Fiber optic sensor for high temperature monitoring.

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ABSTRACT

Recent events such as the fires on the Channel tunnel (1996), St. Gotthard (2001), the Twin Towers in New York (2001), the Windsor Building in Madrid (2005) and the collapse of the MacArthur Maze in Oakland (2007) show the importance and the necessity of a monitoring strategy for fire vulnerable structures. Through this strategy, the assessment of fire damaged structures would be possible and if necessary, the demolition operation would be guided. In order to monitor structures subjected to fire it is essential to have high temperature sensors. Nowadays, the measurements of temperatures during fires are done by high temperature thermocouples (electric sensors), that have the typical inconvenience of the electric sensors.

In this article the steps in the development of high temperature fiber optic sensor are presented. The operating principle of the fiber optic sensor to measure temperature is exposed. Then, the experimental tests to prove the performance of the sensor are explained and their main results are shown.

Keywords: Fire, high temperature measurment, structural health monitoring (SHM), fiber optic sensor, fiber bragg gratting.

1 INTRODUCTION

Structural Health Monitoring (SHM) has been defined as the use of in-situ, continuous or regular (routine) measurements and analyses of key structural and environmental parameters under operating conditions, for the purpose of warning impending abnormal states or accidents at an early state to avoid casualties as well as giving maintenance and rehabilitation advice [1].

Although the formal establishment of this discipline is relatively recent, dam or building monitoring is relatively old (first half of the twentieth century). Currently, structural health monitoring is booming and is very common to install sensors in complex structures, in dangerous construction process or in structural repairs

Monitoring systems are composed of three elements: a sensor array, a data process system (acquisition, transmission and data storage) and a structural assessment system. To monitor structures submitted to fire, high temperature sensors are essential. In the case of accidental loads like fires, earthquake (which frequently results in occurrence of fire) and terrorist attacks, continuous monitoring is very helpful to evaluate structural safety, evacuation and, if is necessary, define a safe procedure for demolition.

Sometimes, structures have been monitored taking into account the earthquake action (see e.g. [2]), but, as far as the authors know, fire action has not been considered in structural monitoring, except laboratory test (see e.g. [3]). For this reason, a monitoring strategy for fire vulnerable structures has not been defined yet.

2 PRINCIPLE OF FBG (FIBBER BRAGG GRATTING) SENSORS

In recent years the use of fibre optic sensors (FOSs) has attracted much attention in research and development as shown in both review and application articles (e.g. [3-8]). The main reasons for this interest are the decreasing price of FOSs as well as the advantages of FOSs over conventional sensors:

a) Immunity to electrical or magnetic interference.
b) Embeddability.

c) Multiplexity.

Of all the types of fiber optic sensors, the use of FBG (Fiber Bragg Gratting) type was decided, for its simplicity of manufacture, installation and inspection. The operating principle of FBG sensor is based on diffraction gratings.

A diffraction grating is an optical device that is created by altering, periodically or quasi-periodic, the refraction index of the optical fiber core.

For Bragg diffraction gratings of uniform period, greater interaction and coupling between modes, the incident and the reflected, occurs at the Bragg wavelength λ_B (Figure 1) which is determined by the equation (1), where n_{eff} is the effective refractive index of the fiber core and Λ is the Bragg grating period or distance between two consecutive alterations of the fiber core [6].

$$\lambda_B = 2\, n_{eff}\, \Lambda \qquad (1)$$

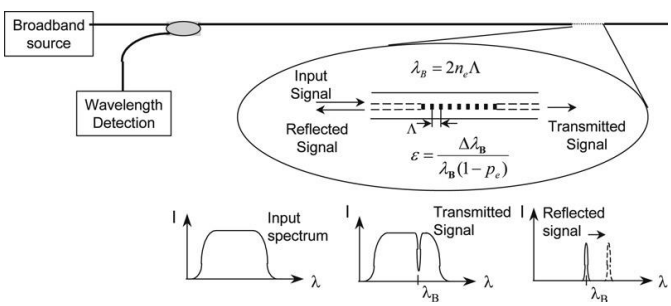

Figure 1: Input Spectrum, transmitted and reflected signal (Ref. [6]).

Both the Bragg grating period Λ and the effective refractive index n_{eff} induced in the fiber core depend on the temperature ΔT and the strain $\Delta\varepsilon$ in the optical fiber. Therefore, they induce a shift in the Bragg wavelength. This shift is given by Equation 2:

$$\frac{\Delta\lambda_B}{\lambda_B} = K_\varepsilon \Delta\varepsilon + K_T \Delta T \qquad (2)$$

K_ε and K_T are the coefficients of sensitivity of the deformation and temperature, respectively.

To measure the strain and temperature, these responses need to be separated and distinguished. For a pure temperature sensor, it is necessary to isolate the optical fiber mechanical deformation. Thus the variation of Bragg wavelength is proportional to the temperature variations (3):

$$\frac{\Delta\lambda_B}{\lambda_B} = K_T\ \Delta T \qquad (3)$$

Standard FBGs experience an important degradation when they are exposed to high temperatures. In fact, conventional fiber optic sensors based on FBGs, which are available on the market, can measure maximal temperatures of 250ºC (482 ºF), except some sensors which can measure maximal temperatures up to 600-700ºC (1112-1292 ºF) (see Table 1).

