Measuring vertical strains and temperature with fiber optics in diaphragm walls

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ABSTRACT:

The Geotechnics Division of the Flemish Government uses fiber optics in civil constructions to measure strains and temperature during construction. In the summer of 2016 the construction of a tunnel under an existing road started. In a first phase diaphragm walls were constructed. Those walls will keep the tunnel open during excavation and will function as the future walls of the tunnel. For safety reasons the deformation and stability of these walls are closely monitored. During construction of the diaphragm walls, fiber optics were attached to the reinforcement cage. The fiber optics runs on both sides along the complete depth of the wall. This emplacement allows to monitor the vertical strain and temperature changes during the different construction phases. An inclinometer tube is placed in the diaphragm wall in the vicinity of the fiber optics. This allows the researchers of the Geotechnics Division and the KU Leuven Technology Campus Ostend to closely monitor both the forces in the wall and the horizontal displacement of the wall. When these exceed the allowable limits, corrective actions can be undertaken. This paper presents both the practical aspects of installation and some preliminary results.

1 DESCRIPTION

1.1 Project Aalst

The project described in this paper is the construction of a tunnel under an existing crossroad in the city of Aalst. Before the excavation of the tunnel diaphragm walls are installed. It was an opportunity to experiment with different fiber optics installation methods in these diaphragm walls. The purpose of the fiber optics is to monitor the derived bending moments in the diaphragm wall. Some fiber optics were connected directly to the reinforcement cage. Other fiber optics were placed afterwards in hollow rectangular steel tubes, which were connected to the reinforcement cage. The challenge was to install the fiber optics in a way the fibers would survive the installation process of the diaphragm wall. Moreover the installation of the fiber had to be done in a minimal time.

An inclinometer, a second monitoring system, was placed in the diaphragm walls. The inclinometer measurement is done in inclinometer casings which are placed inside the steel tube and over the complete depth of the diaphragm wall. The inclinometer measures the horizontal displacement along the full height of the diaphragm wall.

It is the purpose to combine and compare the results of those two monitoring methods.

1.2 Fiber optics cables

Several sections are instrumented with fiber optic cables. For the first instrumented sections, "sensoLuxTM" fibers of the company "Cementys" were used (see Figure 1). This cable has some advantages and disadvantages (see table 1). Two single mode (SM) cables, with a core of 9µm are used to measure strain. Two multimode (MM) cables, with a core of 50µm are used for the temperature measurement.

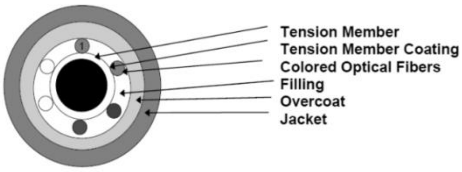


Figure 1. Cross section cementys sensoLuxTM (Cementys, 2014)

Table 1: Advantages and disadvantages Cementys sensolux Tm

Advantages	Disadvantages
+ There are 2 types of fiber inside. Multimode fiber (MM) and single mode fiber (SM), allowing both BOTDA and RAMAN measurements on the same cable + The fibers are glued inside the coating, leading to a good transfer of the movement and temperature. + The cable is easy to strip and splice + fairly low cost/m	– The cable is susceptible to brittle breaking – The fibers appear to rotate inside the cable – There are no loose fibers. Temperature measurements can therefore only be done with the RAMAN technique.

2 FIBER OPTIC INSTALLATION

During the installation of the fiber optics (FO) in the diaphragm wall, some practical difficulties had to be overcome. Firstly, because of the length of the diaphragm wall, the reinforcement cage exists of 2 elements, which need to be connected halfway installation. This made it impossible to fix the cable beforehand to the reinforcement cage, as we learned from the past that no splices should be made at an inaccessible location. Secondly it was not allowed to have a large time delay due to the installation of the FO. Thirdly the upper meter of the concrete of the diaphragm wall always has an inferior quality and has to be shot off and replaced, which could damage the FO. Keeping these difficulties in mind two different installation methods were used.

Both methods were used in the first instrumented section of the diaphragm wall. Fiber optic OV1 was connected directly to the reinforcement cage and had a free loop at the bottom of the lower cage. The fiber was held close to the cage with small guiding tubes, which were fixed to the cage every 2m.

