

## Monitoring high thermal performance concrete for concentrated solar power plants with fibre optic sensors

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**ABSTRACT:** In this paper a monitoring system for concrete structures at high temperatures (500°C) is presented. The aim of the monitoring strategy based on fibre optic sensors (FOS) is to develop a high-tech monitoring technology for future installation in Concentrated Solar Power (CSP) plants with the purpose of lifecycle analysis and predictive maintenance via structural health monitoring (SHM). The monitoring strategy is based on embedding FOS in high thermal performance concrete while it is casting. The FOS technology employed to monitor both temperature and strain in concrete is known as Fibre Bragg Grating (FBG). In this work, the development of the special metallic coating and smart packaging employed to protect the sensors in this harsh environment, the calibration of the sensors and the thermal validation of the monitoring system at lab scale working in a range of temperatures between 200°C and 500°C is demonstrated. The lab tests were performed over a sample of 30x30x30cm, composed of 2 different layers and 4 tubes of steel, the core is made with concrete specially manufactured to have a very good thermal behaviour, and the second layer is for the insulating, and it is formed by foam concrete. The FBG sensors were positioned longitudinally, parallel to the tubes by drill holes on the casting structure at 14 different positions. The concrete curing process and some different heating cycles up to 500°C, simulating the thermal behaviour of CSP plants, were monitored using the fibre sensors.

### 1 INTRODUCTION

Nowadays, structural health monitoring is a fundamental tool in different fields such as energy generation, civil infrastructures or industrial sector, among others. Particularly, SHM systems based on FOS have been employed with good results for years to monitor different structures, highlighting the monitoring of bridges, tunnels, power plants or pipelines, Lopez-Higuera et al. (2011). The renewable energy industry is another area where the employment of these systems has been increased during the last years. There are solutions to monitor different working parameters or structural parts of wind turbines, e.g. Schroeder et al (2006), or to monitor the temperature profile of down-wells in geothermal power plants like in the study of Reinsch et al (2013). Inside renewable energy, solar energy has experienced high growth during the last 10 years, especially in the case of CSP plants. It is believed that solar energy will be one of the most relevant energy sources of the 21<sup>st</sup> century. CSP plants concentrate the heat of the sun with lenses and mirrors, then this heat is employed to raise the temperature of a fluid used to produce the steam necessary to move the turbines that generate the electricity. CSP technology presents a great advantage over other technologies like solar photovoltaic. It is possible to generate electricity even when the rays of the sun are not directly focused over the mirrors, for example in conditions of some clouds blocking the sun, after sundown or in the early morning. This is via the thermal energy storage system employed, where the heat transferred by the sun to a fluid



is stored using different approaches such as the selection of materials with high thermal performances that guarantee adequate temperature levels enabling the correct performance of the turbines. Another option is the use of solar molten salts like Kuravi et al (2013). This solution has been tested keeping a CSP plant working during all night. Even though the use of CSP plants to generate electricity have lots of benefits, nowadays there are still some areas to which great research efforts are devoted to improving their final performance. One of them is the employment of new materials with very good thermal performances, not only that, but they also must preserve a good agreement between their efficiency, their durability and their associated cost. Concerning this, NEWSOL project addresses the specific challenge towards high-efficiency solar energy harvesting by advanced materials solutions based on innovative thermal energy storage media for CSP.

