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THE MONITORING OF BARCELONA'S SAGRADA FAMILIA CHURCH WITH FIBER OPTIC TECHNOLOGY. CONTROL OF THE CONSTRUCTION OF A NEARBY TUNNEL.

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In this document we will present the performed implementation in the Sagrada Familia, using fiber optic sensors for the monitoring and control of the strains the construction of a nearby tunnel may cause. We will describe the characteristics of the performed sensorization, the data acquisition and processing and the results obtained during the tunnel's construction.

The first aim of the monitoring with fiber optic was to control fissures, joints and other elements in various areas of the structure during and after the passage of the TBM. The implementation was performed with long-base fiber optic sensors and optic extensometers which use the light intensity variation principle for the measurement and dynamic and static behavior.

1 DESCRIPTION OF THE CHURCH

The Sagrada Familia's structure, designed by the famous architect Antoni Gaudí, is Barcelona's symbol and one of the most studied structures due to its complexity, singularity and beauty. The Church is still under construction, therefore it is an interesting example of the evolution of new constructive techniques.

The structure is defined by geometrical figures which interpret in the construction what was observed in nature. In the design Gaudí uses ruled surfaces such as hyperboloids, paraboloides and ellipsoids intersected and connected to each other.

The construction started in 1882 but it was in 1884 when Gaudí took over the works, turning the project into a church of great dimensions.

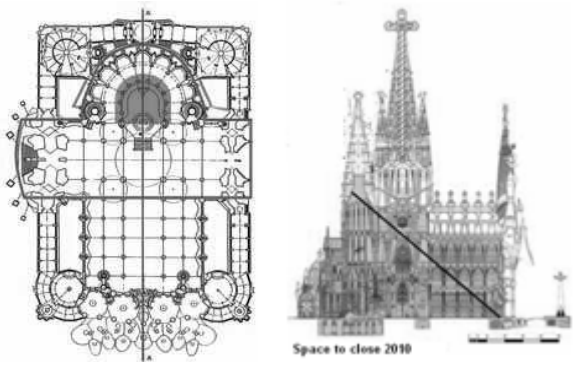


Figure 1. The Sagrada Familia's Plan and Elevation. Source: Archives of the Basilica and Expiatory Church of the Holy Family.

As it can be seen in Figure 1, the Sagrada Familia has a classic plan in the shape of a latin cross with five longitudinal naves and a three-nave transept, an apse and a crypt under the main altar.

In the future there will be three facades, the two lateral ones are already constructed. The structure will be crowned by six big towers. The planned towers can be seen in figure 1 where the parts that have been completed so far are highlighted. In the Elevation we can see that Gaudí planned a maximum visibility for the apse and the central hyperboloid, so that the Pantocrator's figure, which will be located in the interior of the apse's hyperboloid at 70m high, can be seen from the Gloria, the main facade. Using the drawn line as a reference, we can see the dimensions the towers will reach.

The proportionality and visibility imply a constantly high level in the aesthetic aspect regarding the perception of the parishioners and visitants and they turn the church into a very unique work.

2 WORKS IN THE SURROUNDINGS

It was in the surroundings of this unique sector where the Spanish Railway Infrastructures Administrator (ADIF) designed a tunnel for the new High-Speed Railway line. The chosen technique to perform the excavation was the use of a shield or Tunnel Boring Machine (TBM). As you can see in Figure 2, the tunnel goes by Mallorca street, which gives access to the Church from the Nativity Facade.