Type of sensor	Manufacturer	Commercial Name	Temperature measurement range ºC
ThC	JMI	Tipo K	-200 / +1372
ThC	Rosemount	Tipo B	+600/+1700
IT	PCE-Iberica	PCE-890	-50/+1600
FBG	AOS	IndusTemp	-80/+600
FBG	O-eland	OETMS-700	-50 / +700
FBG	FBGS	PT-01	-50/+700
FBG	Micromaterials	Opto Temp200 -	+200 / +950
FBG	Chiral Photonics	Helica Fiber-Optic	+1000

ThC = Thermocouples; FBG = Fiber Bragg Gratting; IT = Infrared Termometer

Table 1: Coventional sensors comparison.

To avoid the fiber degradation, is necessary to increase the refractive index thermal stability. Several techniques have been developed for this purpose. However, even applying these techniques the refractive index modulation decays until complete depletion [9].

A way to overcome this temperature limitation is to use regenerated FBG (RFBGs). To create this sensor, a standard telecommunications optical fiber is needed. The use of standard telecommunications optical fibers to produce RFBGs has an important advantage in terms of sensor simplicity and compatibility over other high-temperature Bragg gratings such as Chiral fiber gratings [10] or sapphire gratings [11], [12].

3 REGENERATED FBG (RFBG).

RFBGs are fiber Bragg gratting that undergo a physical and chemical process to be able to resist high temperatures. To create the RFBGs the fiber is first placed into a hydrogenation chamber at room temperature for 14 days at a pressure of 25 bar. The hydrogen inside the FBG will be the responsible of the chemical and physical transformation that will occur later. The FBGs is inscribed into the hydrogen loaded fiber using a laser. The RFBGs are regenerated in a subsequent annealing process. Finally, the

fibers are placed inside a tubular furnace (regenerated temperature around 950 ºC, 1742 ºF). During this last phase, as the temperature increases, the original FBGs are progressively degraded, untill full erasure and subsequent development of the regenerated grating at a temperature of approximately 950 ºC (Figure 2).

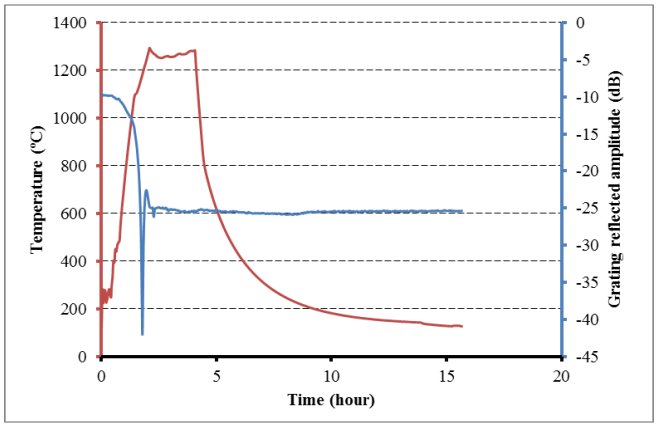

Figure 2: Process of FBG regeneration

In this case, RFBG response is proportional to thermal variation (see Figure 3). Temperature and reflected wavelength have a parabolic relation (Figure 4).

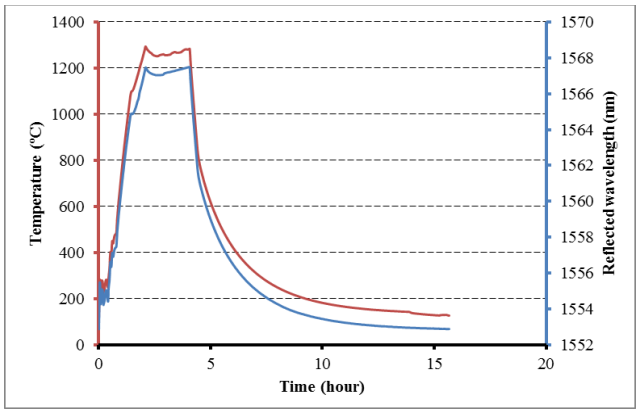

Figure 3Response of the RFBG sensor.

Obtained RFBGs have been tested at temperatures up to 1250 ºC (2282 ºF), and degradation occurs at slower ratio than observed in conventional FBGs. RFBGs than are able to measure continously maximal temperatures up to 1250ºC (2282 ºF) are an important innovation to measure high temperatures. Due to their fragility, fiber has to be protected with a packaging to fix them to the structure. Packaging design and its fixation to the structure is a vital topic in sensors design development.

