Technical Note 1025 I Revision 2014.1.31.1

FBG Total Strain Thermal Considerations I **Five Steps to Meaningful Strain Data**

Micron Optics Inc.
1852 Century Place NE
Atlanta, GA 30345 USA

phone 404 325 0005
fax 404 325 4082
www.micronoptics.com

I. FBG Sensors Inherently Measure Accurate Total Strain

Continued adherence to this methodology ensures that the user never computes the total strain in a measured substrate, and has limited visibility into: 1) real substrate thermal strains resulting from temperature changes, 2) error-inducing thermal gradients within the material or system, 3) errors in substrate temperature estimation, 4) errors in published substrate CTE estimates, or 5) effects on “perceived” substrate CTE (observed substrate thermal response) due to impacts from other parts of the structure.

How do we improve?

- Five simple steps to meaningful strain data.
- Two equations yield accurate measurements of total strain.
- Three additional considerations help to decompose total strain into thermal and mechanical responses.

Why is this significant?

With this measurement methodology, we are realizing a fundamental capability of the optical sensor system that no competing technology offers: the ability to simultaneously and independently measure both thermal and mechanical strain responses of a system easily and conveniently with a single technology and data acquisition system.

II. The Five Steps to Meaningful Strain Data - Accurate Total Strain Measurements from Micron Optics Optical Strain Gages

1. COLLOCATION:

The strain sensing FBG and temperature compensation FBG must be at the same temperature.

The strain sensing FBG will respond to substrate mechanical strains, substrate thermal strain, and thermally induced effects in the optical gage itself. In order to completely correct for the thermally induced optical gage effects, the user must ensure that the strain sensing FBG, measured as λ_S, and the temperature compensation FBG, measured as λ_T, are at the same temperature. Micron Optics strongly recommends the use of its internally compensated gages, such as the os3155 or os3610 sensors, or installation of strain and temperature compensation sensors in a 1:1 ratio. For best performance, strain sensing and temperature compensation elements should of similar material construction, solar exposure, sensor protection and/or insulation methods, and be as physically close to one another as the installation will allow.

2. TOTAL STRAIN:

Total strain can be accurately calculated by first subtracting out thermally induced optical gage effects.

Total strain ε_{Total} is computed as the total strain sensing FBG's response, corrected for the thermally induced changes in the gage optics.

Equation 1 takes into account the change in refractive index and thermal expansion of glass for both the strain sensing and gage temperature compensation gratings, FBG_S and FBG_T.

Equation 1:

$$\varepsilon_{Total} = 10^6 \left[\frac{(\Delta\lambda / \lambda_0)_S - (\Delta\lambda / \lambda_0)_T}{F_G} \right] + \frac{(\Delta\lambda / \lambda_0)_T}{S_T} CTE_T$$

where, F_G is the gage factor for the optical strain gage in units, and is specified in the attached appendix, CTE_T is the coefficient of thermal expansion for the temperature compensation FBG mount, and S_T is the temperature compensator thermal response, and is specified in the attached appendix.

NOTE: Total strain is the measurement that optical sensor products should be specified to deliver. End users will want and expect to get thermal or mechanical strains from the sensors, but further decomposition into those elements is highly dependent on the end user's application of the gages and understanding that he has of his application. The following sections should serve as guidelines for data analysis and to help gauge end user expectations, but cannot not form the basis for sensor product performance specifications.

3. SUBSTRATE TEMPERATURE - Decomposition of Total Strain into Thermal and Non-Thermal Components

The substrate temperature T_{subst} can sometimes be accurately represented by the strain sensor's temperature compensation FBG, measured as λ_T, but sometimes requires an auxiliary temperature sensor.

T_{subst} or the abbreviated "substrate temperature" refers the average substrate temperature within the gage length of the strain sensor. In most cases, this average temperature can be represented by a single measure of temperature. However, in the case of very long strain sensor gage length, the weighted average of two or more sensors may be needed to accurately represent the average temperature of the substrate over the gage length of the sensor.

The substrate temperature T_{subst} can be represented in one of two ways:

i) If the substrate temperature T_{subst} is ***known*** to be at the same temperature as the strain sensor's thermal compensation grating FBG_T (as would usually be the case with a well-insulated os3155 sensor welded to steel, or an os3600 gage embedded in concrete without` large thermal gradients) then the changes in substrate temperature ΔT_{subst} can be effectively represented the strain sensor's thermal compensation FBG, measured as λ_T through Equation 2.

Equation 2a: $$\Delta T_{subst} = \frac{(\Delta\lambda / \lambda_0)_T}{S_T}$$

ii) Should the substrate temperature T_{subst} and the strain sensor's thermal compensation FBG, measured as λ_T, ***NOT*** be at the same temperature (as would usually be the case with an os3160 strain sensor bracket-mounted to the surface of a concrete substrate) an additional temperature sensor such as an or os4350, as:

$$\Delta T_{subst} = \frac{(\Delta\lambda / \lambda_0)_{os4350}}{S_T}$$

as a measure of relative temperature change, or

Equation 2b: $$\Delta T_{subst} = T - T_0$$

as the change in measured absolute temperatures will need to be used to correctly represent the change in substrate temperature ΔT_{subst} in Equations 4 and 5 below.

4. SUBSTRATE CTE

Thermal and mechanical components of total strain can be accurately decoupled if the exact substrate CTE and the substrate temperature are known.

Total strain ε_{Total} is defined in as follows:

Equation 3: $$\varepsilon_{Total} = \varepsilon_{therm} + \varepsilon_{mech}$$

where, ε_{therm} is the thermal strain response, and ε_{mech} is the substrate non-thermal strain response, and may comprised of load-induced, creep, shrinkage or other strains, depending upon the material nature of the measurement substrate.

Once total strain is calculated, the thermal strain ε_{therm} and the non-thermal strain ε_{mech} can be decoupled through a measurement of the change in substrate temperature ΔT_{subst} multiplied by the exact coefficient of thermal expansion of the substrate CTE_{subst} as in Equation 4 below:

Equation 4: $$\varepsilon_{therm} = \Delta T_{subst} CTE_{subst}$$

Equation 5: $$\varepsilon_{mech} = \varepsilon_{Total} - \Delta T_{subst} CTE_{subst}$$

The degree of accuracy in the decoupled thermal and mechanical strains is directly dependent upon the accuracy to which the substrate CTE and temperature are known. The exact CTE may be available materials from the specimen supplier. Common techniques to directly measure material CTE on sample specimens include Michelson laser interferometry, quartz dilatometry, and other laboratory methods. Material CTEs can also be measured/derived in the field by making total strain measurements on unstrained "dummy plate" samples of substrate material. Please see Micron Optics' Technical Note 1027 for details.

5. SYSTEM THERMAL RESPONSE

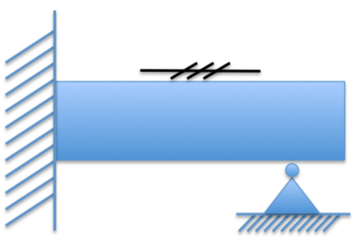
Strain deviations from typical structural system thermal response can be observed by knowing the substrate temperature and deducing an effective thermal response coefficient of the system.