## 2 THEORETICAL ASPECTS

During the last years, the monitoring of concrete structures has been an extensive area of research. There are two main reasons for it. The first one is that the hydration and hardening are the processes of curing in which the concrete gains its strength. They are very related to concrete temperature, so monitoring the temperature during these processes, it is possible to estimate the strength of the concrete. On the other, continuous monitoring of the concrete lets to know the temperature and loads that it is suffering in real time, allowing to take the necessary actions if cracks or defects appear in it. Lots of sensing technologies based on different approaches have been employed with these purposes. One of the most employed monitoring solutions is based on the use of classical electrical sensors, such as thermocouples or strain gauges. Nevertheless, there is an alternative monitoring solution known as optical fibre sensor that has lots of different advantages in comparison with traditional sensors, highlighting their immunity to electromagnetic fields, or their capabilities to measure different magnitudes like temperature, strain, or pressure with the same sensor. FBGs are the most advanced and employed fibre optic sensors for structural health monitoring. Their operation is based on the alteration of the refractive index of the core of the optical fibre via the use of a high-power laser. This periodic refractive index variation reflects a wavelength through the so-called Bragg diffraction phenomenon, and transmits all others, acting as an optical filter in transmission. Since strain and temperature variations affect the period and refractive index of the FBG, the reflected wavelength also changes. Recording these wavelengths variations, it is possible to translate into temperature or strain variations. These data can be analysed using data analytics solutions trying to detect failures in the structures. In this way, it would be possible to estimate the lifecycle of the structures and to enable a predictive maintenance service via the employment of machine and/or deep learning approaches that automatize the decision making of the monitoring system.

Maybe, one of the biggest problems of optical sensors is that optical fibres are fragile, so a coating is employed to protect it. Typically, this coating is made with acrylate, provoking that the maximum temperature that they can withstand is less than 100°C. For applications at high temperatures, it is needed to use metalized coatings, enabling to monitor temperatures up to 600°C. In this case, to protect the FBG sensors during the embedding process, Nickel coatings were applied on the cladding fibre made through sputtering and electroplating processes described by Grandal et al (2018). Also, the Ni coating provides robustness to the FBG for a better and safe embedding into a harsh environment like concrete structures.

### 3 EXPERIMENTAL RESULTS

In order to validate the feasibility of fibre optic sensors to monitor the performance in terms of temperature and strain variations in a high thermal performance concrete specimen when it is at high temperatures (500°C), 22 FBGs were embedded in it during its manufacturing process. The composition of this high thermal performance concrete was specifically designed to withstand high temperatures, due to it is thought to be employed to store the heat of fluids on a CSP plant, which is one of the innovations that are developed in NEWSOL project.

The sample was made up of two different components, the core and the insulating layer. Each one of them was formed by a different type of concrete, the first was made with high thermal performance concrete and the other with foam concrete. The dimension of the core is 150x200x300mm, and the insulating layer 300x300x300mm, surrounding the core. Moreover, 4 steel tubes of 400mm long and 34mm of diameter were embedded along the core, simulating the pipes employed to propagate the heat of the fluid through the structure. The design of the specimen is depicted in Figure 1, where frontal A) and top B) views are detailed. Moreover, in part C) of this figure, it is shown the location of the sensors in both concrete layers. In this study, the most relevant information is provided by monitoring the behaviour of the high thermal performance concrete, and according to this, most of the embedded sensors are in the core of the specimen, as shown in the figure. The location of sensors was selected trying to maximize the relevance of the measured data when the thermal cycles were performed. The purpose of the selected points was to monitor the temperature profile of the concrete and also the temperature changes in the interface between the different layers. According to this, 14 different locations were monitored, separated in 10 points for the core and 4 for the insulating.

