INSTRUCTION MANUAL

EMBEDDED STRAIN GAUGE

Model EM-5

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NOVA METRIX

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1 PRODUCT

1.1 DESCRIPTION

The model EM-5 vibrating wire embedment strain gauge is designed to measure internal strains in mass concrete placed in foundations, bridges, dams, nuclear power stations, tunnel linings, etc., where long-term reliability coupled with high resolution are required. The gauge consists of two end flanges separated by a stainless steel tube with a tensioned high-strength steel wire clamped into the end flanges and running axially through the center of the tube. An electromagnet potted in epoxy resin and mounted at the center of the tube is used to vibrate and measure the vibration frequency of the wire when used in conjunction with the MB-6T readout unit or the MB-6TL datalogger and readout unit. When the gauge is cast into concrete, the concrete strains or deformations are conveyed to the gauge through the end flanges and measured as changes in the wire vibration period by the readout. The MB-6T displays the NORMAL readings digitally directly in microseconds units, and the LINEAR readings in units of microstrains.

The EM-5 embedment strain gauge is illustrated with design details and relevant dimensions in Figure 1 below. Two optional models EM-2 and EM-10 are also shown on that figure. The two end flanges serve to lock the gauge into the concrete matrix and, thus, set the gauge length for the measurement. An internal spring within the gauge pre-tensions the wire prior to embedment in the concrete, and an adjustment screw is provided in one of the flanges to enable the initial wire tension to be set at any pre-determined level. The initial gauge reading is usually specified on ordering and set at the factory. Once the gauge is embedded in concrete, the concrete movements completely override the spring forces, and so the changes in wire strain are directly proportional to the concrete strains, that is the deformation measured between the flanges.
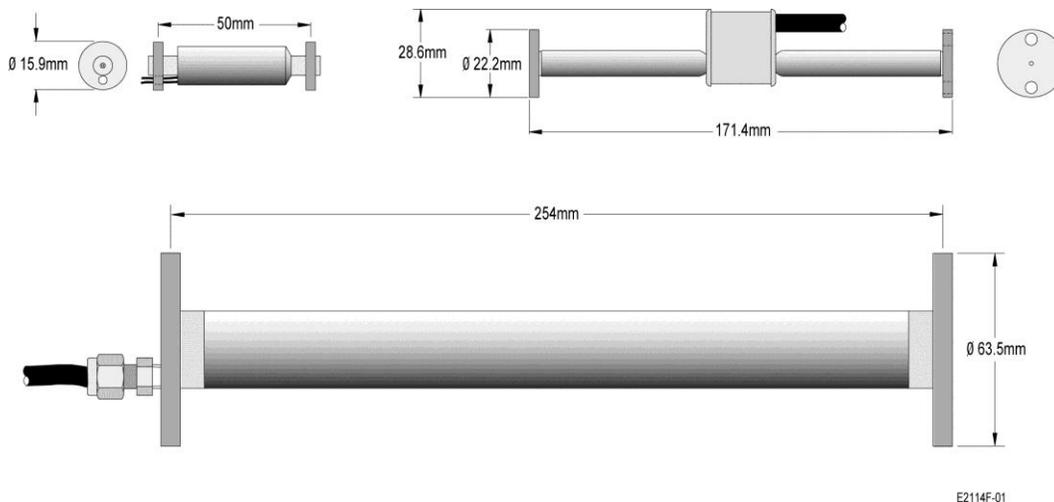

Figure 1: Schematic of EM-5 and two optional models (EM-2 and EM-10)

The two end flanges are sealed into the closed steel tube by double o-rings. The electromagnet is positioned over the gauge in the crimp at the center of the tube, and moulded in place with an epoxy resin. There is no direct connection between the electromagnet and the tensioned wire as the magnetic field used to excite the wire passes through the walls of the stainless steel tube.

To install the embedment gauge, it can be cast directly into the wet mix or encapsulated into concrete briquettes, which are subsequently cast into the wet mix. Installation in shotcrete is also possible, but care must be taken to avoid direct impact of the wet mix onto the gauge. It is also possible to grout the gauge into holes either drilled or cast into concrete.