Often, the total structural system thermal response of the measured substrate is governed not only by the real material CTE of the substrate, but also by mechanical boundary conditions dictated by other elements of the structural system and their coupled thermal responses.

The following three cases will highlight differences in substrate boundary conditions and how those differences affect the distribution of total strain into thermal and mechanical components.

i. Unbound Substrate.

In this idealized example, the measurement substrate is completely free to expand and contract with temperature changes, and its corresponding changes in total length are completely unbound by any opposing direct or frictional forces. By definition, the mechanical component of strain ε_{mech} is zero. So,

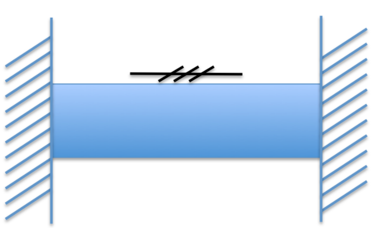


$$\varepsilon_{Total} = \varepsilon_{mech} + \varepsilon_{therm}$$
$$\varepsilon_{Total} = 0 + \varepsilon_{therm}$$
$$\varepsilon_{mech} = \Delta T_{subst} CTE_{subst}$$

In the case of a completely unbound substrate, the mechanical strain ε_{mech} is zero and the total strain ε_{total} is equal to the thermal component of strain ε_{therm}.

ii. Bound Substrate.

In this idealized example, the ends of the measurement substrate are fixed and are not free to expand or contract with temperature change. By definition, the total strain ε_{total} is zero. Applying that constraint to the total strain equation yields:



$$\varepsilon_{Total} = \varepsilon_{mech} + \varepsilon_{therm}$$
$$\varepsilon_{total} = 0 = \varepsilon_{mech} + \varepsilon_{therm} = \varepsilon_{mech} + \Delta T_{subst} CTE_{subst}$$
$$\varepsilon_{mech} = -\Delta T_{subst} CTE_{subst}$$

In the case of a completely bound substrate, the total strain ε_{total} is zero and the mechanical component of strain ε_{mech} is equal in magnitude and opposite in sign to the thermal component of strain ε_{therm}.

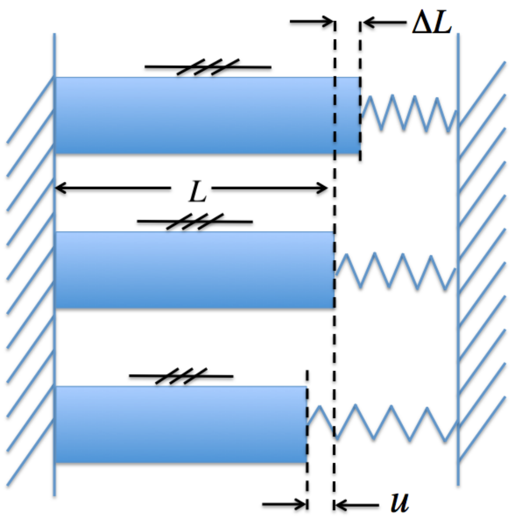
iii. Partially Bound Substrate

Cases i and ii represent two sets of idealized boundary conditions for measurement substrates, which can sometimes be reasonable approximations of structural behavior. However, in many cases, the complexities of a real structure or forces generated within a measurement substrate due to internal thermal gradients render these simplified cases as poor models of actual structural behavior.

Case iii offers a generalized model for more complex structural behavior in response to temperature change.

$$\varepsilon_{Total} = \varepsilon_{mech} + \varepsilon_{therm}$$

In this case, we know that one end of the measurement substrate is not fixed yet is not completely free to expand or contract with temperature change. As such, we cannot make any simplifying assumptions about the total strain or the mechanical component of strain being equal to zero. Consider what happens when temperature changes and the substrate material attempts to expand.



In the modified graphic above, the middle portion of the image shows the substrate structure at its original length, L. The top portion of the image depicts the thermal expansion ΔL (the thermal component of strain) experienced by the substrate due to temperature change ΔT_{subst} and its thermal expansion coefficient CTE_{subst}. The bottom third of the image depicts the amount of compressive length change u (a thermally coupled mechanical component of strain) imparted on the substrate by other elements of the structure, modeled here as a spring. The ultimate actual change in length of the substrate structure is a function of both of these

According to Hooke's law of elasticity, the extension of that spring and thus the compressive length change u of the substrate is defined as

$$u = -\frac{F}{k}$$

where, F is the restoring force applied by the spring, and k is the spring constant.

As the left boundary of the substrate and the right boundary of the spring are fixed in space, and knowing that all internal forces must sum to zero, we can solve for the mechanical strain in the substrate that results from the spring force opposing the thermal expansion of the substrate as the following:

$$\varepsilon_{mech} = -\Delta T_{subst}\left(\frac{CTE_{subst}}{1+\frac{E\times A}{L\times k}}\right)$$

where,

E is the Young's modulus of the substrate material,
A is the effective cross sectional area of the substrate,
L is the nominal length of the substrate, and
k is the spring constant.

Due to the reactive force from the spring in response to the thermal expansion of the substrate, there is a real mechanical strain in the substrate that is also a function of temperature ΔT_{subst}. This thermally coupled mechanical strain, along with the substrate thermal strain ε_{therm}, comprise the overall thermal response of the system.

Should the goal of the measurement be to specifically monitor the actual thermal and mechanical components of strain within the substrate material, those quantities can be accurately decoupled from total strain by an accurate measure of substrate temperature ΔT_{subst} and a correspondingly accurate value for the material coefficient of thermal expansion for the substrate CTE_{subst}.

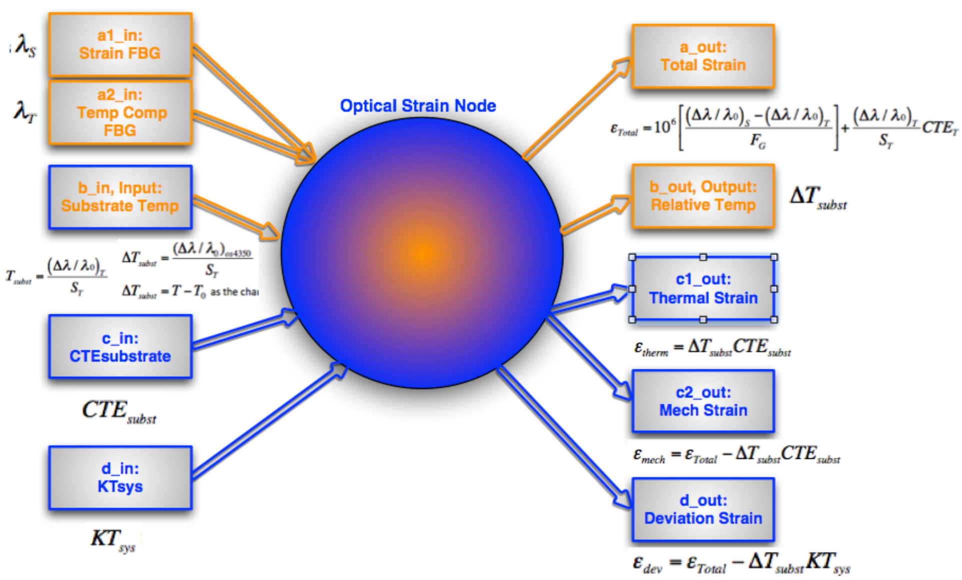
However, in many cases it is not the exact mechanical strain in the substrate that is of interest to the observer. Rather, the goal of the measurement is to observe any strain phenomena that differ from normal system behavior and might be indicative of changes in the structure. As such, it becomes useful to characterize the typical thermal response of the overall structural system by deducing an effective thermal response coefficient of the structural system within the gage length of the strain sensor KT_{sys} and highlight strain deviations from that typical behavior. KT_{sys} incorporates both the material response of the substrate to temperature changes, as well as the coupled mechanical responses of other elements within the structure. Once the effective system thermal response coefficient KT_{sys} is derived, total strains may be compared against the expected system thermal response, and any changes relative to that expected response regarded as indicative of structural change. Strain deviation from typical thermal behavior, ε_{dev} , is defined as those strains that differ from the normal, repeatable thermal response (both thermal strain and thermally coupled mechanical strain) of the measurements system.