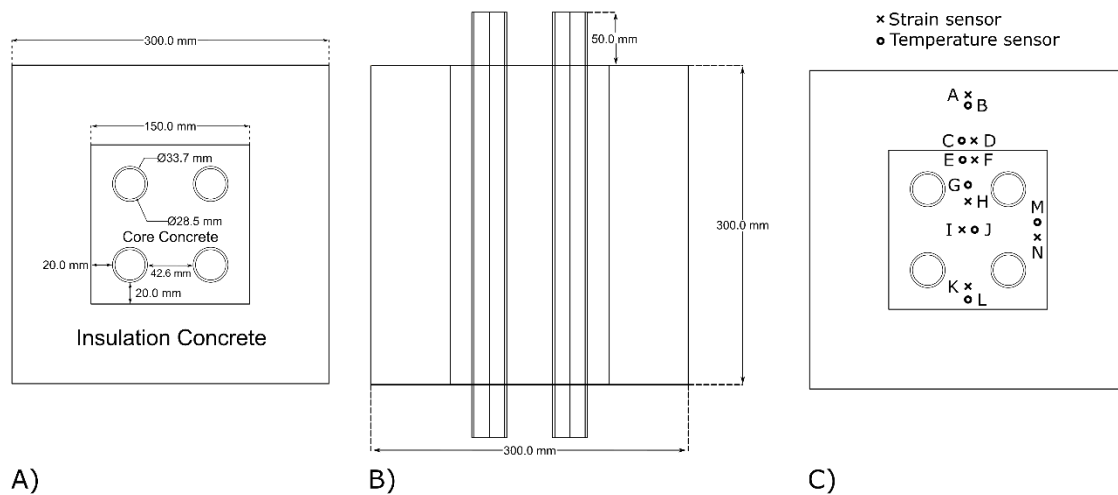


Figure 1. Design of the concrete specimen. A) Frontal view. B) Top view. C) Sensors location.

To monitor the sample, different configurations of sensors have been employed. All sensors are femtosecond FBGs coated with Ni, the difference between the temperature and the strain ones is that the firsts are encapsulated on 316 stainless steel capillary tubes, making them insensible to strain variations, while the others are directly in contact with the concrete, without using any encapsulation. Strain sensors depend on both temperature and strain, so temperature references are necessary to calculate the strain. One of the advantages of the FBGs is that it is possible to multiplex various sensors in only one optical fibre. According to this, some monitoring locations of the specimen have sensor arrays formed by 2 or 3 FBGs in the same fibre, the others only have one FBG. In this last case, the FBG is in the centre of the long axis of the core,

meanwhile, when arrays are employed, sensors are equally spaced. All sensors belonging to the same array are only used for one type of measurements. The total number of embedded sensors was 22 at 14 different locations of the specimen, 11 of these sensors were employed to monitor temperature and the other 11 to monitor strain. The temperature sensors have a double purpose, to determine the temperature of the concrete, and to use them to eliminate the temperature variations that the strain sensors suffer, allowing the strain calculation. This is the reason why the locations are in pairs and very close.

The specimen was manufactured in two separated steps, first the core with the tubes and its corresponding sensors, and after 24 hours, once it was dry, the insulating layer of foam and the remaining sensors. During the casting, the sensor at F position was broken, losing the opportunity to monitor it. Therefore, the final number of monitoring sensors was 21.

Although the aim of the manufacturing of this sample is the characterization of the response of the embedded sensors at high temperatures, since the sensors had been already embedded in the concrete layers, the curing process was monitored during 28 days for the most relevant sensors. Due to the reduced number of channels of the interrogator employed, it is not possible to monitor all the sensors at the same time. Considering the above and knowing that strain sensors contain the most relevant information, all the strain FBGs embedded were monitored during the whole curing process. On the other hand, temperature sensors were monitored partially, some of them were recording the data only during the first 24 hours, because of the specimen was built in two phases, and some channels of the interrogators were still free for monitoring, but when the second concrete layer was manufactured, some of these temperature sensors were disconnected to connect the sensors of this new layer to monitor the response of the insulating.

In Figure 2 it is represented the measured response, strain and temperature FBG sensors respectively, during the complete curing process (28 days) of the foam insulating concrete layer of the specimen. Also, a zoom version of the figure representing the first 80 hours of the curing, which represent the hydration and hardening, is depicted for each one of the measurements. In these zoomed graphs it is easy to see the increase in the strain and temperature levels during the first hours, due to the hydration process of the concrete while the setting is happening. The temperature evolution was not completely monitored, it started after some hours when the temperature was already decreasing slowly to the room temperature. In Figure 2, it is possible to detect that the sensors show different response for each location. The sensor at position A suffers more strain than the other in D, this is due to the D sensor was close to the border of the two different layers, meanwhile, the A sensor is embedded in the middle of the piece.