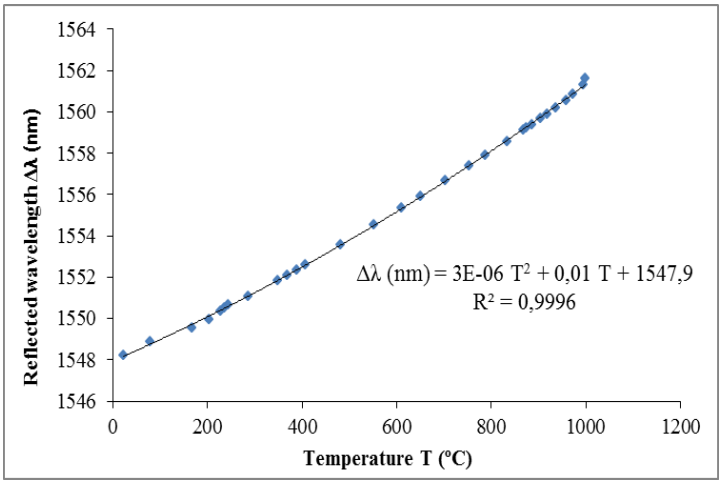

Figure 4: Relation between wavelength and temperature

4 MULTIPLEXED HIGH TEMPERATURE SENSORS.

Fiber optic sensors are proposed due to their advantages compared to electric sensors. For example, they are immune to electromagnetic interference; they have high precision and reliability on the measurements, they have good temporal stability, outstanding resistance to adverse environments and they can be **multiplexed.** In the cases of extraordinary events, such as fire or seismic (which as a consequence frequently build up fire) and terrorist attacks; the capability of fiber optics sensors of being multiplexed results essential to enable a continue monitoring of structures and to evaluate its structural safety. In spite of the outstanding advantages of fiber optic sensors, its availability on the structural monitoring market of structures under fire is null or limited. This is because of the excessive difficulties involved in the development of a monitoring system, compound by fiber optic sensors and cables that connect them which should also be capable to withstand high temperatures.

The company CalSens and the research institute Icitech from the *Universitat Politecnica de Valencia* in Spain have developed a measurement system, that includes multiplexed high temperature sensors, their wiring and their connections, which is **able to measure up to 1250ºC** (2282ºF, Figure 5).

Figure 6 shows the response of a multiplexed optical sensor developed by Icitech and Calsens. There the two different signals of the optical sensors can clearly be distinguished using only one optical fiber cable.

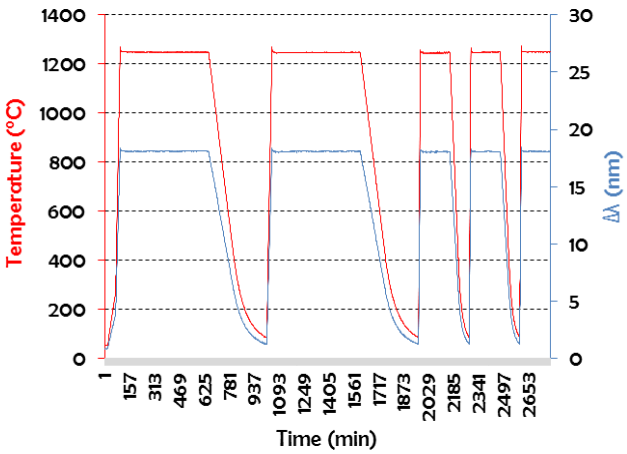

Figure 5. Fiber optic sensor under high temperatures up to 1250ºC (2282 ºF).

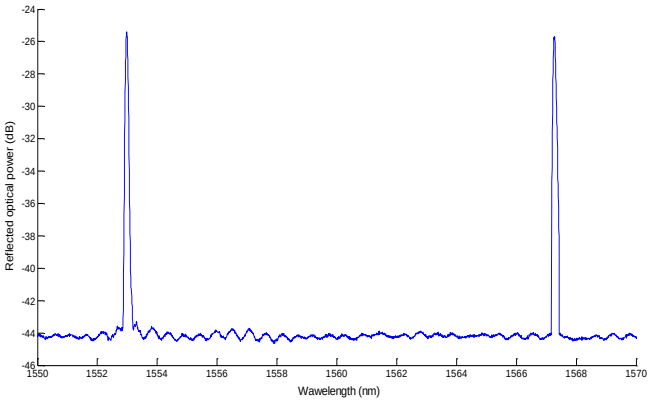

Figure 6. Reflected spectrum of two multiplexed high temperature sensors.

5 CONCLUSIONS.

A new high temperature fiber optic monitoring system which includes multiplexed sensors, wiring and connections has been developed by the research institute Icitech from the *Universitat Politecnica de Valencia* in Spain and the company CalSens. The sensor is based on the use of reganerated FBGs and is able to measure temperatures up to 1250ºC. The monitoring system has undergone very successful testing in harsh conditions. The relation between temperature and wavelength is a second order function with an excellent fit.

This new monitoring system has a wide number of applications in the field of structural safety and structural security, but also in other areas such as green energies (e.g. solar plants) or aerospace engineering**.**

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