Equation 6: $$\varepsilon_{dev} = \varepsilon_{Total} - \Delta T_{subst} KT_{sys}$$

where, KT_{sys} is the effective thermal response coefficient of the structural system within the gage length of the sensor and can be deduced as the slope of the total strain versus substrate temperature plots over time.

III. A Graphical Representation of the Five Steps to Meaningful Strain Data – The Optical Strain Node

This section will capture the same concepts outlined in section I above as inputs and outputs to an "optical strain node" as illustrated below.



What is an optical strain node?

- A physical measurement area into which two or more FBG sensing elements are applied, depending on the physical requirements of the node.
- A collection of optical sensor calibration expressions and gage constants.

The inputs to the node are:

- **a1_in**, **a2_in**, and **b_in**, which are measured FBG wavelengths as illustrated above.
- **c_in** and **d_in** , CTE and KTsys, respectively, which are application/substrate specific parameters used to calculate strain and temperature quantities.

The outputs of the node are:

- **a_out**, **b_out,** which are measures of substrate total strain and relative temperature, respectively.
- **c1_out**, **c2_out,** and **d_out**, which are measures of substrate thermal, mechanical, and deviation strains, and are defined in detail in Section II of this document.

Items of note:

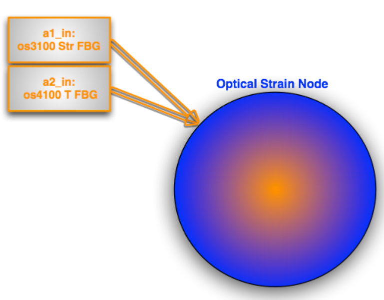
- No single FBG measurement can yield any thermally compensated measure of strain. In order to get any measure of strain, the node must have both **a1_in** and **a2_in** inputs.
- The specified measurement output from an optical strain node is **b_out** – the Total Strain from the node. Total strain is the sum of both substrate thermal and mechanical strains and completely compensates the gage's own thermal response. Thermal, mechanical, and deviation strain measures require application specific inputs from the user.
- The node input/output labels **a, b, c, d,** are used on individual sensor information sheets, ENLIGHT template selection paths, and white paper examples offering a consistent nomenclature among these documents.

IV. Examples of the Five Steps to Meaningful Strain Data

Example 1. os3110/os4100 pair welded to a steel substrate.

Calculate total strain ε_{Total}, thermal strain ε_{therm}, and mechanical strain ε_{mech} with an os3110/os4100 strain/temperature compensation pair, welded to a steel substrate with a known and well-defined CTE. Characterize the typical thermal response the substrate as part of the overall structural system, and plot any deviations from that typical response.

1. **COLLOCATION -** *The strain sensing FBG and temperature compensation FBG must be at the same temperature.*



In this example, an os3110 sensor is welded to a steel structure to measure the strain. On os4100 sensor is welded adjacent to the os3110 sensor to compensate for any thermally induced changes in the os3110 sensor itself.

Measurements over the course of several months are made on the wavelengths of both the os3110 strain sensing FBG and the os4100 temperature compensation FBG, yielding the following delta wavelength plots for λ_S and λ_T, the **a1_in** and **a2_in** inputs to the optical strain node.

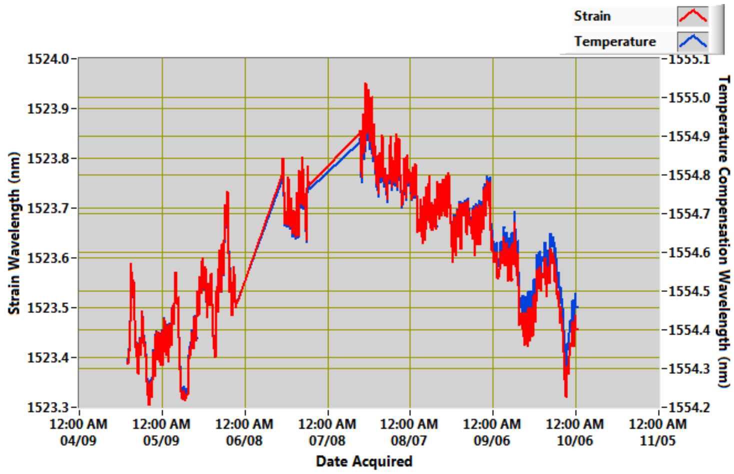
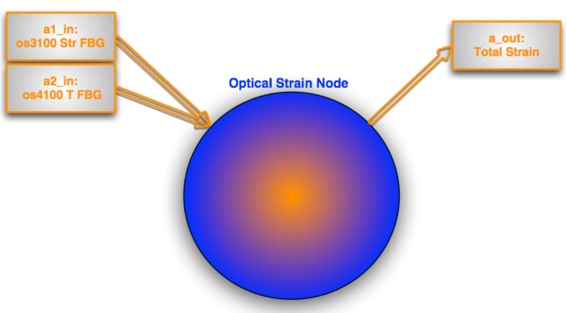


Figure 1.1. Time varying wavelength plots for gage strain and temperature FBGs, λ_S and λ_T.

2. TOTAL STRAIN - *Total strain can be accurately calculated by first subtracting out thermally induced optical gage effects.*



Plugging these values into Equation 1, along with the appropriate constants from the Sensor Information Sheet corrects for any optical gage thermal response contributions to the strain sensor wavelength change, yielding an accurate total strain measurement as shown in the following plot. The total strain is the **a_out** output from the optical strain node.