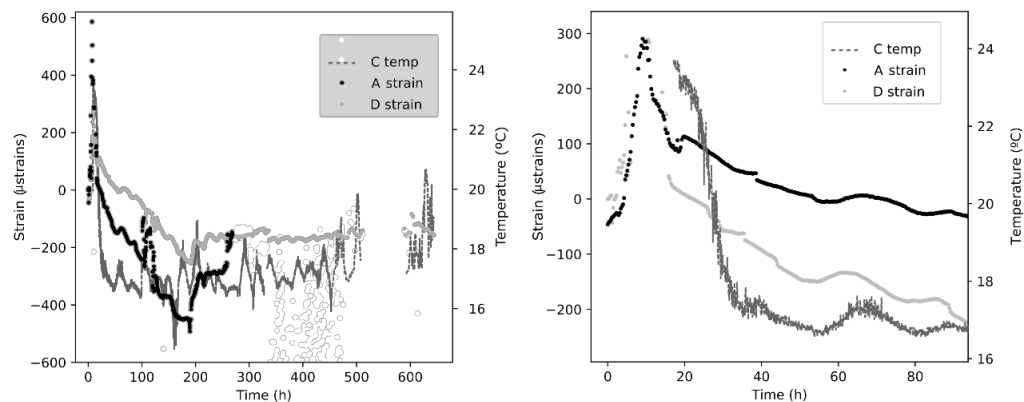


Figure 2. Response from the FBG sensors embedded in the foam concrete of the specimen. (left) Response for 28 days. (right) Response during the first 80h of the curing process.

The next figures, Figure 3 and Figure 4, show the same strain and temperature monitoring of the curing process than before, but for the sensors embedded on the core of the specimen. Also, the firsts 80 hours of the curing process are depicted in zoom graphs. As appears in the previous results, during the first hours, when the setting of the concrete is happening, the temperature and the strain responses increase quickly, and when the exothermic process finishes, the response of the sensors start to return to room temperature. Moreover, after 24 hours, it is possible to see that this phenomenon appears again producing another peak on the response of the sensors, being more evident in the temperature ones. This is due to the second phase of the manufacturing process, related to the manufacturing of the insulating layer, which was built 24h later around the core. All sensors show a comparable behaviour, as expected, being the relative variations of the sensors of the same type very similar among them. The strain response of the FBGs represented in Figure 3 is quite noisy at the beginning of the monitoring, but it is possible to estimate that the relative strain variation for all sensors between the beginning and the end of the curing process was around 70-100 $\mu$ strain.

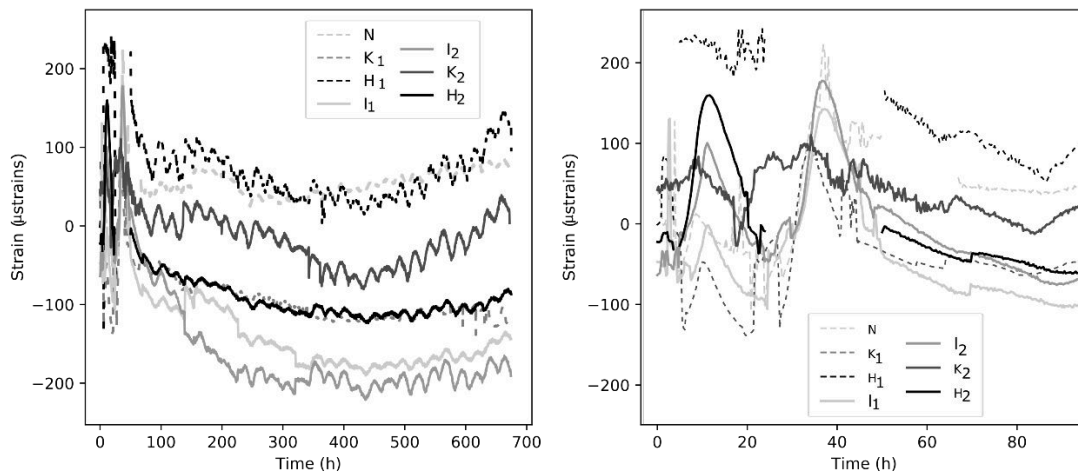


Figure 3. Response from the strain FBG sensors embedded in the core concrete of the specimen. (left) Strain response for the 28 days. (right) Strain response during the first 80h of the curing process.