1.2 STRAIN RANGE

The nominal range of the EM-5 embedment strain gauge is 3000 microstrains, which corresponds to a deformation of roughly 0.5 mm between the end flanges

Positive values of ε represent tensile strains and negative values of ε represent compressive strains. Figure below is a plot showing the strain reading vs the period of the EM-5. The mid range setting is approximately 2500 microstrains and corresponds to a NORMAL reading with the MB-6T or MB-6TL readout of 1275 microseconds.
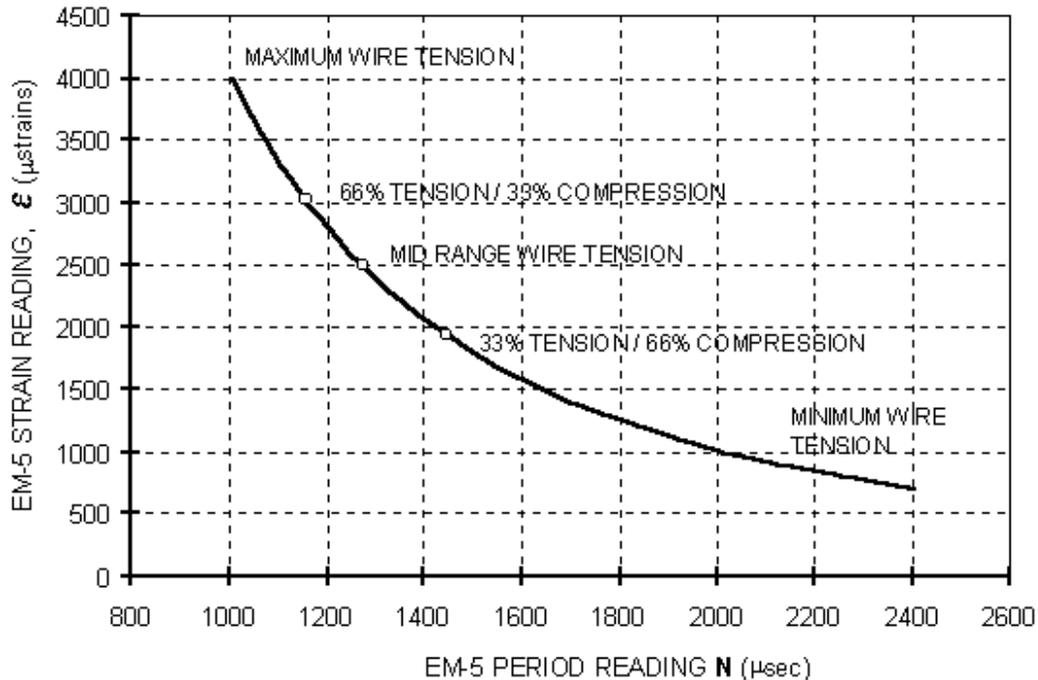

Figure 2: Microstrain versus period with EM-5 gage

2 INSTALLATION PROCEDURE

2.1 PRELIMINARY TESTS

The type EM-5 embedment strain gauge is supplied with the electromagnet already mounted and potted and with the wire tensioned so as to give a "NORMAL" reading corresponding roughly to mid-range, i.e. 1275 ±100 μsec, which corresponds approximately to 2500 linear units. With this setting, the measuring range is about 1500 microstrains, tension or compression. The gauge reading should always be checked prior to installation. To do this, follow the instruction given in the MB-6T(/TL) instruction manual.

The correct resistance readings between the conductors in the lead cable are:

Leads	Resistance
Black	140 ± 10 Ω
Red	
Green	3000 Ω at 25°C varies with temperature
White	

Table 1: Resistance readings

2.2 INSTALLING THE GAUGE

The EM-5 embedment gauge is usually set into concrete structures in one of two ways; casting directly into wet concrete or precasting into briquettes, which are then set into the concrete mix. It is also possible to set the gauges in shotcrete and also grout them into holes drilled or cast into concrete.