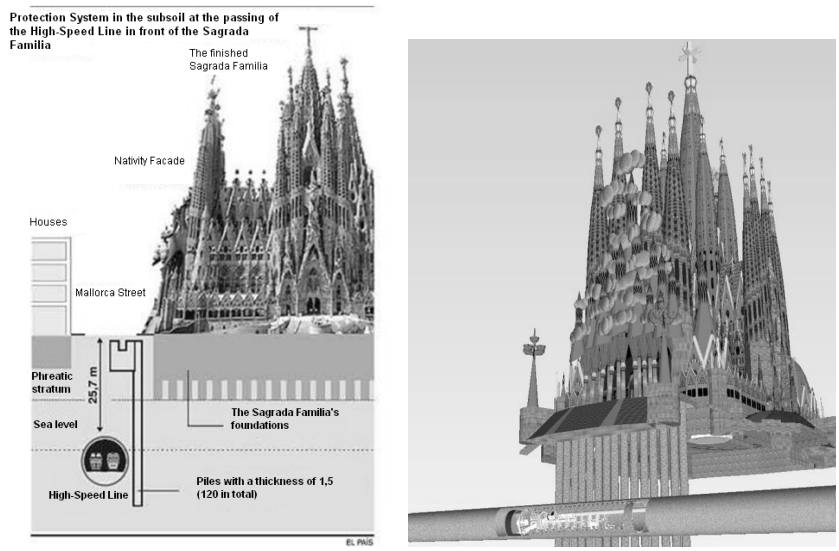


Figure 2. Articles in the press about the works and 3D simulation of the tunnel's passage, facing the executed screen.

The works started in September 2010 and had a great echo in the press, radio and television, due to the doubts about how they could affect the performance and the stability of the Church. In the project there were some already performed design measurements to avoid affecting the structure and the foundations and there was even a pilot screen, carried out before the arrival of the TBM, between the pavement close to the Church and the street under which the tunnel was planned to be excavated.

The Railway Administrator designed and performed an excavation control implementation to detect subsidences the TBM might provoke in the street. The Church was also implemented, both on the outside and the inside by monitored topography systems.

3 IMPLEMENTATION WITH FIBER OPTICS

In addition to the implementation described above, the Sagrada Familia Council, with the UNESCO's advising and collaboration, requested a permanent monitoring during the works, in particular when the TBM passes in front of the church.

The Council wanted to make sure that the monument does not experience any damage and, in particular, that the monitoring is able to detect any structural risk caused by tension accumulation as soon as possible. To achieve this, Euroconsult implemented the Sagrada Familia with fiber optic technology.
The first aim of the monitoring with fiber optic was to control fissures, joints and other elements in various areas of the structure during and after the passage of the TBM. We also thought it was important that the system is modular and that it is possible to extend it with new sensors if it is necessary.

The parameters to measure were microstrains, inclinations and settlementes and it was indispensable to have the information in real time, with high accuracy in the measurement of all the parameters in perfect synchrony, a permanent electric current

and telephone communication assurance, with system redundancy. Also, all the sensors and cables had to be protected and "invisible" to the visitor or tourist.

4 THE INSTALLATION OF THE SENSORS

All the installation had to be carried out in one week due to the proximity of the TBM and that we needed certain time before its arrival without any actions and the control and monitoring system had to have alarm thresholds and the necessary applications to send messages, alarms, relay control, etc.

The monitoring was carried out in the following sections or tasks:

4.1 Continuous recording of movements in the joints of the facade that is nearest to the street under which the TBM was to be excavated

We placed optic extensometers for the continuous recording and monitoring of the joints in the windows and the longitudinal and transverse expansion joints. In Figure 3 you can see the emplacement of the optic extensometers.

