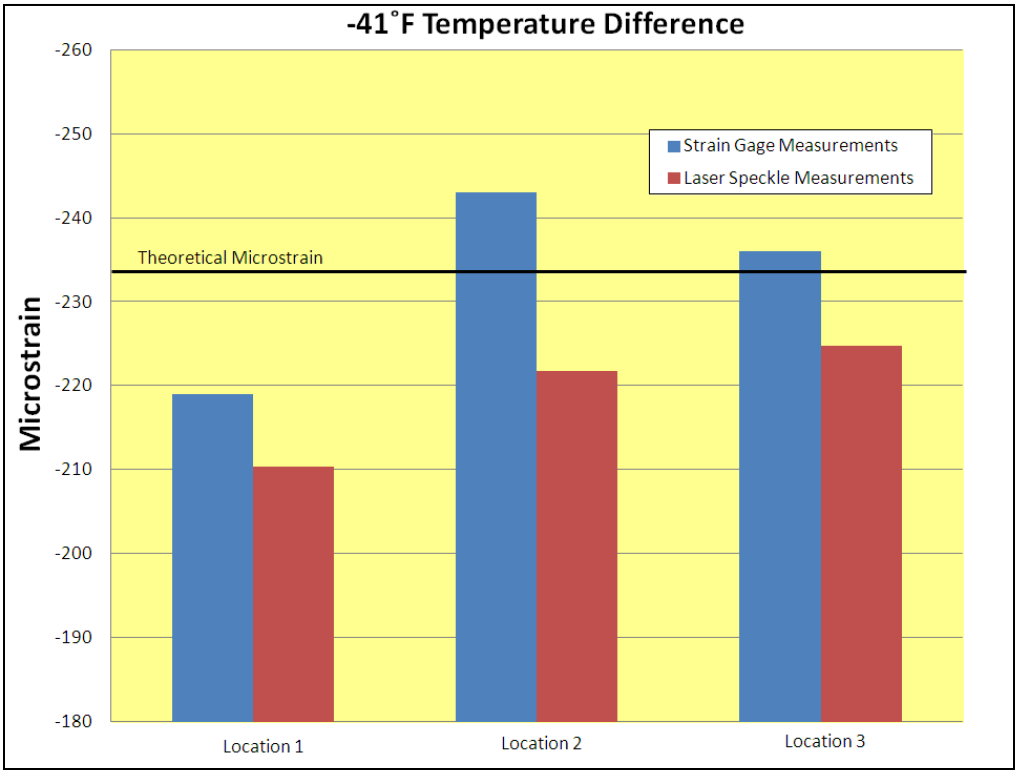

Figure 3.2 Strain measurements with a -41˚F temperature difference

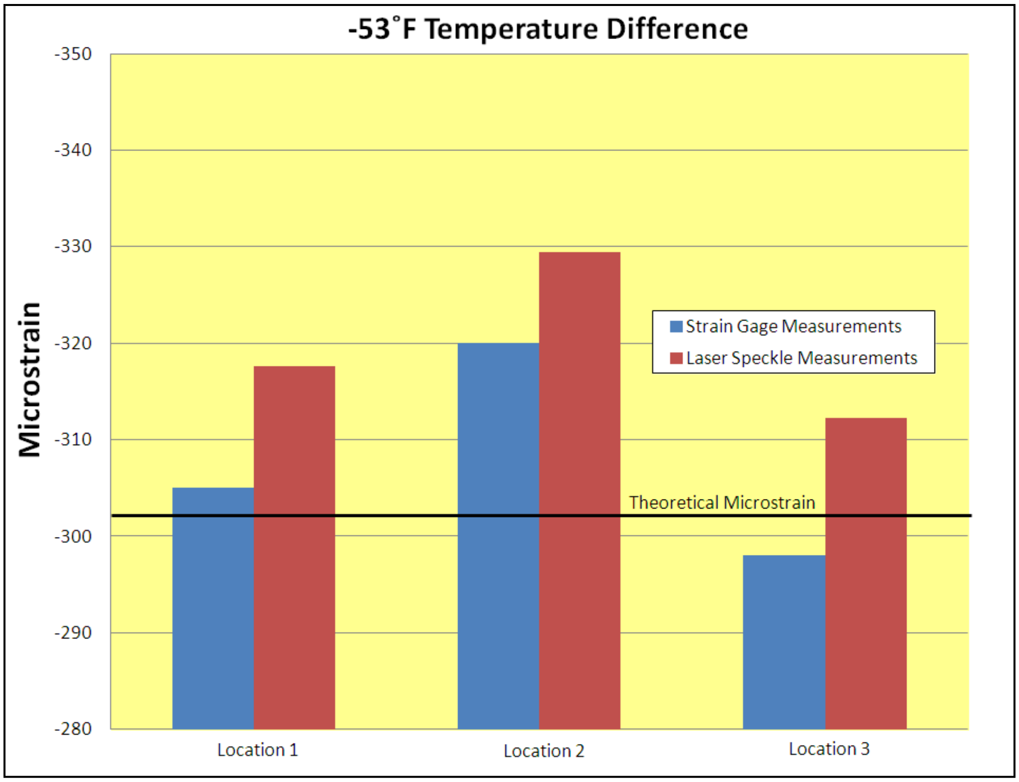

Figure 3.3 Strain measurements with a -53˚F temperature difference

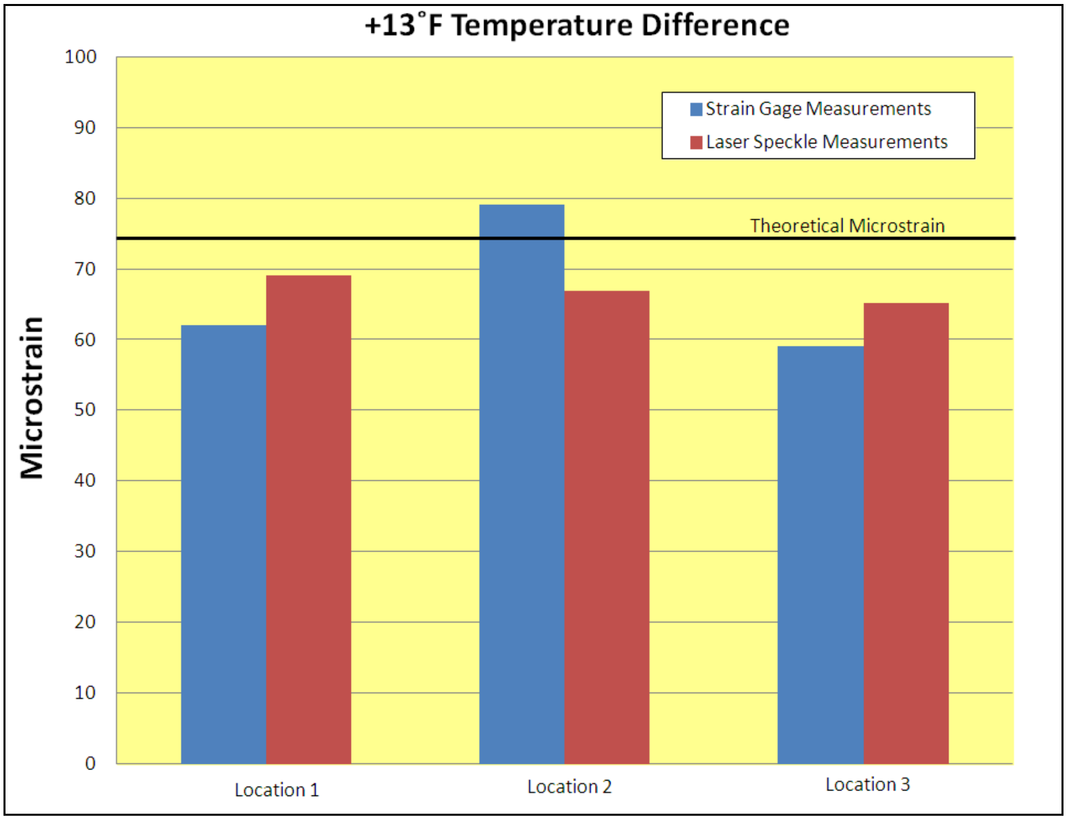

Figure 3.4 Strain measurements with a +13˚F temperature difference

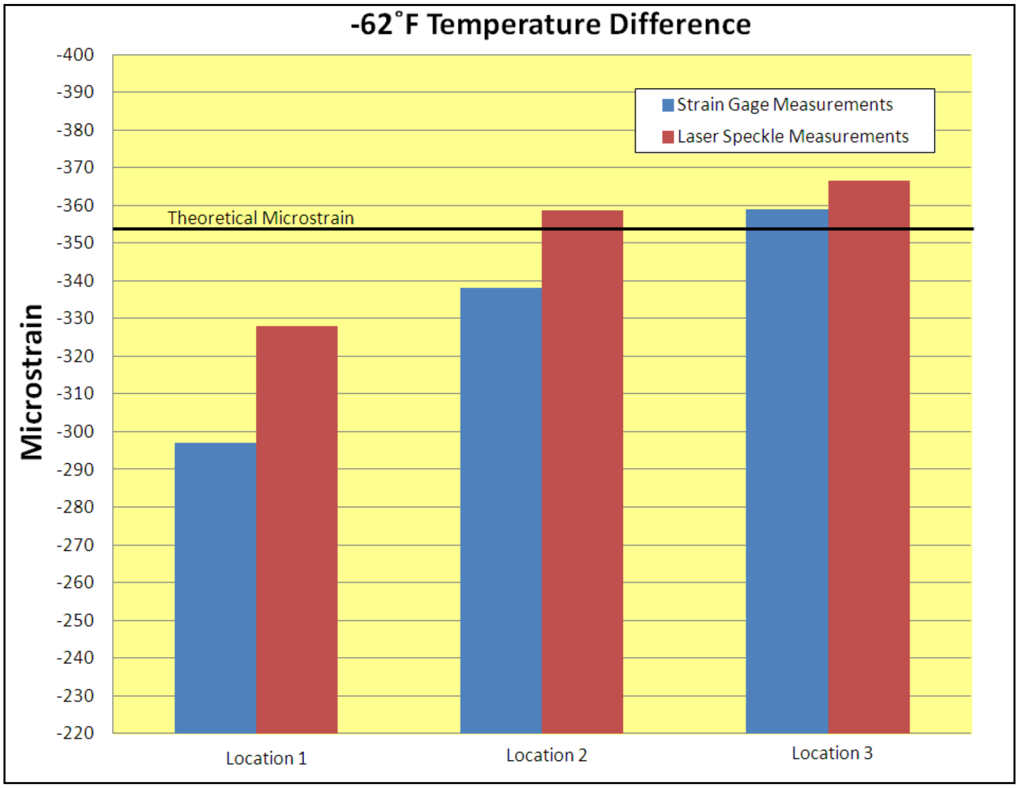

Figure 3.5 Strain measurements with a -62˚F temperature difference

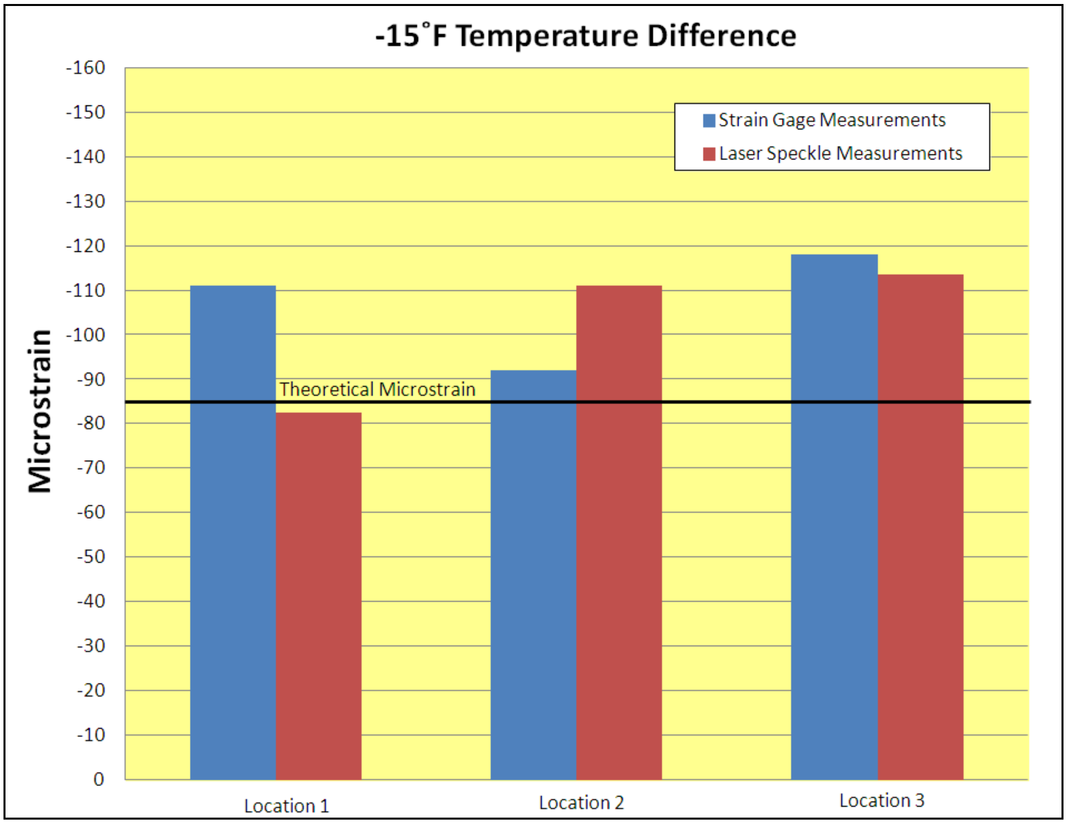

Figure 3.6 Strain measurements with a -15˚F temperature difference

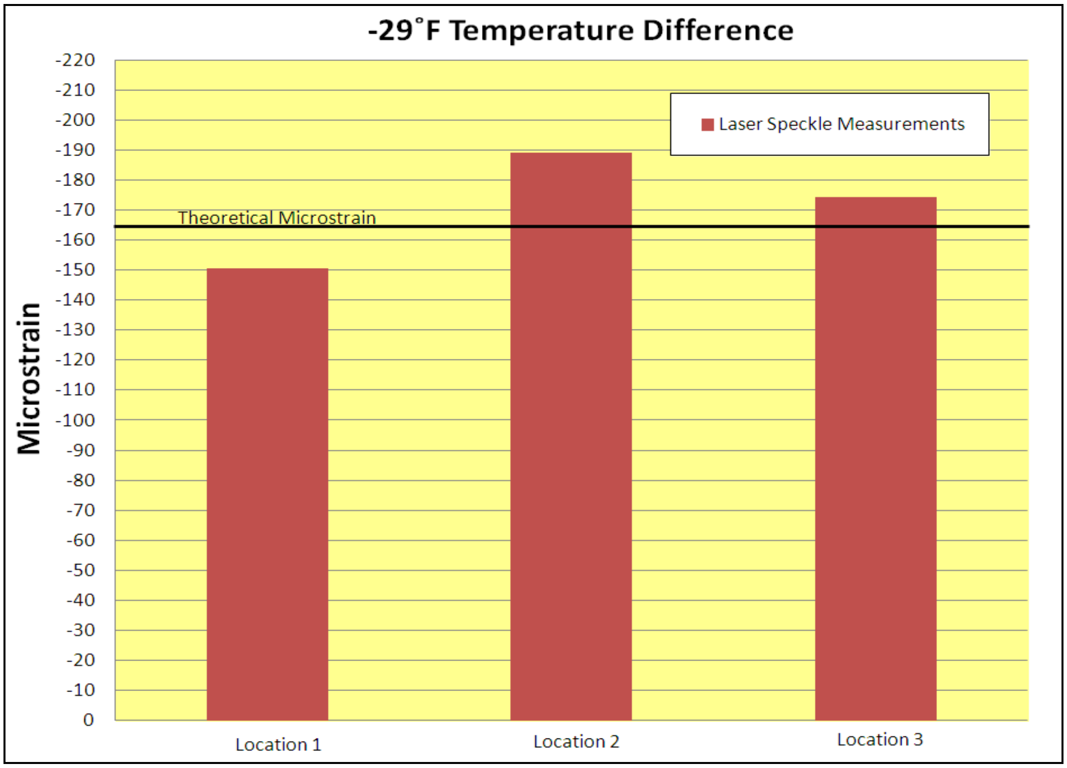

Figure 3.7 Strain measurements with a -29˚F temperature difference

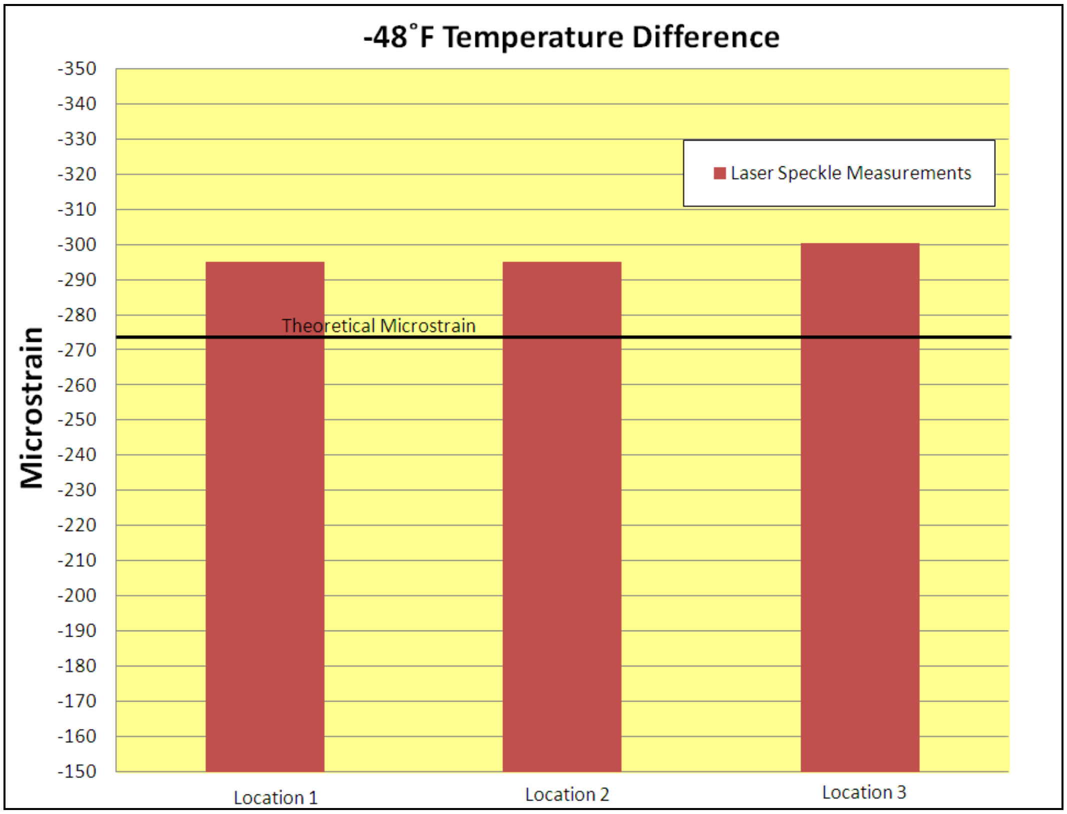

Figure 3.8 Strain measurements with a -48˚F temperature difference