2.2.1 CASTING DIRECTLY INTO WET MIX

Tie wire may be connected to the central tube to enable the strain gauges to be wired in place to rebar or form work, etc., and, thus, hold the gauge in its pre-determined orientation. Precautions should be taken to avoid damage to the cable or gauge from vibrators. It is also essential that large pebbles or aggregate do not rest against the gauge, as these will cause localized strain discontinuities that may influence the gauge readings. This is important and, if necessary, coarse aggregate (larger than 13 mm) should be picked out by hand from around the gauge where possible.

Theoretically, to obtain uniform strain readings, the maximum aggregate size within an envelope of 1-1/2 gauge length around the gage should not exceed 1/5 of the gauge length i.e., for the EM-5 gauge, the maximum aggregate size within a radius of 250 mm from the gauge should not be greater than 25 mm. Care should also be taken to avoid air pockets around the gauge and to minimize interference of the gauge with support wires.

Where strain changes in two or three dimensions are to be investigated, it may be helpful to construct a wire framework of strain gauge mounting spider to hold the various gauges in correct orientation to each other (contact manufacturer for details). Care should be taken to ensure that the support wires do not restrain the gauge movements.

2.2.2   PRECASTING INTO CONCRETE BRIQUETTES

To avoid damage to the gauges and also to ensure that the gauge is not subjected to grossly non-uniform strain fields due to large aggregates lying alongside the sensing member, many users prefer to cast the gauges into concrete briquettes in the laboratory and then cast these into the wet mix on-site. Do not cast the briquettes more than 48 hours in advance of the main concrete pour in which the briquettes will be embedded.

The briquettes should be made up from an identical mix to that used on-site, but with fine aggregate (less than 12 mm), and should be cured underwater and kept fully saturated to avoid localized shrinkage strains.

2.2.3   CASTING IN SHOTCRETE

Because of the danger of damaging the gauges by the shotcrete and the difficulties of controlling aggregate size around the gauge, it is preferable to cast the gauges into briquettes made from shotcrete material prior to actually placing them in the shotcrete. The serious possibility of damaging the gauges and cables should be recognized and as much care as possible be taken to avoid this happening.

2.2.4   NO-STRESS GAUGE

It is generally a good practice to have a dummy gauge, also called No-Stress gauge, installed in proximity of other EM-5 gauges in order to follow their strain behavior in the very same environmental conditions but without the stress and loading effects generated from the structure itself. The No-Stress gauge is basically an EM-5 strain gauge mounted in a special housing in which no stress from the structure is applied. However, strain variation occurring from temperature effects and other factors such as hydric effects can be observed with the dummy gauge and used later to evaluate the real load applied on EM-5 strain gauges.