In the case of temperature sensors, the profiles are clearer, showing a variation around 6-9°C during the hydration of the core concrete, but when the second stage is built in, the increase was around 10°C, which means that the exothermic reaction for the foam concrete during the hydration process is higher than for the core concrete. In this case, to have a better resolution of the temperature gradient, some of the temperature FBG sensors are multiplexed, like the G and L position sensors. They have two and three FBG sensors, respectively, multiplexed in the same fibre forming two array sensors. In Figure 4, it is possible to notice that one sensor of each array differs from the rest around 3°C, this is explained taking into account that the arrays are located along the longitudinal axis of the core, doing that the sensor with different response is close to the end of the concrete being more influenced by the changes on the room temperature. This means that the temperature and consequently the strain around this “small” sample is no homogeneous, causing strain differences along it, which could lead critical points that may provoke cracks or failures in service. Also, in these graphs, it is observable the wave-shape fluctuations that the sensors suffer after the first 48 hours due to the room temperature difference between the days and the nights.



After the 28 days needed for the curing process, the thermal characterization at high temperatures was performed. With this purpose, the specimen was tested with different heating cycles, trying to replicate the final and real conditions for which this kind of concrete is thought.

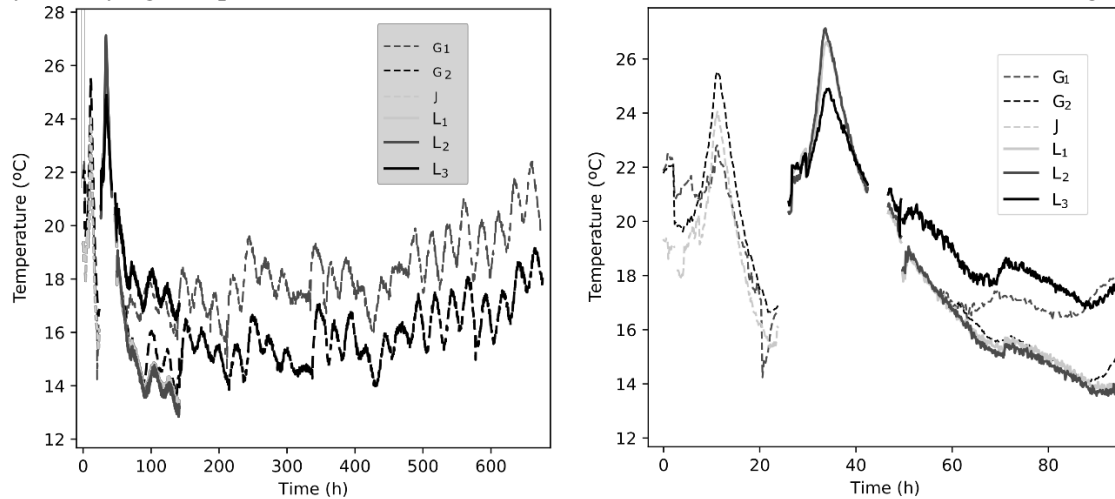


Figure 4. Response from the temperature FBG sensors embedded in the core concrete of the specimen. (left) Temperature response for the 28 days. (right) Temperature response during the first 80h.

Two kinds of heating cycles were made. The first cycle was made slowly from room temperature to 700°C, in order to get the dehydration of the concrete and avoid the collapse of the piece during the fatigue cycles. Taking advantage of the tubes embedded on the core, the specimen was heated by Joule's effect through them. Both ends of one of these tubes were connected to a current source, heating the metal, and therefore, all the specimen. The selected tube for performing the thermal test was the one placed at bottom right in the design of Figure 1. This approach was chosen due to the real application where this concrete is going to be employed. The embedded pipes will be heated by hot solar salts passing through them, and therefore, all the concrete will be heated. Then, we can monitor the temperature at different positions analyzing the response of the FBGs.