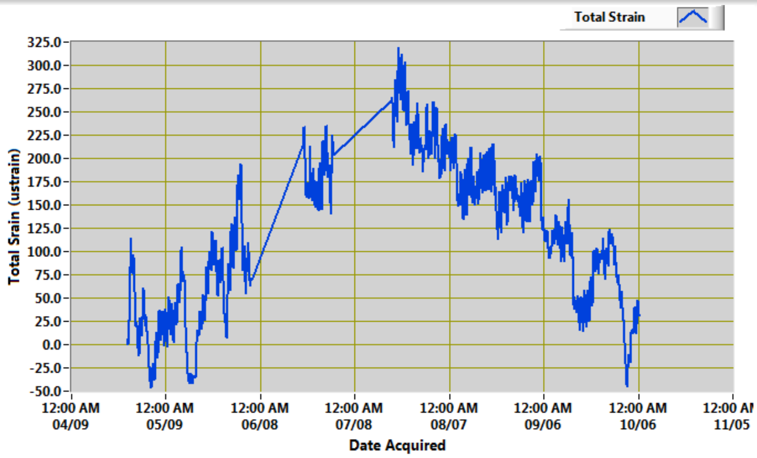
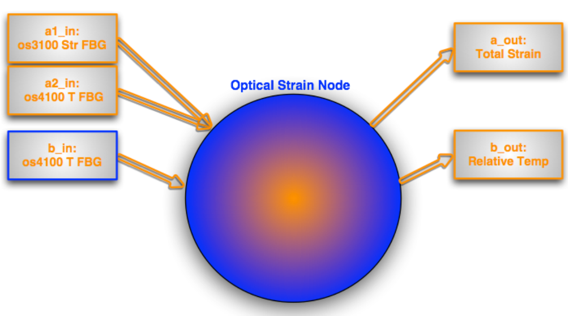


Figure 1.2. Time varying total strain plot for temperature compensated os3110/os4100 sensor pair.

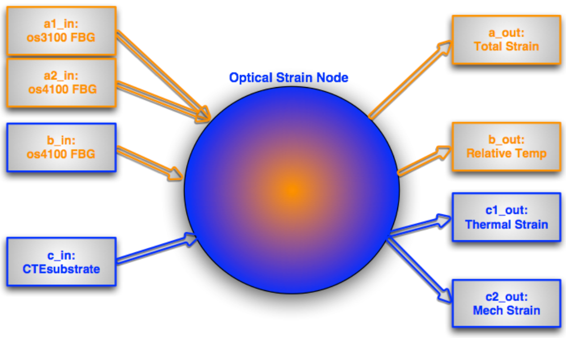
At this point, the total strain is reported correctly, fully accounting for any gage induced thermal effects. Further decomposition of this measurement into thermal strain and mechanical strain components, as executed by Equation 2, requires that we have a good representation of the substrate temperature, as well as the CTE of the substrate.

3. SUBSTRATE TEMPERATURE - *The substrate temperature can sometimes be accurately represented by the strain sensor's temperature compensation FBG, measured as* λ_T *, but sometimes requires an auxiliary temperature sensor.*



From the introduction to this example, we conclude that the os4100 sensor is a good representative of the substrate temperature and is used as the **b_in** input to the optical strain node.

4. SUBSTRATE CTE - *Thermal and mechanical components of total strain can be accurately decoupled if the exact substrate CTE and the substrate temperature are known.*



Since the os4100 is a valid source of substrate temperature data, we can substitute Equation 2 into Equation 4, along with our exact published material CTE, input **c_in** to the optical strain node, yielding the following plot for substrate mechanical strain, output **c2_out** from the optical strain node.

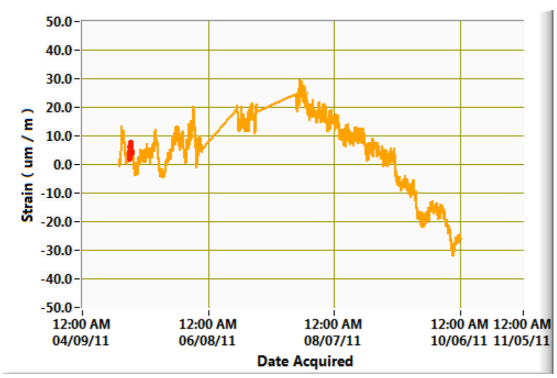
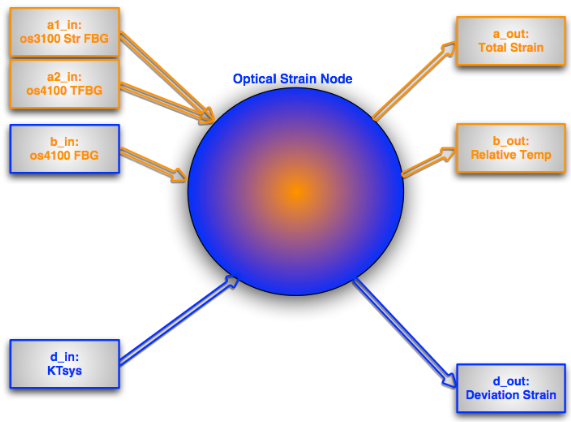


Figure 1.3. Mechanical component of strain, factoring in exact substrate CTE.

Self Check: Does this result make sense? Do we expect to see this much variability in day-to-day strains the substrate really free to expand and contract with temperature? Or is its expansion/ contraction "bound" by other materials in a more complex structure?

Given a high degree of confidence in a well-characterized material CTE of the substrate, the plot in Figure 1.3 is an accurate representation of mechanical strain in the substrate. It may be possible, though that the overall system thermal response is governed by more than just the material CTE of the substrate.

5. **SYSTEM THERMAL RESPONSE -** *Strain deviations from typical structural system thermal response can be observed by knowing the substrate temperature and deducing an effective thermal response coefficient of the system.*



We have already made the measurements needed to characterize total structural system thermal response. The following section shows how to plot and analyze the data to deduce an effective thermal response coefficient of the structural system, including the substrate thermal strain and coupled strains induced by any other elements of the system that may affect its boundary conditions. If we plot the output of Equation 1, the total strain, versus the best measure of substrate temperature within the gage length of the strain sensor, the os4100 relative temperature measurement in this case, we reveal the following relationship over the course of many months' measurements between total strain and substrate temperature.