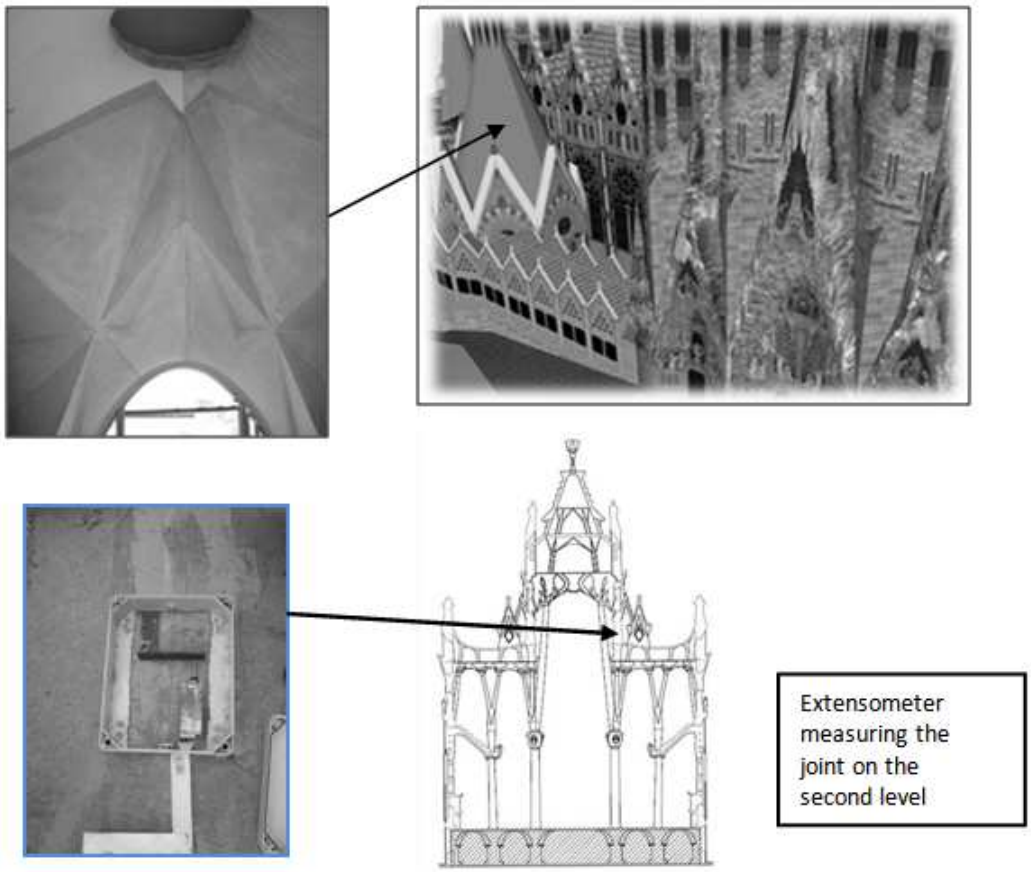


Figure 3. The emplacement of the optic extensometers.

4.2 Monitoring of the union or connection between the oldest zones of the Church (the ones in which Antoni Gaudí directly participated) and the more recent parts

4.3 Continuous measurement in various preexistent vertical fissures in the oldest built zone.

Figure 4. Control of the fissures in the masonry with extensometers and 2m long optical strands.

4.4 Strains in the base of the pillars in the nave crypt

The installation of the Optical Strands for the measurement of strains in the base of the pillars of the nave crypt was carried out in the base of the four main pillars of the Nativity Facade.

Figure 5. Installation of optical strands in the nave crypt's pillars.

4.5 Control of the openings in the pillar heads by extensometers

The extensometers were installed by uniting the four pillars in their head to measure possible convergencies.