Fiber optics OV2 and OV3 were placed in 2 rectangular hollow steel tubes, which were fixed to the reinforcement cage at both sides of the diaphragm wall and along the total length of the reinforcement cage. After the replacement of the upper part of the concrete, the FO were installed in these tubes. This method is more robust than the previous method, as the shooting of the concrete forms a large risk of damaging the cables. To allow pre-stressing of the fiber, the cable was attached to a metal weight, which was lowered in the tube. At the bottom, the fiber has again a free loop. After pre-stressing the fiber, the tubes were carefully filled with grout from bottom to top. In one of the rectangular tubes, an inclinometer was placed centrally in the tube. The main disadvantage of this method is that the coupling of the rectangular tubes, fixed to the 2 parts of the reinforcement cage, caused a 2 hour time delay during placement. Another disadvantage is that the fiber can only be placed after the replacement of the concrete, and a small part of the excavation (executed before the replacement of the concrete) could not be monitored.

In the second instrumented section of the diaphragm wall, only the first installation method (OV1) was used. This method was the most rapid and the cable of OV1 survived the placement, which was the largest concern. However, as there were some unexpected and inexplicable peaks of strain in OV1 after installation, two different guiding methods of the fiber were used for this installation: one FO was mounted on the cage without any guiding tubes between the top and the bottom fixation (OV5), the other FO has guiding tubes every 60 cm (OV4). An inclinometer will be installed in a separate hollow metal tube, in the vicinity of the FO cables. To gain insight on the development of the strain peaks, several measurements were made during the installation.

2.1 Preparation and installation

All the FO cables where carefully prepared in the office. The preparation is an important part of the installation process. A small mistake can cause a failure during installation on site. First, the exact length of the cable must be determined. The required length is influenced by the necessary pre-stressing, the free loop at the bottom and the free sections, needed to reach the analyzer. Protection tubes need to be placed over the sensitive areas and over the free lengths. During preparations, the small pieces of guiding tube, used to keep the fiber close to the cage, are placed over the fiber. Furthermore, the connection points (the part of the fiber which will be fixed to the cage) were glued in a protection tube with a length of 20cm and pigtails are spliced to simplify the connection with the analyzer.

2.2 OV1 – 4 – 5

OV1, 4 and 5 are placed with a similar installation method. The size of the reinforcement cage (+/- 24 m), which is divided in two parts, can differ slightly from cage to cage. When the cages were constructed, the exact lengths were measured and all the points that were necessary for the installation on the field were marked:

- The free loop at the bottom of the cage
- The 2 points where the cable will be anchored at the bottom of the cage
- The length of the pre-stressed fiber
- The top of the 1st cage and at the bottom of the 2nd cage (used to account for the overlap of the cages during installation)
- A zone at the top of the top cage where the 2nd anchor of the fiber will be fixed (exact location depends on the overlap of the cages).

The reinforcement cage is made out of vertical and horizontal rebars. The free loop of the fiber is always placed on the 2nd horizontal rebar, starting from the bottom. This loop, which is located in the center of the cable, is protected with 2 rubber tubes (see Figure 2a). At the end of the loop the fiber is brought from horizontal to vertical at both sides. At this location the FO is fixed to the cage (see Figure 2d). To be able to fix the FO to the cage, without damaging the cable (micro-bending and pressure), the FO is tightly glued into the inner protection tube over a distance of +/- 10 cm. Clamping rings are used to quickly fix the reinforced part of the fiber to the cage. Because the vertical bars are laying inwards a dummy bar was installed to avoid local discontinuities (see Figure 2d). The 2 markers at the top of the first cage and the bottom of the second cage are necessary to compensate for the overlay of the 2 cages. The difference between the theoretic and the real overlap distance is required to determine the exact location of the anchor point at the top.