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UNIAXIAL FRAME SUPPORT

NO-STRESS GAGE
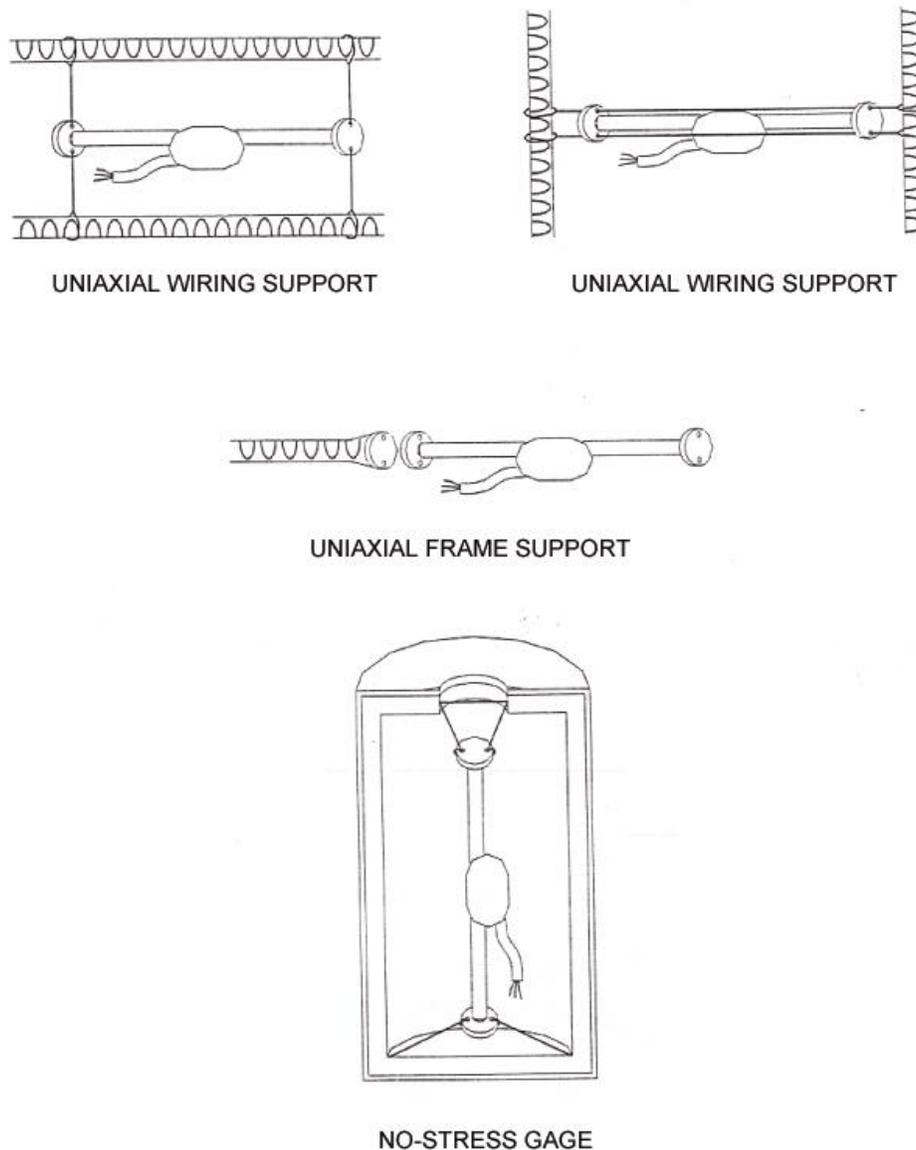
Figure 3: Typical installations of the EM-5

3 READING PROCEDURE

It is usual to run the leads from different gauges to a central measurement station and to connect them to terminal boxes for easy reading. Where required, protective covering should be provided to protect the lead wires particularly when shotcreting. Also, the cables should not be tensioned.

3.1 TAKING READINGS

To take strain and temperature readings, follow the instructions for operating the MB-6T readout contained in the MB-6T and MB-6TL instruction manual.

3.2 CONVERSION OF READING TO ENGINEERING UNITS

3.2.1 MB-6T AND MB-6TL NORMAL READING (N)

The total change in strain from an initial reading to a subsequent reading when using MB-6T or MB-6TL NORMAL readings is given by:

$$\Delta\varepsilon = \varepsilon_1 - \varepsilon_0 = K \times 10^9 \times \left[\frac{1}{N_1^2} - \frac{1}{N_0^2} \right]$$

where: $\Delta\varepsilon$ =   Total strain measurement, in μstrains

    ε_1 =   Current strain reading, in μstrains

    ε_0 =   Initial strain reading, in μstrains

    K   =   4.0624, gauge constant

    N_1 =   Current period reading, in μsec

    N_0 =   Initial period reading, in μsec

Example for EM-5 strain gauge:

    K   =   4.0624

    N_0 =   1112.0 μsec

    N_1 =   1800.0 μsec

$$\varepsilon = 4.0624 \times 10^9 \times \left[\frac{1}{1800^2} - \frac{1}{1112^2} \right] = \text{-2031 μstrains (compression)}$$

3.2.2 MB-6T AND MB-6TL LINEAR READINGS (L)

To determine the total strain change in the concrete using the LINEAR readings, use the following equation:

$$\Delta\varepsilon = \left(L_1 - L_0 \right)$$

where: $\Delta\varepsilon$ =   Total strain measurement, in μstrains

    L_1 =   Current reading, LINEAR units

    L_0 =   Initial reading, LINEAR units

Example for EM-5 strain gauge:

    L_0=   1253.0 LINEAR units

    L_1=   3284.0 LINEAR units

$$\Delta\varepsilon = \left(3284.0 - 1253.0 \right) = \text{+2031 μstrains (tension)}$$