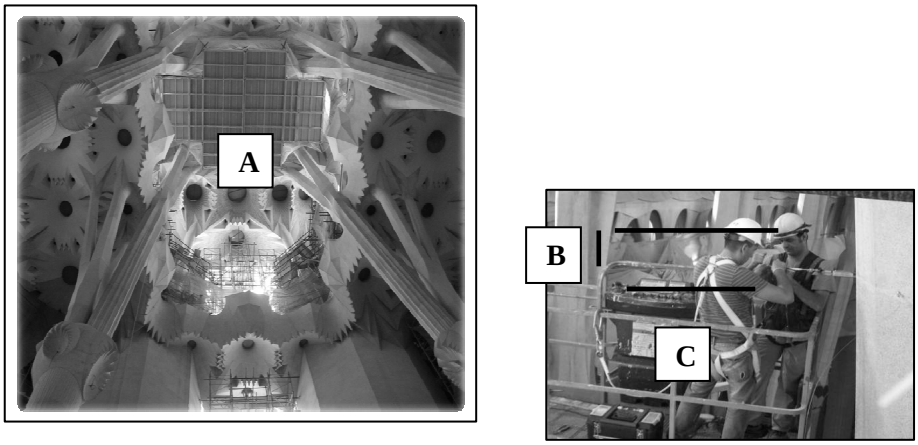
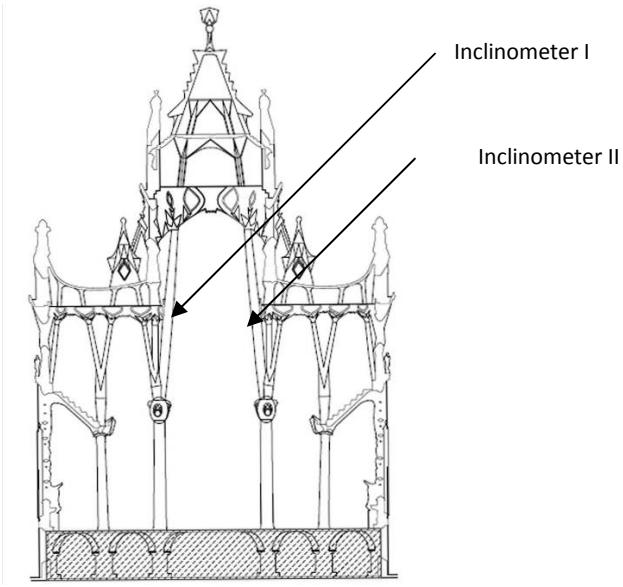


Figure 6. Installation of extensometers for the measurement of convergencies.

As we said, the implementation was performed with long-base fiber optic sensors and optic extensometers which use the light intensity variation principle for the measurement and dynamic and static answer.

The extensometers were used for the control of joints and fissures and also to connect the cables installed for the measurement of convergency in the heads of the pillars.

The installation of the Optical Strands (long base sensors) was performed based on the four main pillars of the facade of the glories, grouping a fissure zone of one of the facade of the glories' four towers and an expansion joint of the facade of the glories.
We also installed inclinometers in the pillars that are coincident with the optic sensors to measure convergencies, a speed sensor and a sensor for the wind's direction in the most suitable accessible location.



Installed sensor

Inclinometer protection

Figure 7. Installation of inclinometers in the heads of the pillars.

The performed installation consisted in the following elements:

1 Optic monitoring station
6 2 m long Optical strands
8 fiber optic extensometers
2 Clinometers
2 Temperature sensors
A speed sensor and a wind speed sensor

5 ACQUISITION AND MONITORING SYSTEM

The results were monitored with permanent alarm and data processing and applications and they clearly showed the Church's behavior during the tunnel's construction. The presentation and alarm establishment system was created for this case and meant a permanent, 24/7 control of all the involved elements with permanent connection to the TBM. However, the monitoring was not designed only for the crossing of the TBM and it continues the controlling even now, since it is integrated to the chruch's installations. For example, we also installed a speed and wind speed sensor to see the actions provoked by it in the structure.

6 OBTAINED RESULTS

As we explained in the previous chapters, the monitoring was centered in the implementation of three fundamental aspects that are represented in figure 8.

1. Measurement of the opening or closing of the expansion joint between the Nativity facade and the rest of the Church.
2. Measurement of the opening or closing of fissures.
3. Behavior of the facade's main pillars.