After a week of taking measurements, the epoxy securing the strain gauges to the steel began to crack, presumably due to thermal changes and perhaps moisture ingress. This made the strain gauges obsolete and limited the number of measurements that could be taken. However, enough data was gathered in one week to prove the accuracy of the laser-speckle device. Further data was gathered using the LSI device after the strain gauges could no longer be used. All of the strain measurements taken using the LSI device correlated well with the calculated theoretical strain values.

In this test, the laser-speckle proved to be the more effective method of measuring surface strains. Strain gauges are susceptible to becoming damaged and require a great deal of work to keep them protected. In order to ensure long-term correlation with the laser-speckle device, the surface of the steel should be covered with a protective paint. The paint allows the surface correlation to be preserved for approximately a three month period. The surface could be further protected by covering the paint with a strip of plastic or other suitable means.

3.2 Results from tests at Union Pacific Depot in Manhattan, KS

Once the laser-speckle measurements were verified by strain gauge readings and theoretical strain calculations at the KSU laboratory, the LSI device was tested on a section of track at the Union Pacific Depot in Manhattan, KS. Surface strain measurements were taken over a ten day period. Because the section of track is owned by the city of Manhattan, the surface was not allowed to be painted. This required the measurements to be taken on the bare steel surface and limited the amount of time that surface correlation could be preserved. Initial readings were taken when the rail was 22°F. Every time readings