INSTRUCTION MANUAL

SENSOPTIC FIBER-OPTIC SENSOR

Model EFO - Embedded Strain Gage

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1 INTRODUCTION

The SENSOPTIC line of fiber-optic sensors are specially developed instruments that can be used in a variety of applications where their small size, high accuracy, broad measurement range and complete immunity to EMI / RFI (electromagnetic and radio frequency interferences) are of paramount importance. In addition, they have an excellent dynamic response which opens the possibility of combined static and dynamic measurements, according to the specific needs of the investigated structure.

The model EFO-Embedded Strain Gage is designed to measure internal strains in mass concrete placed in foundations, bridges, dams, tunnel linings, etc.

2 EQUIPMENT DESCRIPTION

2.1 DESCRIPTION OF FABRY-PEROT STRAIN GAGE

The EFO sensor is based on a unique fiber-optic strain gage which constitutes a breakthrough in fiber-optic sensing. The gage, namely a Fabry-Perot strain gage, is based on a white-light interferometric extrinsic principle that uses a common multimode fiber.

The patented principle consists in assessing the length of a Fabry-Perot cavity contained in the strain gage by means of a Fiso interferometer located in the readout unit, that optically reproduces the length of the Fabry-Perot cavity and allows to digitize that length on a high density linear photo diode array attached along one side of the interferometer (Figure 1).

The Fabry-Perot cavity is made of two 125 microns diameter fibers facing each other and fused in a 200 microns diameter glass micro-capillary, with a semi-reflective mirror coating on each fiber’s tip. Then, when the Fabry-Perot strain gage is bonded in EFO sensor, the strain variations transferred to the gage are converted into cavity length variations.

The length of the Fabry-Perot cavity, as compared to the distance between the fused welding on the fibers, defines the range of the strain gage, whereby the sensitivity of the gage is defined by the density of the photodiode array used in the readout unit.