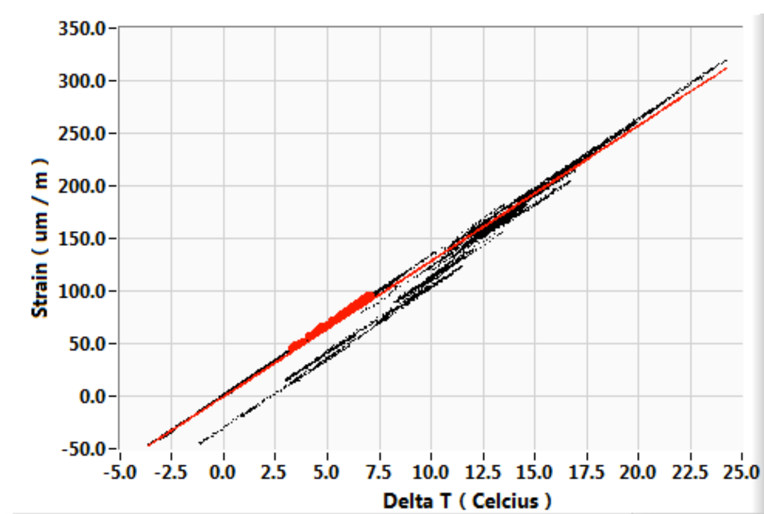
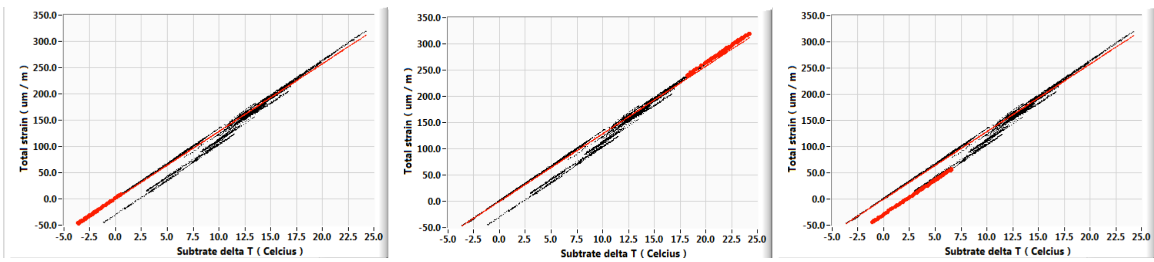


Figure 1.5. A plot of total strain versus substrate temperature change.

Careful review of this plot reveals a couple of interesting behaviors. First, over any short period of time, illustrated by the red week-long highlight, the slope of the total strain versus substrate temperature is relatively constant. Over time, there are changes in the y-axis offsets, but over most of the dataset, there is strong linear local relationship between substrate temperature and total strain. The slope of those parallel segments is the effective thermal response coefficient of the total structural system within the gage length of the strain sensor, or KT_{sys}. Any shifts of those common sloped segments on the plot are indicative of strain deviations from the typical structural system thermal response.

Plotted below are three week-long data highlights from three different periods throughout the year:



Figures 1.6.1 – 1.6.3 show three one-week highlights of the total strain versus substrate temperature curve.

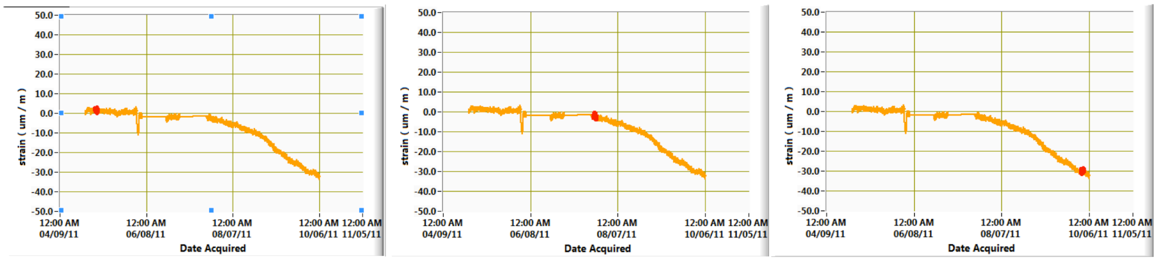
Figure 1.6.1 highlights total strain versus substrate temperature during a week in spring, while temperature was low.
Figure 1.6.2 highlights total strain versus substrate temperature during a week in summer, while temperature was high.
Figure 1.6.3 highlights total strain versus substrate temperature during a week in fall, while temperature was again low.

Close inspection of each one week of highlighted data reveals a nearly identical slope of 13.3 ppm/°C. This slope is constant for each segment, despite the vertical offsets from one another due to non-thermally correlated strains. Thus, post processing of the data affords us more insight and precision with regard to the overall thermal response of the structural system, accounting for both the actual material CTE of the substrate, as well as boundary conditions dictated by other elements of the structural system and their coupled thermal responses. Therefore, we can effectively isolate strain deviations from the now-characterized typical thermal response of the structural system, which we have deduced to be 13.3 ppm/°C.

Executing Equation 6 with the refined value of the effective KT_{sys} yields the following plots of strain deviations from the typical thermal response of the structural system over time. KT_{sys} is used as the **d_in** input to the optical strain node to yield **d_out**, the deviation strain from the optical strain node.

Figure 1.7.1 – 1.7.3 shows the same strain deviation plot for this sensor three times, each with a single highlighted week of data that correlates to the same timeframes highlighted in plots 1.6.1 – 1.6.3.

Upon review, the dataset presented in these plots makes physical sense, as it shows minimal daily thermal fluctuations, and clearly reveals a sharp strain deviation on 6/1/11, which for this dataset is an event known to be associated with a real mechanical load-induced strain.



Figures 1.7.1 – 1.7.3 show three one-week highlights of the same set of strain deviations as a function of time. These plots are corrected for optical gage thermal effects and are isolated from the typical thermal response of the structural system.

Example 2. os3610 sensor bracket mounted to concrete substrate (with auxiliary os4350 temperature sensor)

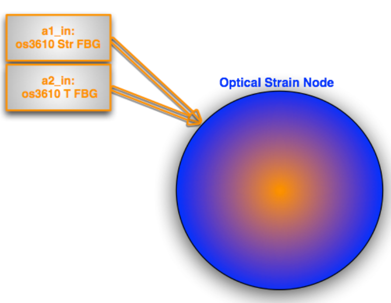
Calculate total strain ε_{Total}, characterize the typical thermal response of the structural system within the gage length of the strain sensor, and plot any strain deviations from that typical system thermal response.

In this example, an os3610 sensor is mounted via grout-in brackets above the surface of a large concrete structure. An os4350 absolute temperature sensor is also applied adjacent to the os3610 sensor, in direct contact with the surface of the concrete. Both sensors are protected and under a stainless steel enclosure with embedded insulating polystyrene foam.

Total strain on the concrete substrate will be accurately calculated.

As the material CTE is not well known or characterized, it is not possible to accurately decouple total strain into exact thermal and mechanical strain components. However, the sensors can be used to deduce the overall CTE of the structural system within the gage length of the strain sensor and plot any deviation strains from the typical system thermal response. Deducing this structural system behavior will be done both with and without the use of the os4350 auxiliary temperature sensor.

1. COLLOCATION - *The strain sensing FBG and temperature compensation FBG must be at the same temperature.*



As both the strain sensing and temperature compensation FBGs are housed in the same insulated os3610 enclosure and protected from direct sun exposure, we can reasonably assume that they are at the same temperature.

Measurements over the course of several months are made on the wavelengths of both the os3610 strain sensing FBG and the os3610 temperature compensation FBG, yielding the following delta wavelength plots for λ_S and λ_T, the **a1_in** and **a2_in** inputs to the optical strain node.