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4 INTERPRETING READINGS

4.1 GENERALITIES

The problem of interpreting the readings of embedment strain gauges is beyond the scope of this manual, but it is imperative that the users have some idea of the pitfalls of trying to interpret concrete strains in terms of stresses over long-time periods. Strains being measured comprise the strains due to stresses and those due to other causes. These other causes are temperature variations, humidity (moisture) variations (hydric effects), strains due to the setting of the concrete itself (so-called autogenous volume changes of concrete) and finally, strains caused by the presence of the gauge itself. Additional factors that also have to be taken into consideration are the strains due to internal effects which have no net external resultant; i.e., they are not due to externally applied loads. These are primarily due to thermal and moisture gradients and local strain discontinuities caused by reinforcing bars and wire nets, etc.

The influence of many of the above factors is not fully understood and is still the subject of dispute, which means that it is not really possible to be able to draw up meaningful guidelines for potential users. When the readings are taken at the same time as applied loads, the interpretation becomes much easier.

The coefficient of expansion of gauge steel at around 11.5 μstrains/°C is very close to that of concrete varying generally between 7.0 μstrains/°C and 20 μstrains/°C, so correction factors for temperature effects caused by differential expansion are usually negligible.

4.2 METHODS

Total EM-5 readings include strain from various factors in addition to effective stress applied:

$$\varepsilon = \varepsilon_e + \varepsilon_c + \varepsilon_h + \varepsilon_s$$

where: ε =   Total strain measurement, in μstrains

ε_e =   Strain due to applied effective stress, in μstrains

ε_c =   Creep strain, in μstrains

ε_h =   Strain due to hydric and moisture effects, in μstrains

ε_s =   Strain caused by other factors such as local strain discontinuities.

The value of ε_s can be omitted since it is considered negligible, except for some very specific installation. ε_s can also be considered hidden into the ε_e value.

Therefore, the main equation above becomes:

$$\varepsilon = \varepsilon_e + \varepsilon_c + \varepsilon_h$$

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4.2.1   METHOD 1 - DIRECT CORRECTION FROM NO-STRESS GAUGE

When the No-Stress gauge can be considered as following the very same environmental conditions as other EM-5 strain gauges after installation, and especially after the curing period, it is very acceptable to subtract directly the total strain read by the No-Stress gauge from the total strain read by that EM-5 gauge. Since we consider both ε_h equal, as well as εe and εc of No-Stress gauge being zero, we have:

$$\varepsilon_e = \varepsilon - \varepsilon_c - \varepsilon_{nsg}$$

where: ε_e =   Strain due to applied effective stress, in μstrains

              ε =   Total strain reading, in μstrains

              ε_c =   Creep strain, in μstrains

              ε_{nsg} =   No-Stress gauge total strain reading, in μstrains

The above equation is true if and only if both the gauge and the No-Stress gauge are under the very same environmental conditions at the same time and are cast into the very same concrete.

When the ε_c value cannot be evaluated, it is usual to hide it. Many people hide ε_c in ε_e. Refer to Creep Strain ε_c sub-section in Method 2 of data reduction for additional details.

Example for first method

              ε_0 =   2505.6 linear units, EM-5 initial reading

              ε_1 =   2210.0 linear units, EM-5 current reading

              ε_{0nsg} =   2402.1 linear units, EM-5 dummy gauge initial reading

              ε_{1nsg} =   2320.4 linear units, EM-5 dummy gauge current reading.

If we assume that ε_c is hidden in ε_e, we then obtain:

       $\varepsilon = \varepsilon_1 - \varepsilon_0 = 2210.0 - 2505.6 = -295.6$ µstrains

       $\varepsilon_{nsg} = \varepsilon_{1nsg} - \varepsilon_{0nsg} = 2320.4 - 2402.1 = -81.7$ µstrains.

Then, the strain due to the effective stress applied is:

       $\varepsilon_e = \varepsilon - \varepsilon_{nsg}$

       $\varepsilon_e = (-295.6) - (-81.7) = -213.9$ µstrains.

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4.2.2 METHOD 2 - INTERPRETING THE READINGS WITH THEORETICAL CORRECTIONS

With this second method, the use of a No-Stress gauge may be very useful, but can be omitted if all behaviour parameters are known.