were taken afterwards, the temperature of the rail was measured with the infrared thermometer and the temperature difference was recorded. This was done to determine the thermal strains in the rail.

Once the thermal strains had been determined for the steel rail, these strains were then used to determine the mechanical strain and the stress in the rail due to the inherent restraint of the installed rail. The stresses (σ) in the steel rail were calculated using the following equations:

$$\varepsilon_M = \varepsilon_A - \varepsilon_T \tag{3.2}$$

$$\sigma = \varepsilon_M \cdot E \tag{3.3}$$

where ε_M is the mechanical strain, ε_A is the apparent strain obtained directly from the LSI device, and ε_T is the thermal strain. In addition, E is the modulus of elasticity of the steel rail (29×10^6 psi).

The values of strain and calculated stresses are shown below in table 3.2. The corresponding values of strain at each location are shown in figures 3.9 through 3.13. From these graphs, it can be seen that the LSI implied strain is almost always less that the theoretical thermal strain calculations. This implies that the restrained rail is being placed in compression, as the full amount of free expansion (due to the increasing temperatures as noted in table 3.2) is not allowed to occur.

Table 3.2 Calculated stresses in track at Union Pacific Depot

	Apparent Strain (microstrain)					Thermal	Mechanical	Implied Stress
ΔT (°F)	Location 1	Location 2	Location 3	Location 4	Average	Strain	Strain	(psi)
40	225	208	219	210	215.5	232	**-17**	-479
32	170	169	156	142	159.3	185.6	**-26**	-764
22	103	111	109	107	107.5	127.6	**-20**	-583
15	62	106	102	97	91.8	87	**5**	138
10	24	27	43	59	38.3	58	**-20**	-573