The first heating cycle was very slow due to the remaining water that could be inside the specimen (dehydration), and it had to be evaporated gradually to avoid the possibility that cracks appeared or even the collapse of the sample. Moreover, a slow heating cycle enabled that the shrinkage of the concrete would be minimized. According, the following thermal heating cycle was applied to the specimen: increasing from 20°C to 80°C in 12 hours; maintaining constant for 6 hours, raising to 110°C in other 6 hours; raising to 290°C in 12 hours; stable for 6 hours and finally 12 hours more to reach the desired temperature of 500°C. When the desired temperature was reached, the temperature was progressively increased up to reach near 700°C when the process was stopped. Due to limitations on the programming of the machine employed to heat the tube, the total time needed to finish this first heating cycle was 170h. The temperature control of the heating cycles was done with thermocouples located inside the heated tube and connected to the machine. The measured responses of the fibre sensors, both temperature and strain, are depicted in Figure 5 for this first thermal cycle. For a better understanding of the obtained results, only the most relevant positions of the sample are represented. The temperature response of the sensors follows the expected profile configured on the thermal machine, obtaining higher temperatures the ones located on the core of the specimen, between 650°C to 680°C, than the ones at the insulating concrete, which only reaches around 170°C. With respect to the strain measurements, it is possible to see that the response of sensors located at position A

and D start to fall when the temperature was around 200°C, after 75 hours from the beginning of the cycle. This fall is explained taking account that when this first cycle started, the top face of the insulating concrete had a small superficial crack very close to these sensors. As the temperature started to rise, the crack also increased and therefore the sensors were released from concrete. When 120 hours had passed, there was a power failure of the heating machine, provoking a decrease in the temperature of sensors. The other sensors had a response in accordance with the expected, showing an increase in their strain levels as temperature increased due to the deformation of the concrete. The maximum temperature and strain were measured for the L and H positions. It is remarkable that during this first heating cycle there is no significant change in the response of the sensors which could be related to the end of the dehydration process.

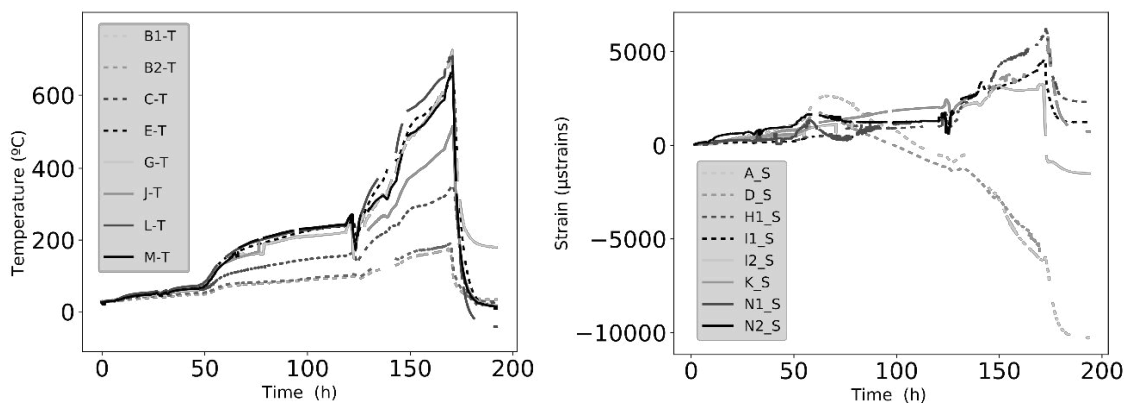
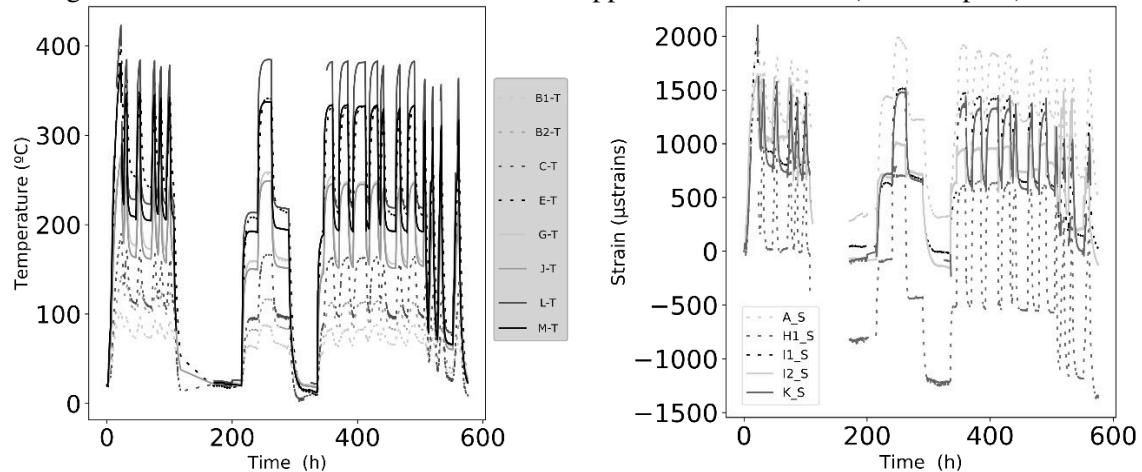