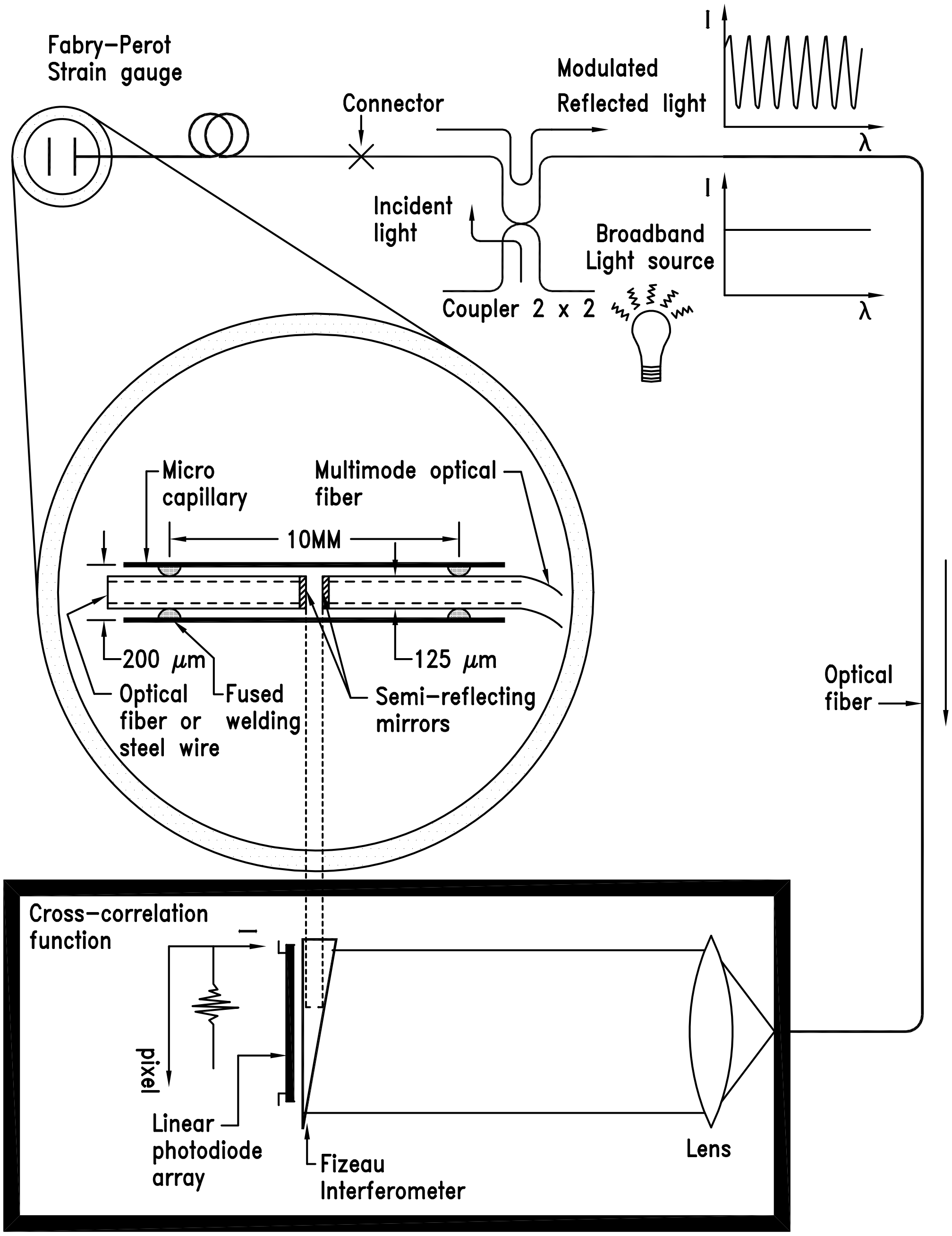

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Figure 1: Schematic principle of a Fabry-Perot strain gage

2.2 DESCRIPTION OF EFO-STRAIN GAGE

The standard EFO is a 70 mm long sensor designed to be embedded in concrete. It consists of a solid stainless steel body provided with two end flanges for better adherence to the concrete and incorporating a longitudinal small diameter hole in which a Fabry-Perot strain gage is bonded. The sensor can be used in different types of concrete, including conventional concrete and newly developed high-performance and powder reactive concretes. The sensor is illustrated with design details and relevant dimensions in Figure 2.

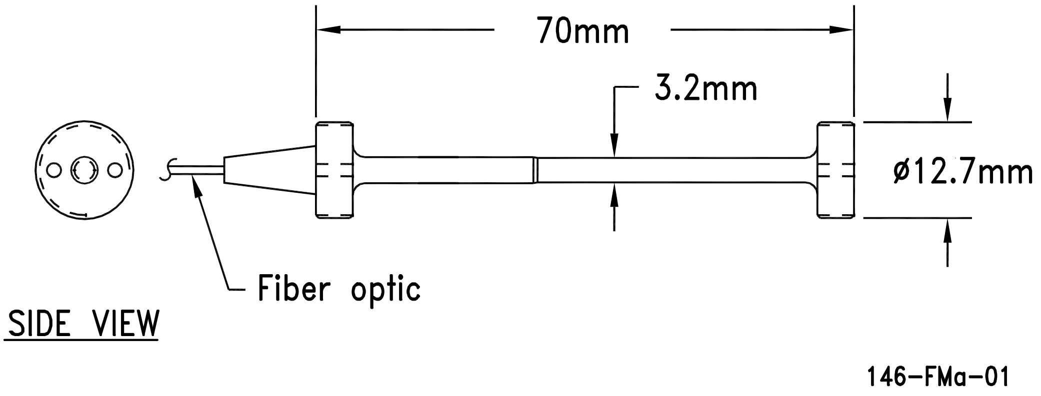

Figure 2: EFO-Embedded Strain Gage

3 INSTALLATION PROCEDURE

3.1 SETTING THE GAGE

Before installing and using the gage, you must define it within the readout memory. To do this, you must enter its gage factor (7 digit number, example: 1004103) in the permanent memory of the readout. After the gage has been defined, you can connect the gage to the readout. Please see the instruction manual of the readout you are using for more details.