We have seen in method 1 that total strain read is:

$$\varepsilon = \varepsilon_e + \varepsilon_c + \varepsilon_h + \varepsilon_s$$

with ε_s considered negligible or hidden in ε_e.

a. COMPUTING OF REAL STRAIN ε_r

Real strain ε_r is the total strain on which we add the thermal expansion of wire, as if the EM-5 strain meter was not confined.

$$\varepsilon_r = \varepsilon + (\alpha_c - \eta\beta) \times (T_1 - T_0)$$

where:
- ε = Total strain reading, in μstrains
- ε_r = Real strain, in μstrains
- α_c = Linear expansion factor of EM-5 gauge wire = 11.5 μm/m/°C
- T_1 = Temperature reading, in °C
- T_0 = Initial temperature reading, in °C
- β = Concrete expansion factor in μm/m/°C, similar to α_c

7μm/m/°C $< \beta < 20\mu$m/m/°C. The $\eta\beta$ expansion factor is known from laboratory test or can be estimated from each EM-5 reading with a linear regression of ε versus T°, after removing all erratic values from data table. In some application the value of $\eta\beta$ or β can vary from one EM-5 gauge to the other depending on their location in the structure and the behavior heterogeneity in the concrete mass.

η = Freedom factor of the concrete structure in surrounding material ($0 \leq \eta \leq 1$). For the EM-5 No-Stress gauge, the value of η is 1.

Generally speaking, the value of η is 1 also, since the surrounding material is confining the unit and allows no movement but the strain imposed by the concrete mass.

Since the value of η is not easy to obtain from laboratory test, it is preferable to compute it from field data as described above. The slope of the graph gives directly $\eta\beta$ which is β if $\eta = 1$.

b. EFFECTIVE STRAIN ε_e

The effective strain ε_e is the strain caused by the structural load only, without thermic effects, creep or hydric effects:

$$\varepsilon_e = \varepsilon_r - \varepsilon_c - \varepsilon_h$$

where: ε_e = Strain due to applied effective stress, in μstrains

ε_c = Creep strain, in μstrains

ε_h = Strain caused by hydric effects, in μstrains

ε_r = Real strain, in μstrains

c. CREEP STRAIN ε_c

The creep strain ε_c is the strain caused by creep of concrete mass and is time dependent behavior. ε_c can be evaluated in laboratory, but generally, the maximum ε_c value will reach 2 times the instantaneous elastic strain.

Since ε_c may be caused by the load applied to the structure, it can be kept hidden into ε_e value, the effective strain. It is the responsibility of the laboratory in charge of concrete tests to estimate ε_c.

d. HYDRIC STRAIN ε_h

What we call ε_h, the hydric strain of the concrete mass, comprises all strains caused by chemical and mechanical reactions of material that may become permanent, such as differential expansion among the structure during curing, water absorption around the structure, chemical reactions, etc.

The value of ε_h can be considered similar for all EM-5 embedment gauges submitted to similar environmental conditions in the very same concrete at the same time.

Example of second method

General formula:

$$\varepsilon_e = \varepsilon_r - \varepsilon_c - \varepsilon_h \ (1)$$

Other formulae:

$$\varepsilon_r = \varepsilon + (\alpha_c - \eta\beta) \times (T_1 - T_0) \ (2)$$

$$\varepsilon = \varepsilon_1 - \varepsilon_0 \ (3)$$

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Using these three formulae, we obtain:

$$\varepsilon_e = (\varepsilon_1 - \varepsilon_0) + (\alpha - \eta\beta) \times (T_1 - T_0) - \varepsilon_c - \varepsilon_h \quad (4)$$

Example:

ε_0	=	3535.7 LU, initial reading
ε_1	=	3229.0 LU, current reading
α	=	10.0 μm/m/°C, linear expansion factor
T_0	=	20.2°C, initial temperature reading
T_1	=	25.4°C, current temperature reading
β	=	11.0 μm/m/°C, concrete expansion factor
η	=	1, freedom factor of the concrete structure

If we consider that ε_c is included in ε_e and ε_h is negligible, then we obtain:

$$\varepsilon_e = (\varepsilon_1 - \varepsilon_0) + (\alpha - \eta\beta) \times (T_1 - T_0) \quad (5)$$

$$\varepsilon_e = (3229.0 - 3535.7) + (10.0 - 1 \times 11.0) \times (25.4 - 20.2)$$

$$\varepsilon_e = -306.7 - 1 \times 5.2 = \text{-311.9 μstrains}$$

5 TROUBLESHOOTING

Maintenance and troubleshooting of vibrating wire transducers are required. Periodically check cable connections and terminals. The transducers themselves are sealed and cannot be opened for inspection.