Figure 5. FBG response during first heating. (left) Temperature response, (right) strain response.

To conclude the thermal characterization some thermal fatigue tests were made. The tests were divided into three different stages, all of them setting a maximum temperature of 500°C. The first stage of the cycles was based on heating the tube from 20°C to 500°C, and when the temperature is reached, starting to decrease it to 290°C. At this point, 5 consecutive cycles of heating and cooling from 290°C to 500°C were scheduled. This stage is easily recognizable in the graph, showing 6 consecutive peaks of heating and cooling. The time needed to go from 290°C to 500°C was around 5-6 hours. After this first stage, the temperature of the specimen decreased to room temperature, and then the second stage was launched. It was only one heating and cooling process, from 20°C to 290°C, maintaining stable for 20 hours, and continue rising to 500°C, another 20 hours and then the cooling to 290 first, and to room temperature to end. Finally, the last stage is composed of a temperature cycle from 20°C to 500°C and returning to 290°C. At this point, cycles from 290°C to 500°C are repeated 10 times, varying the duration that the temperature is stable. At the end of these thermal cycles, the test was finished, returning to room temperature. The response of the sensors in these thermal cycles is represented in Figure 6. The temperature profiles measured with the FBGs show the same temperature changes than the applied to the specimen. One important detail is the difference in temperature between sensors, reaching higher temperatures those sensors closer to the heating tube, being the highest temperature, around 400°C for L sensor. Also, there is a clear thermal difference between the sensors embedded into the core and those embedded into the insulating layer, that does not reach 200°C. The other part of Figure 6 represents the deformation (dilatation and contraction) that the specimen suffered when it went through temperature changes. In this graph, the results show a similar behaviour between all the sensors, increasing their strain when the temperature was increased, and reducing when it is cooling. There is one exception, the sensor located at H

that suffers a decrease in its strain level just after the first decreasing to room temperature. This change in the strain level could be related to the appearance of a defect (crack or pore) near it.



6. FBG response during the fatigue tests. (left) Temperature response. (right) Strain response.

#### 4 CONCLUSIONS

A monitoring system based on fibre optic sensors for concrete structures at high temperatures (500°C) has been demonstrated. The monitoring technology employed is based on the use of femtosecond Fibre Bragg Gratings written in optical fibres coated with Ni. The results show the possibility of employ these sensors embedded in concrete to monitor both temperature and strain, measuring during long periods of time temperatures around 400°C. With these thermal cycles, it has been demonstrated the feasibility of employ these sensors embedded in real structures of concentrated solar power plants, like thermocline tanks of molten salts used for heat storage. Through the analysis of both temperature and strain data, it would be possible to analyse the purpose of lifecycle analysis and predictive maintenance via SHM.

#### ACKNOWLEDGEMENTS

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