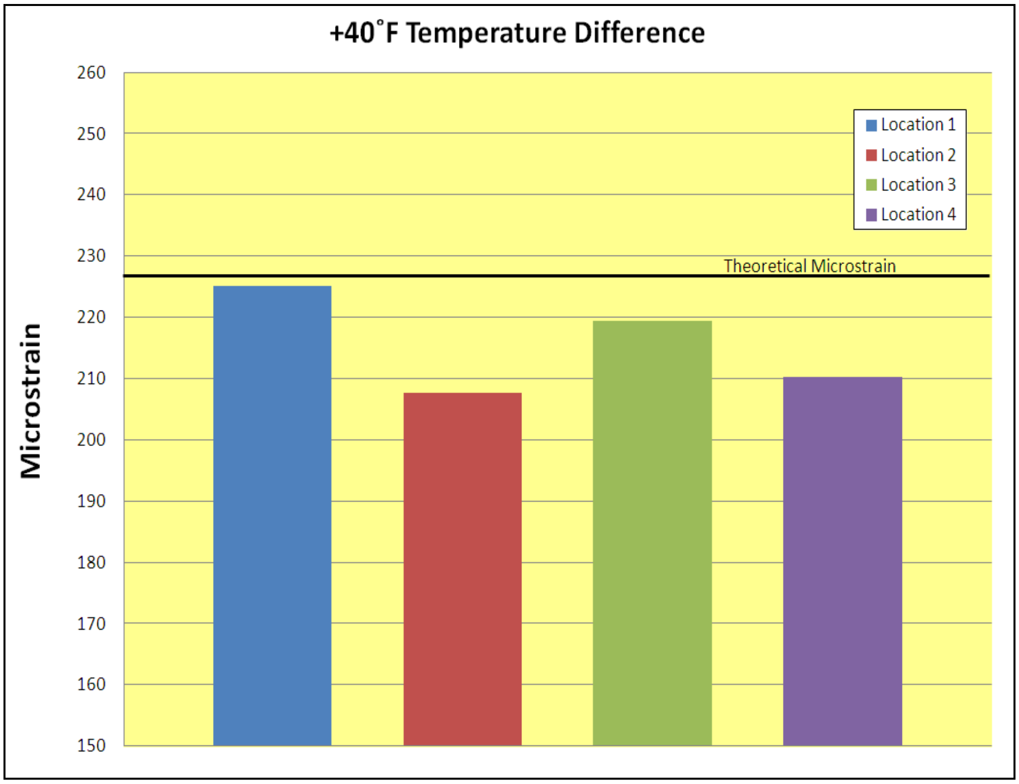

Figure 3.9 Strain measurements on city rail with a +40°F temperature difference

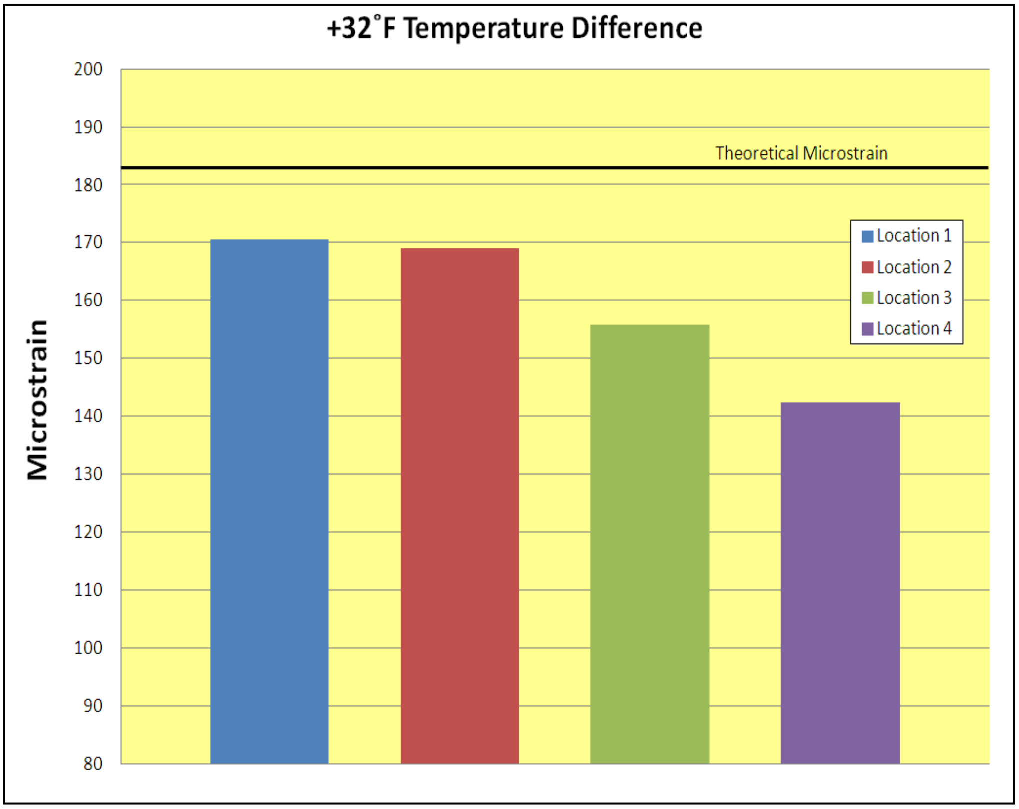

Figure 3.10 Strain measurements on city rail with a +32°F temperature difference

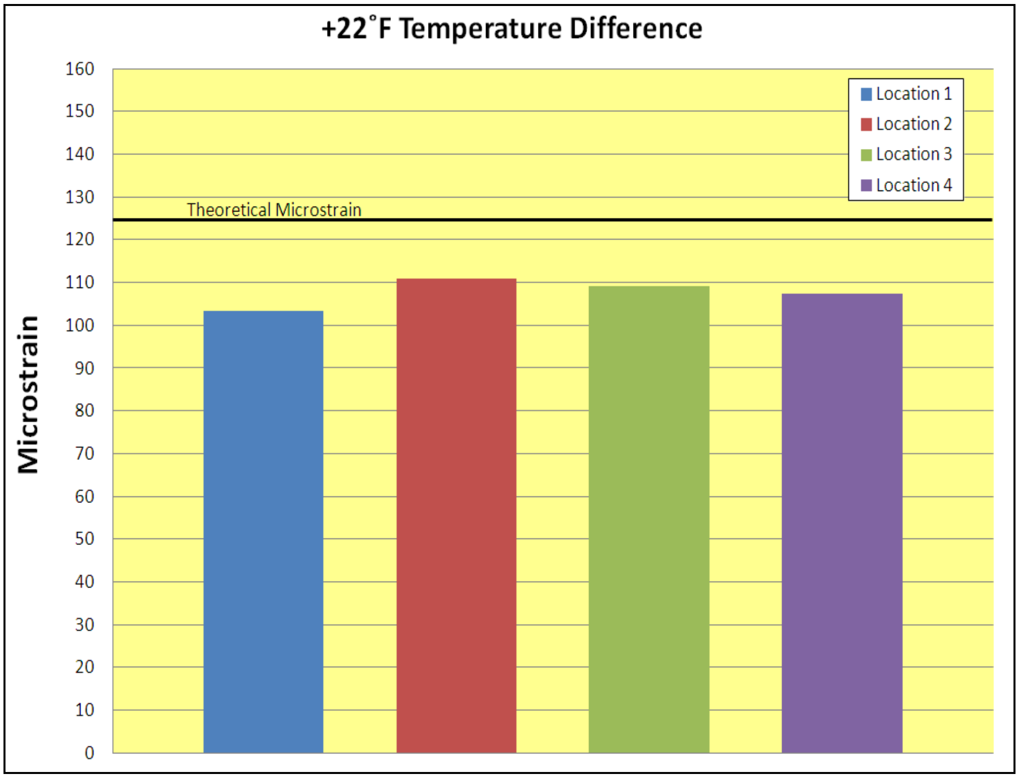

Figure 3.11 Strain measurements on city rail with a +22°F temperature difference

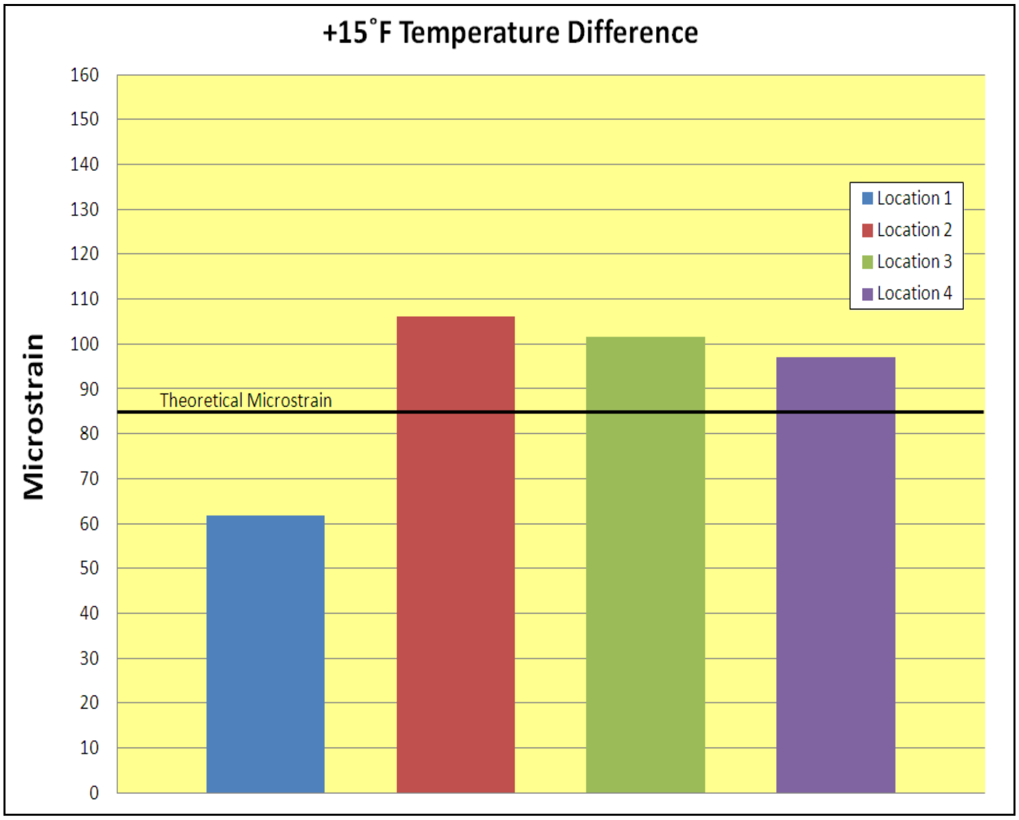

Figure 3.12 Strain measurements on city rail with a +15°F temperature difference

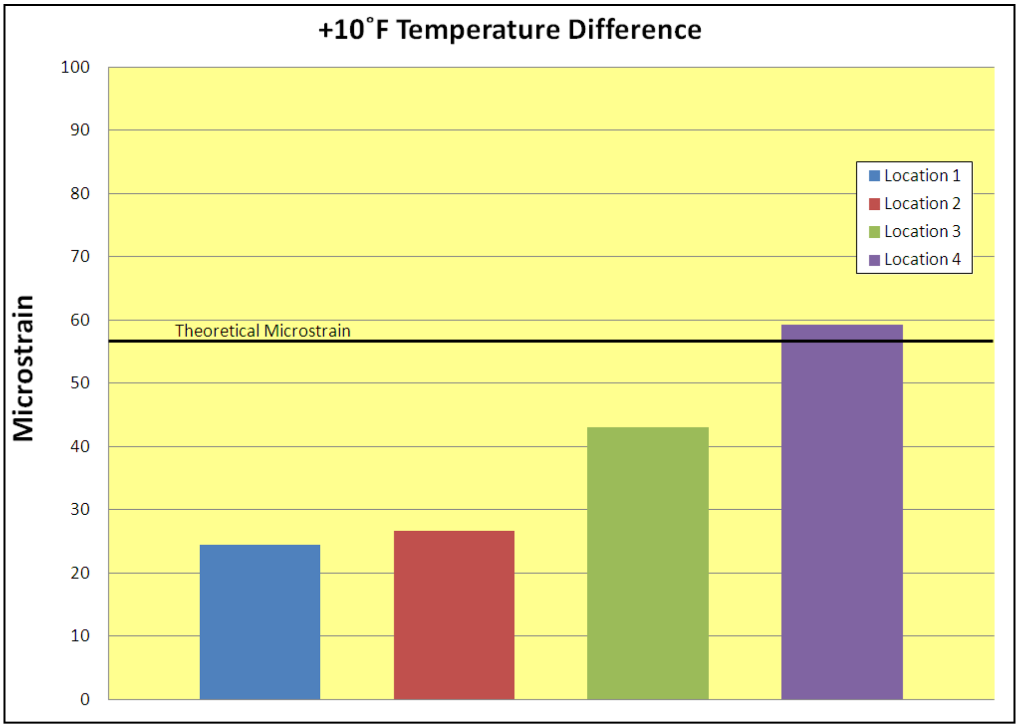

Figure 3.13 Strain measurements on city rail with a +10°F temperature difference

Chapter 4 Conclusions

Based on the research completed, the following conclusions may be drawn:

- The Laser-Speckle Imaging device has been modified to successfully work on steel surfaces. However, the steel rail surface is susceptible to changes due to weathering and abrasion. This causes the surface correlation to be lost and future readings to be flawed.
- The Laser Speckle Imaging device works very well on surfaces that are painted prior to taking readings. The painted surface is able to preserve surface correlation for a period of about three months. Surface correlation could be preserved for longer periods of time if the surface is covered and protected.
- The easiest and most effective method to take readings in this study was by marking the surface and hand-holding the LSI device. This method eliminates many of the problems with a cart riding on a single rail. For future applications, both railway rails should be used to enable better correlation of the mounted device.
- The accuracy of the laser-speckle when using the hand held method is about 25-40 microstrain. This is an acceptable level of accuracy since strains in the steel rails are often in the range of several hundred microstrain.
- Results from the laser-speckle device were comparable to that of strain gauges as well as the theoretically-calculated values of strain.
- The LSI device could be used for a longer duration than electrical-resistance strain gauges if the surface is prepared and preserved well.

- The Laser Speckle Imaging technique is a viable method to determine the strains and stresses in steel rails used on the railroad. Additional field trials are therefore recommended.

References

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