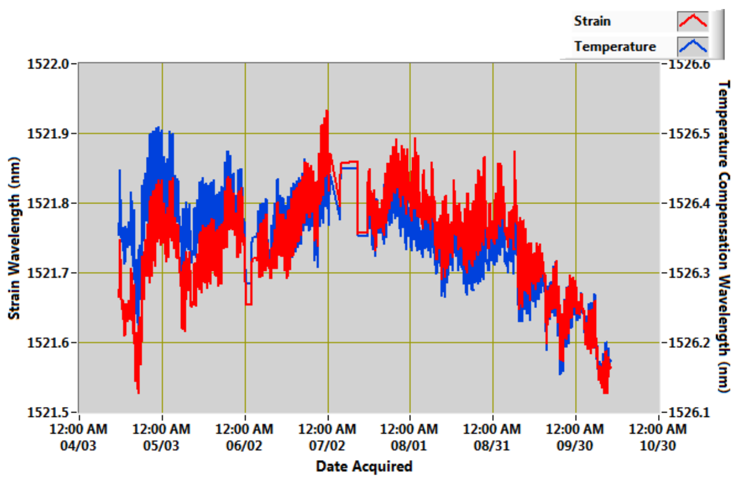
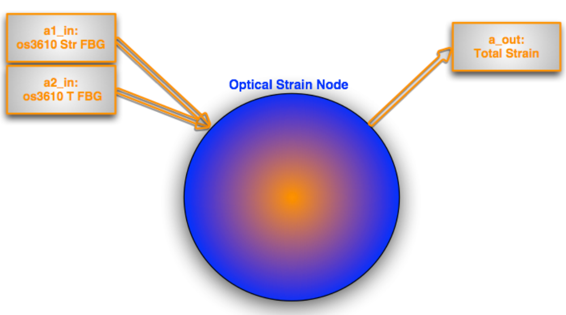


Figure 2.1. Time varying wavelength plots for gage strain and temperature FBGs, λ_S and λ_T.

2. TOTAL STRAIN - *Total strain can be accurately calculated by first subtracting out thermally induced optical gage effects.*



Plugging these values into Equation 1, along with the appropriate constants from the Sensor Information Sheet corrects for any optical gage thermal response contributions to the strain sensor wavelength change, yielding an accurate total strain measurement as shown in the following plot. The total strain is the **a_out** output from the optical strain node.

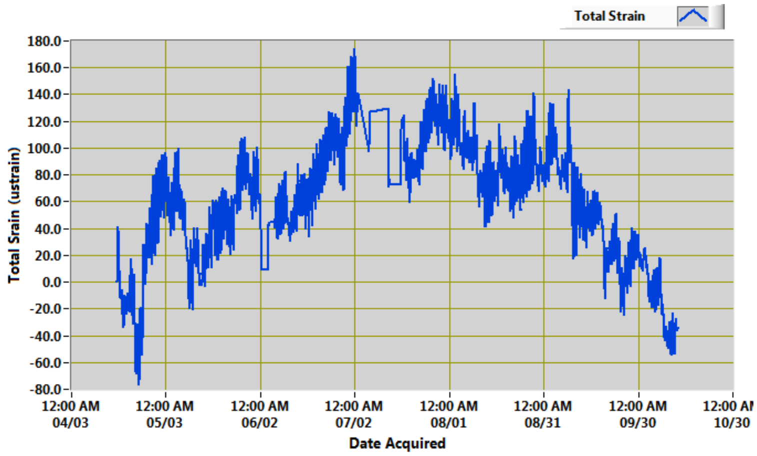
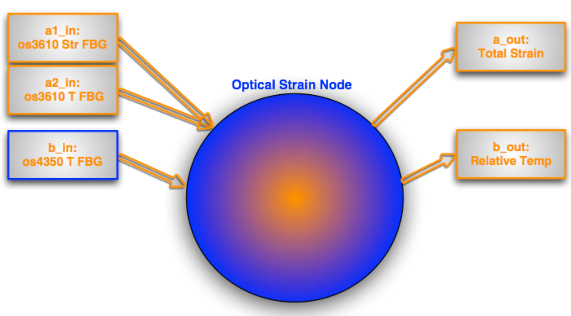


Figure 2.2. Time varying total strain plot for os3610 temperature compensated sensor.

At this point, the total strain is reported correctly, fully accounting for any gage induced thermal effects.

3. SUBSTRATE TEMPERATURE - *The substrate temperature can sometimes be accurately represented by the strain sensor's temperature compensation FBG, measured as* λ_T *, but sometimes requires an auxiliary temperature sensor.*



In the previous os3110/os4100 example, the sensor and substrate were in intimate thermal contact and can assume to be at the same temperature. However, in this example, we know that the sensor is installed several centimeters above the concrete on brackets and is likely seeing a different temperature than is the concrete substrate. For this reason, we chose to add an auxiliary temperature sensor to measure the concrete and will demonstrate the utility of that auxiliary sensor in this example.

Figure 2.3 shows the actual time varying relative temperature measurements from the os3610 gage compensation FBG and from the concrete surface mounted os4350 auxiliary temperature sensor. Even over this short twelve-day time period depicted in Figure 2.3, it is clear that the strain sensor and the concrete substrate are not seeing the same temperatures at the same time. Over the longer five-month time period of Figure 2.4, it is clear that these temperatures continue to diverge.

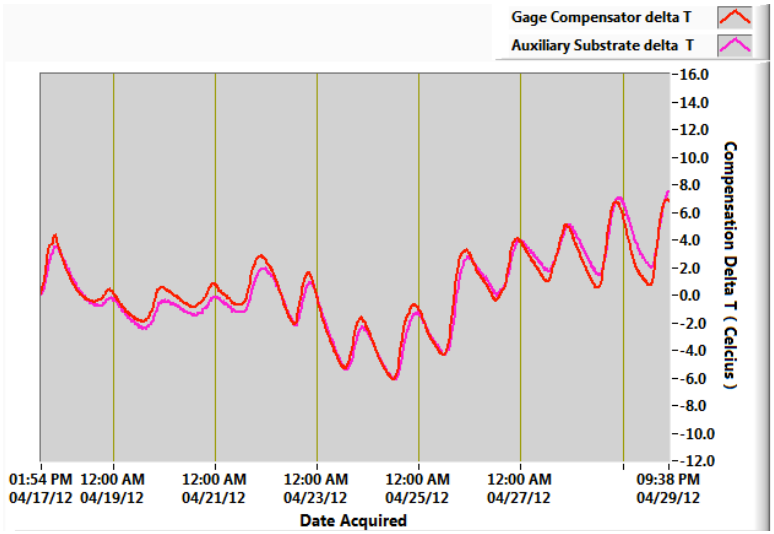


Figure 2.3. A plot showing the time varying temperature phase delays between the gage compensator temperature (red) and an auxiliary substrate surface mount compensation gage (pink).