The EFO Embedment strain gage is usually set into concrete structures in one of two ways: it can be cast directly into the wet mix or encapsulated into concrete briquette which are subsequently cast into the wet mix. It is also possible to set the gage in shotcrete and also grout them into holes drilled or cast into concrete. The use of the gage in this latter manner will not be discussed further here. (Contact Roctest if this technique is considered).

3.2 CASTING DIRECTLY INTO WET MIX

On each end flange, there are two small holes where tie wire may be connected to hold the gage in its pre-determined orientation. Precautions should be taken to avoid damage to the cable or gage from vibrators. It is also essential that large pebbles or aggregate do not rest against the gage, as these will cause localized strain discontinuities that may influence the gage readings. This is important and, if necessary, coarse aggregate (larger than 1/2 inch) should be picked out by hand from around the gage where possible. Care should also be taken to avoid air pockets around the gage and to minimize interference of the gage 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 gage mounting to hold the various gages in correct orientation to each other (contact Roctest for details). Care should be taken to ensure that the support wires do not restrain the gage movements.

3.3 PRECASTING INTO CONCRETE BRIQUETTE

To avoid damage to the gage and also to ensure that the gage is not subjected to grossly non-uniform strain fields due to large aggregates lying along side the sensing member, many users prefer to cast the gage 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 1/2 inch), and should be cured underwater and kept fully saturated to avoid localized shrinkage strains.

Care should be taken to not tension the cables during and after the installation.

3.4 CASTING IN SHOTCRETE

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

3.5 NO-STRESS GAGE

It is generally a good practice to have a dummy gage, also called No-Stress gage, installed in proximity of other EFO gages 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 gage is basically an EFO strain gage mounted in a special housing in which No-Stress from the structure is applied (Consult Roctest for additional details on how to prepare a No-Stress gage on site). However, strain variation occurring from temperature effects and other factors such as hydric effects can be observed with the dummy gage and used later to evaluate the true stress applied on EFO strain gages.

4 READING PROCEDURE

4.1 READINGS

The basic relationship between the reading and the change in strain in the concrete in which the gage is embedded is given by:

$$\varepsilon = \varepsilon_1 - \varepsilon_0$$

where: ε = Total strain change in concrete in □strains

ε_0 = Initial strain in □strains

ε_1 = Current strain in □strains

Example for EFO strain gage:

ε_0 = 3602.00 units, initial reading

ε_1 = 3039.80 units, current reading

$\varepsilon = \varepsilon_1 - \varepsilon_0$ = 3039.80 - 3602.00 = -562.20 □strains (compression)

Positive values of ε represent tensile strains and negative values represent compressive strains.

4.2 INTERPRETING READINGS

The problem of interpreting the readings of embedded strain gages 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. Stresses being measured to determine strains must be measured to enable the strains due to stresses to be separated from 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 gage 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.

One interesting feature of the EFO strain gage is that it can be manufactured with either a temperature compensated or non-compensated Fabry-Perot strain gage. When the temperature compensated gage is used, the coefficient of expansion of the metallic fiber used for compensation is around 10.0 µstrains/°C. This value is very close to that of concrete, which varies generally between 7.0 µstrains/°C and 20 µstrains/°C, so correction factors for temperature effects caused by differential expansion can be negligible with this type of gage.

Roctest is proud to manufacture high quality instruments as EFO strain gages. But Roctest denies any responsibility from the data interpretation. Appendix A is given only as a tool, providing two main approaches of data reduction.

5 MISCELLANEOUS

5.1 TWO METHODS FOR INTERPRETING THE READINGS OF EFO

It is beyond the scope of this manual to solve the problem of interpreting the readings of embedment strain gages, since concrete behavior is not fully understood and may vary with so many factors.

However, following are two methods proposed depending on whether you use a self-compensated or non-compensated Fabry-Perot strain gage. These methods are proposed as tools for interpreting readings properly but in no matter Roctest should not be considered responsible if results obtained are not meeting expectations.