The objective of this sensor distribution was based on three main objectives to detect any impact the TBM's passage might have caused in the Sagrada Familia's surroundings as soon as possible. In case any subsidence is caused by the excavation it would detect an opening in the joint, more accentuated according to the height of the joint. In addition, it would cause a tension redistribution in the main pillars that would be observed by the convergence between them, the inclination and the increase of the strain in its base. And, utlimately, it would observe an increase in the opening of the fissures

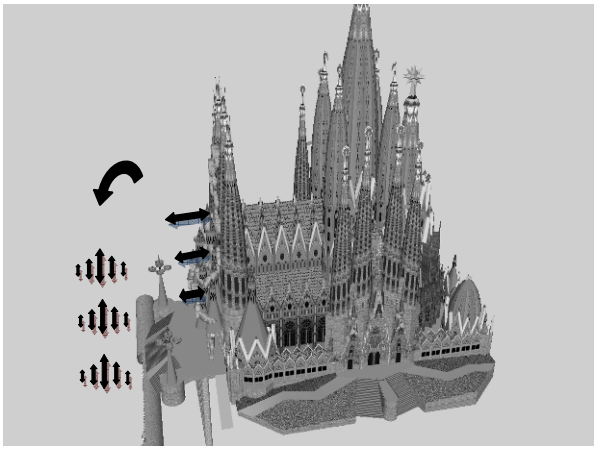
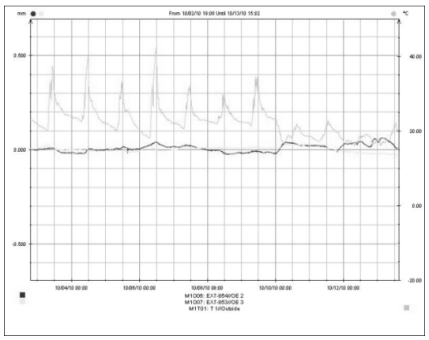


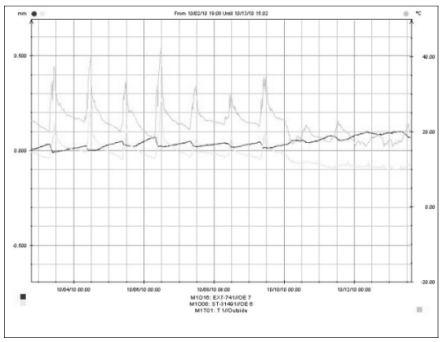
Figure 8. Scheme of the performed measurements.

Observing the obtained records, our conclusion was that the passage of the TBM did not affect the Sagrada Familia's structure. We did not register any variation of the obtained measurements that could be related to the executed works.

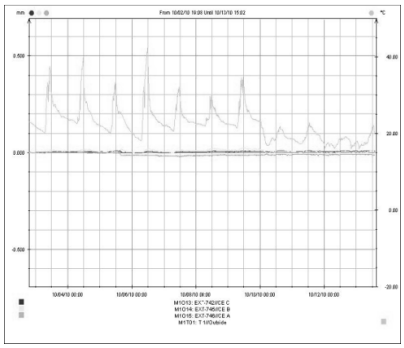
The monitoring also allowed us to confirm that long-term subsidences did not affect the structure and that the pilot screen executed to minimize the possible impact behaved as it was foreseen.



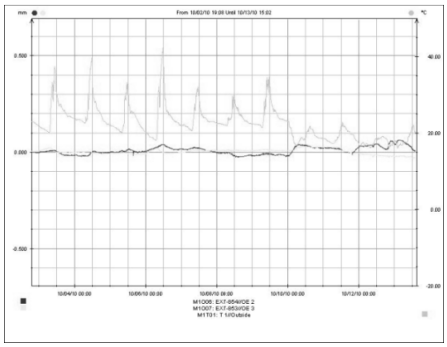
Windows



Fissures



Convergencies in pillars



Second floor joints

Figure 9. Records obtained in the optic sensors during the previous days, the days of the passage and the days following the TBM's excavation. We can also see its variation with temperature.

7 CONCLUSIONS

The very high precision of the optic sensors made it possible to confirm that the Sagrada Familia's structure was not affected by the works.

Also, now we have an initial state of strain before the tunnel's construction that will allow the control of the structure, in case there are long-term variations and other impacts that affect its state.

8 REFERENCES

Buxade C. y otros, junio 2010. *Proyecto y construcción del cierre del ábside de la Sagrada Familia. Design and construction of the apse on the ‚Sagrada Familia"*. Hormigón y Acero Volumen 6, nº 256.