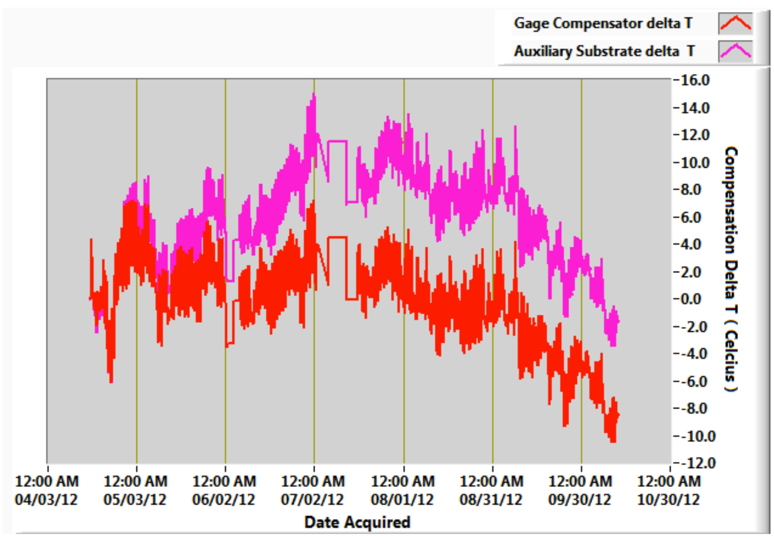


Figure 2.4. A plot showing the divergence of gage temperature and substrate temperature over a five-month period.

From this plot, it is clear that even for a well-insulated os3610 sensor bracket mounted to the surface of a concrete structure, the os3610 temperature compensation gage is NOT a good estimate of concrete temperature within the gage length of the strain sensor and must be augmented with an auxiliary temperature sensor for any additional analysis beyond total strain measurement. Characterizing and understanding any thermal gradients between strain sensor and measurement substrate is essential for any additional thermal analysis beyond a measurement of total strain, independent of the specific sensor technology.

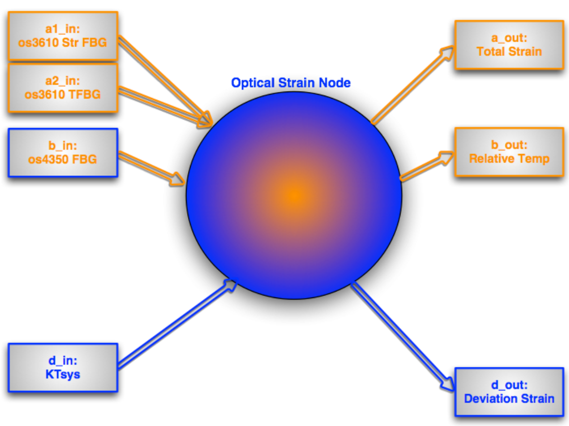
For this application example, the concrete surface mounted os4350 auxiliary temperature sensor wavelength is used as the b_in input to the optical strain node.

The effectiveness of the os4350 auxiliary temperature sensor relative to the use of the os3610 temperature compensator FBG for structural system analysis will be further demonstrated under point 5.

4. SUBSTRATE CTE - *Thermal and mechanical components of total strain can be accurately decoupled if the exact substrate CTE and the substrate temperature are known.*

In this case due to unknown concrete composition and no additional core sample measurements, we do not have a well-known or accurate value CTE for the substrate. As such, the total strain measurement cannot be accurately decoupled into actual substrate thermal and mechanical components. Without precise knowledge of the exact material CTE, this conclusion would be true for any sensor technology selected, optical or otherwise.

5. SYSTEM THERMAL RESPONSE - *Strain deviations from typical structural system thermal response can be observed by knowing substrate temperature and deducing an effective thermal expansion coefficient of the system.*



As seen in the first example, review of the total strain versus substrate temperature plot allows for an accurate characterization of the total thermal response of the structural system, taking into account both the CTE of the measured substrate, as well as boundary conditions dictated by other elements of the system and their coupled thermal responses. In this case, since the material CTE of the substrate is not precisely known, the exact contributions of mechanical strain and thermal strain cannot be accurately calculated. In many sensor installations, the most useful method for analysis of substrate behavior beyond the measurement of total strain is to deduce the typical thermal response of the system and use that KT_{sys} to highlight any strain deviations from that typical structural system thermal behavior.

In order to reiterate the importance of using a temperature sensor that accurately represents the substrate temperature, we will first attempt this analysis using only the os3610 temperature compensation FBG, measured as λ_T. Shown below as Figure 2.5, plot of total strain versus substrate temperature, as estimated by the os3610 temperature compensation gage, exhibits a strange and unexpected degree non-linearity and hysteresis.

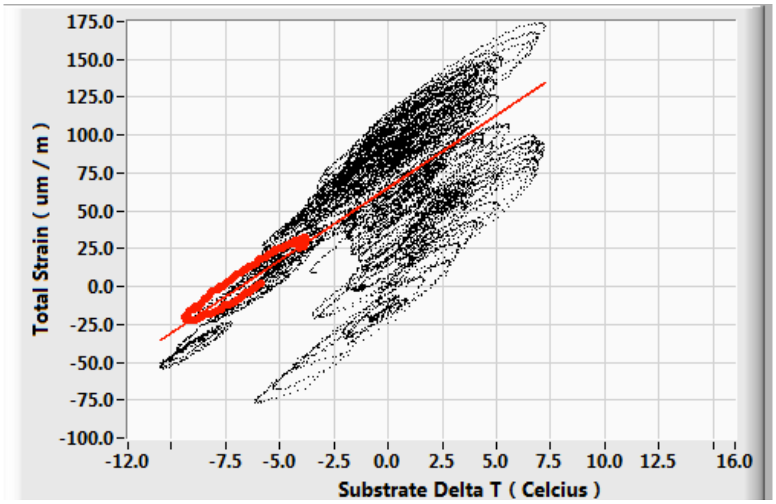


Figure 2.5. A plot of total strain versus os3610 gage compensator temperature change

Self check: Why does the total strain map so non-linearly to the substrate temperature? How can we deduce an accurate effective structural system CTE from this plot?

Still relying only on the os3610 thermal compensation FBG as measure of substrate temperature, Figure 2.6 shows a plot of strain deviations from the typical thermal response of the structural system as estimated by a best linear fit to the data of Figure 2.5.

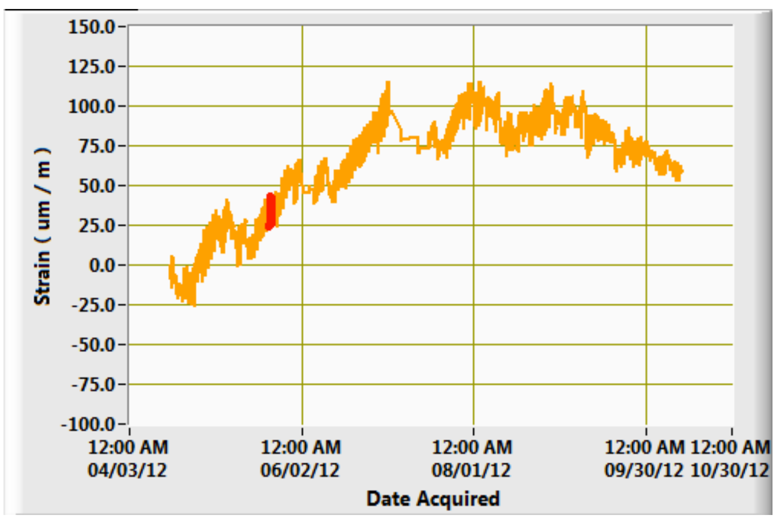


Figure 2.6. Strain deviations from the typical thermal response of the structural system, incorrectly assuming that the substrate temperature is well represented by the os3610 temperature compensation gage.