Total strain ε

Total strain ε is the raw strain obtained directly from EFO readings:

$$\varepsilon = \varepsilon_1 - \varepsilon_0$$

where: ε = Total strain measurement, in □strains

ε_0 = Initial strain, in □strains

ε_1 = Current strain, in □strains

Total EFO readings include strain from various factors in addition to applied effective stress or structural load:

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

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:

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

METHOD 1

Interpreting the readings with non-compensated EFO strain gage and No-Stress gage

When the No-Stress gage can be considered as being following the very same environmental conditions as the other EFO strain gages after installation, and especially after the curing period, it is very acceptable to subtract directly the total strain read by the No-Stress gage from the total strain read by that EFO gage. Since we consider ε_h from both the EFO strain gage and the No-Stress gage to be equal, and also ε_e and ε_c of the No-Stress gage equal to zero, we have:

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

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 gage total strain reading, in µstrains

The above equation is true if and only if both the gage and the No-Stress gage 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 ε_c into ε_e. Refer to Creep Strain ε_c sub-section in Method 2 for additional details.

<u>Example for the first method</u>:

ε_0 = 3505.6 units, initial reading of the EFO strain gage

ε_1 = 3210.0 units, current reading of the EFO strain gage

ε_{0nsg} = 3402.1 units, initial reading of the No-Stress gage

ε_{1nsg} = 3320.4 units, current reading of the No-Stress gage

If we consider ε_c hidden into ε_e, then we have:

$$\varepsilon = \varepsilon_1 - \varepsilon_0 = 3210.0 - 3505.6 = -295.6 \text{ micro-strains}$$

$$\varepsilon_{nsg} = \varepsilon_{1nsg} - \varepsilon_{0nsg} = 3320.4 - 3402.1 = -81.7 \text{ micro-strains}$$

Then the strain due to applied effective stress is:

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

$$\varepsilon_e = (-295.6) - (-81.7) = -213.9 \text{ micro-strains}$$

METHOD 2

Interpreting the readings with self-compensated EFO strain gage

With this second method, we use a self-compensated EFO strain gage to find the effective strain applied.

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 into ε_e

Computing of real strain ε_r

Real strain ε_r is the total strain on which we add the thermal expansion of concrete and the thermal expansion of the metallic fiber in the self-compensated Fabry-Perot strain gage.

Then real strain ε_r can be computed with the following formula:

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

Where: ε_r = Real strain, in µstrains

ε = Total strain reading, in µstrains

α = Linear expansion factor of self-compensated gage = 10.0 µm/m/°C (5.5 µin/in/°F)

T_1 = Temperature reading, in °C

T_0 = Initial Temperature reading, in °C

β = Concrete expansion factor in µm/m/°C, generally similar to α : $7\mu m/m/°C < \beta < 20\mu m/m/°C$. The β expansion factor is known from laboratory test. In some application the value of β can vary from one EFO gage to the other depending of their location in the structure and the behavior heterogeneity in the concrete mass.

η = Freedom factor of the concrete structure in surrounding material $0 \leq \eta \leq 1$.

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

If the concrete expansion factor $\eta\beta$ is similar to α (i.e. 10.0 µm/m/°C), then the total strain read is equal to the real strain.

$$\varepsilon_r = \varepsilon$$

STRAIN DUE TO APPLIED EFFECTIVE STRESS ε_e

The effective strain ε_e is the strain caused by the applied effective stress (or 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_r = Real strain, in µstrains

ε_c = Creep strain, in µstrains

ε_h = Strain caused by hydric effects, in µstrains

CREEP STRAIN ε_c

The Creep Strain ε_c is the strain caused by creep of concrete mass and is a 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 the effective strain value ε_e. It is the responsibility of the laboratory in charge of concrete tests to estimate ε_c.

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 EFO embedment gage submitted to similar environmental conditions in the very same concrete at the same time.

Example for the second method:

The general equation is:

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

and the others equations are:

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

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

Insert the equations 2 and 3 into 1 and you will find:

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

Numerical example:

ε_0 = 3535.7 units, initial reading

ε_1 = 3229.0 units, current reading

α = 10.0 μm/m/°C, linear expansion factor of self-compensated gage

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 ε_c hidden into ε_e and ε_h negligible, then we have:

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

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

$$\varepsilon_e = (-306.7) + (-1) \times (5.2)$$

$$\varepsilon_e = -311.9 \text{ micro-strains}$$