5.1 UNSTABLE READING

- Check if the same troubles occur with other instruments. If so, compare cable routes or check the readout unit.

- Is the shield drain wire correctly connected to the readout unit?

- Isolate the readout unit from the ground by placing it on a piece of wood or similar non-conductive material.

- Check the battery of the readout unit.

- Check for nearby sources of electrical noise such as motors, generators, electrical cables or antennas. If noise sources are nearby, shield the cable of move it.

- If a data logger is used to take the readings, are the swept frequency excitation settings

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well adjusted?

- The sensor may have gone outside its range. See previous records.

- Check the integrity of the cable.

- The sensor may have been damaged by shocks.

5.2 NO READING

- Check the battery of the readout unit.

- Check if the same troubles occur with other instruments. If so, the readout unit may be suspected and the factory should be consulted.

- If a data logger is used to take the readings, are the swept frequency excitation settings well adjusted?

- The sensor may have gone outside its range. See previous records.

- Check the coil resistance. Nominal coil resistance is $140\Omega \pm 10\Omega$, plus cable resistance (22 gage copper = approximately $0.07\Omega/m$).

- If the resistance is high or infinite, a cut cable must be suspected.
- If the resistance is low or near zero, a short must be suspected.
- If resistances are within the nominal range and no reading is obtained, the transducer is suspect and the factory should be consulted.

- Cuts or shorts are located, the cable may be spliced in accordance with recommended procedures.

- The sensor may have been damaged by shocks.

5.3 TEMPERATURE TROUBLES

If troubles occur when reading the temperature, this is likely due to a cable cut or short because of the technology used (simple thermistor). Check the cable and splice it in accordance with recommended procedures.

If furthermore, no reading of strain is got, water may have penetrated inside the sensor body. There is no remedial action.

6 MISCELLANEOUS

6.1 ENVIRONMENTAL FACTORS

Since the purpose of strain gage installation is to monitor site conditions, factors which may affect these conditions should always be observed and recorded. Seemingly minor effects may have a real influence on the behaviour of the structure being monitored and may give an early indication of potential problems. Some of these factors include, but are not limited to: blasting, rainfall, tidal levels, excavation and fill levels and sequences, traffic, temperature and barometric changes, changes in personnel, nearby construction activities, seasonal changes, etc.

6.2 CONVERSION FACTORS

	To Convert From	**To**	**Multiply By**
LENGTH	Microns Millimetres Meters	Inches Inches Feet	3.94E-05 0.0394 3.2808
AREA	Square millimetres Square meters	Square inches Square feet	0.0016 10.7643
VOLUME	Cubic centimetres Cubic meters Litres Litres	Cubic inches Cubic feet U.S. gallon Can–Br gallon	0.06101 35.3357 0.26420 0.21997
MASS	Kilograms Kilograms Kilograms	Pounds Short tons Long tons	2.20459 0.00110 0.00098
FORCE	Newtons Newtons Newtons	Pounds-force Kilograms-force Kips	0.22482 0.10197 0.00023
PRESSURE AND STRESS	Kilopascals Bars Inches head of water* Inches head of Hg Pascal Kilopascals Kilopascals Kilopascals	Psi Psi Psi Psi Newton / square meter Atmospheres Bars Meters head of water*	0.14503 14.4928 0.03606 0.49116 1 0.00987 0.01 0.10197
TEMPERATURE	Temp. in °F = (1.8 x Temp. in °C) + 32 Temp. in °C = (Temp. in °F – 32) / 1.8		

*at 4 °C   E6TabConv-990505

Table 2: Conversion factors

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