Self check: Why does the mechanical strain plot show such high values of strain? We know this particular concrete substrate to be free from such significant mechanical strain and relatively free to move with thermal expansion…

Referring back to Figures 2.3 and 2.4, we used the os3610 compensator gage temperature (red) to eliminate thermal contributions from the gage itself. But the thermal strain component of the total strain is a function of the substrate temperature, not the strain sensor temperature, and is much better represented by the os4350 auxiliary surface temperature sensor (pink).

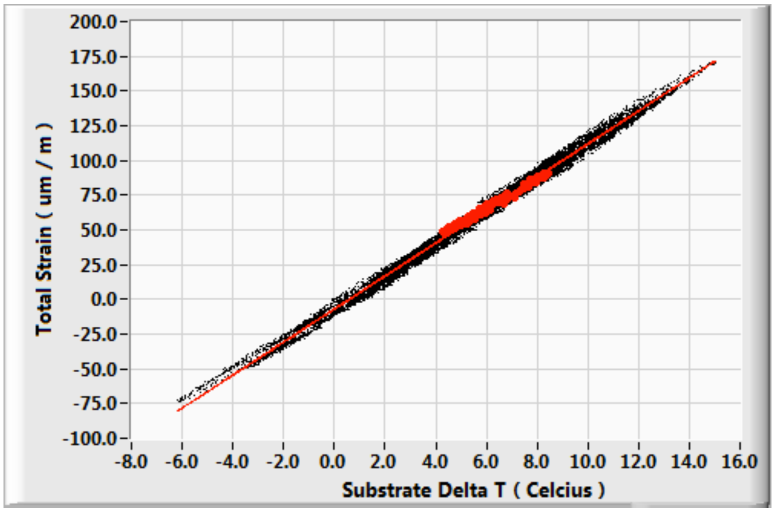


Figure 2.7. A plot of total strain versus substrate temperature, as measured by the os4350 auxiliary temperature sensor.

Now we will repeat the analysis, this time plotting the total strain against the substrate temperature as measured by the os4350 auxiliary temperature sensor, revealing the following near-linear relationship:

Clearly, the total strain exhibits a much more logical and linear response with respect to the os4350 measured substrate temperature than it does with respect to the os3610 temperature compensation FBG, those two temperatures being very different in this type of installation. Exercising Equation 6 again, this time with the os3450 auxiliary temperature sensor as the source for ΔT_{subst} , allows for a better characterization of the effective structural system coefficient KT_{sys} within the gage length of the sensor, and produces the following plot of strain deviations from the typical thermal response of the structural system. KT_{sys} is used as the **d_in** input to the optical strain node to yield **d_out**, the deviation strain from the optical strain node.

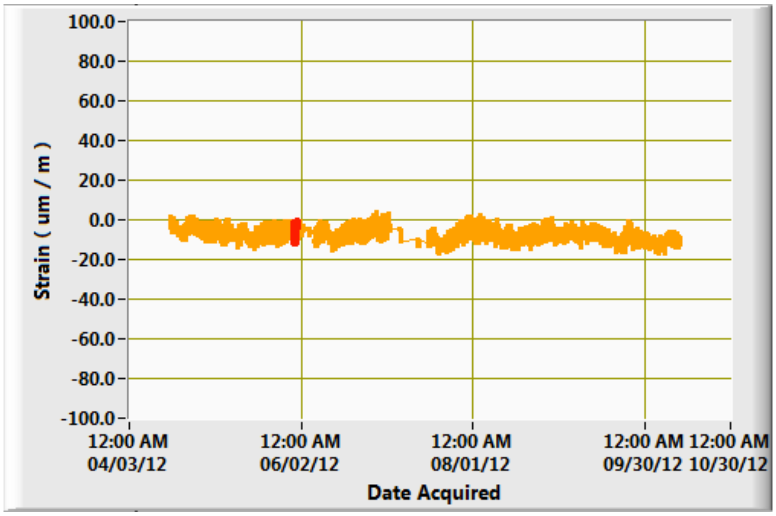


Figure 2.8. A plot of the concrete strains that deviate from the typical thermal response of the structural system.

This result makes physical sense and displays the expected degree of stability in the measurement of the concrete structure.

V. Conclusions

Through two significantly different examples, this document demonstrates how the same five steps can be applied to the full range of Micron Optics optical strain and temperature sensors to achieve meaningful strain data for the measured systems. With consideration of the structural boundary conditions and sufficient temperature sensor coverage, simple and convenient decomposition of thermal and mechanical strain components and system thermal responses have been demonstrated.

V. Appendix – Sensor Coefficients for use with Total Strain (Equation 1 of this document)

F_G is the gage factor for the optical strain gage and is expressed in units of microstrain per normalized wavelength shift of the strain sensing FBG,

$$\frac{\mu\varepsilon}{(\Delta\lambda/\lambda_0)_S}$$

S_T is the temperature compensator thermal response, and is specified in units of degrees C per normalized wavelength shift of the temperature compensation FBG,

$$\frac{^\circ C}{(\Delta\lambda/\lambda_0)_T}$$

CTE_T is the coefficient of thermal expansion for the temperature compensation FBG mount and is specified in parts per million per degree C.

$$\frac{ppm}{^\circ C}$$

Sensor Thermal Compensation Coefficients for Common Sensor Configurations

<u>os3610 with integrated compensation</u>

F_G = 0.830 for 25 cm with universal ends. 0.800 for 100 cm with universal ends.
S_T = 1.41e-5
CTE_T = 11.0

<u>os3600 with integrated compensation</u>

F_G = 0.77 for 25 cm with disk ends.
0.82 for 25 cm with universal ends.
0.786 for 100 cm with disk ends.
0.797 for 100 cm universal ends
S_T = 1.41e-5
CTE_T = 11.0

<u>os3155 with internal compensation or os3150 with os4100 compensation</u>

F_G = 0.811
S_T = 1.833e-5
CTE_T = 16.6

<u>os3100 with 4100 compensation</u>

F_G = 0.89
S_T = 1.833e-5
CTE_T = 16.6

<u>os3200 with os4200 or os4300 compensation</u>

F_G = 0.796
S_T = 6.5e-6
CTE_T = 0.55 (CTE of smf-28)

<u>os3200 with os4100 compensation</u>

F_G = 0.796
S_T = 1.833e-5
CTE_T = 16.6

<u>os3100 with os4200 or os4300 comp</u>

F_G = 0.89
S_T = 6.5e-6
CTE_T = 0.55

<u>os3150 with os4300 comp</u>

F_G = 0.811
S_T = 6.5e-6
CTE_T = 0.55

NOTE: Due to differences in thermal response and diffusivity, best temperature compensation performance is achieved using strain sensors and temperature compensation sensors of similar geometric and material construction. For example, if the sensors are likely to be in an environment of changing temperature or sun exposure, the os4100 sensor is a better choice for compensation of an os3100 or os3200 sensor than is an os4300.