a b c d e

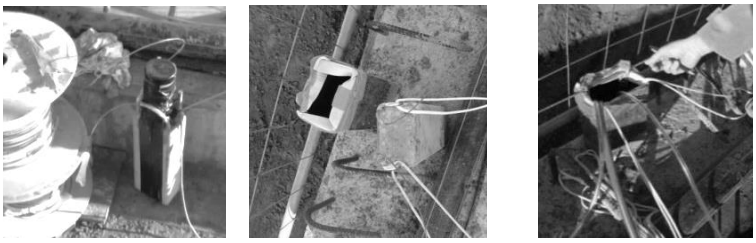
Figure 2. Pictures of the installation details of OV1: a) loop; b) guiding tube; c) protection at the top; d) fixed anchor point at the bottom; e) fixed anchor at the top (hook)

At the end of the -to be- pre-stressed part, the fiber is again tightly glued in a protection tube. A hook is glued at the outside of this tube, allowing to pre-stress and hook the cable to an iron band with holes which is connected to the cage (see Figure 2e). A measurement is made to check the pretention. Thanks to this flexible hook-system, it is possible to easily change the amount of pretention if required. After verifying the pretention, the tube is fixed firmly to the cage with cable ties. From that point on, the cable is again unstrained, and a very firm protection tube is used to cover the cable over its full remaining length (see Figure 2c). This extra protection is necessary as the top part when the concrete will be removed. It is the pre-stressed part of the cable that will be used to determine the bending moments in the diaphragm wall. Temperature measurements are made to be able to compensate the strain readings of the Brillouin Optical Time Domain Analysis (BOTDA) measurement, which is also temperature sensitive. The differences between OV 1, 4 and 5 is the connection of the pre-stressed part of cable with the cage. the guiding tube is used for OV1 every 2 meter, for OV4 every 60cm and no guiding tubes were used for OV5. The cable can move freely in these guiding tubes, which are fixed to the rebars. For this connection small hard rubber tubes are used (see figure 2 b).

2.3 OV 2 – 3

A different installation method is use for OV 2 and 3. This method is less prone to damage, as the placement is postponed till after most work at the diaphragm wall is finished. They are installed in a hollow rectangular steel tube (100 to 150 mm²). The hollow rectangular tubes are connected to the reinforcement cage before installation. The advance of this method is that the installation of the fiber takes place after the construction of the diaphragm wall and crunching of the concrete.

Again, the first step is to prepare the fiber. To allow pre-stressing of the fiber after installation in the hollow rectangular tube, the cable was attached to a metal weight (accounting for Archimedes uplift and pretention force), which was lowered in the tube (see Figures 3a and 3b). At the bottom, the fiber again has a free loop, which is incorporated in the metal weight. Because of the rectangular shape of both the weight and the tube, the cable cannot rotate or twist during the installation. The weight is lowered in the steel tube with assisting ropes, which are also used to descend the grouting pipe. At the top end of the fiber the same system is used as in the first method, where the cable is glued in a short protection tube and a hook is fixed to this protection tube. OV2 differs from OV3 as an inclinometer was placed in the same rectangular tube. The anchor tube of the inclinometer tube was connected to the metal weight (see Figure 3a). As for all inclinometers placed in grout, the Archimedes force must be carefully compensated by filling the tube with water and adding extra weight at the bottom until the grout has hardened out. After pre-stressing the fiber, the tubes were carefully filled with grout from bottom to top (see Figure 3c).



a b c

Figure 3. Pictures of the installation details of OV2 and OV3: a) metal weight for OV2; b) metal weight for OV3; c) OV3 before grouting

3 DETERMINATION OF TEMPERATURE AND STRAIN COEFFICIENT

3.1 Temperature compensation

The BOTDA measurement results in a frequency in GHz, which is strain and temperature dependent. As the main interest is the strain variation, a temperature compensation is required. When knowing the temperature along the fiber, the temperature coefficient C_T and the strain coefficient C_ε, the strain can be calculated according to equation (1) with v_b the Brillouin frequency, ε the strain and ΔT the temperature difference. The determination of the temperature and strain coefficients is explained in 3.2 and 3.2.

The temperature can be determined with the MM graded index fibers, which can be used as a distributed temperature sensor (DTS) based on Raman scattering. Because raman scattering is independent of strain the MM fiber can be tight in the cable.

$$\Delta v_b = \frac{\partial v_b}{\partial \varepsilon}\Delta\varepsilon + \frac{\partial v_b}{\partial T}\Delta T = C_\varepsilon\,\Delta\varepsilon + C_T\,\Delta T \qquad (1)$$

3.2 Determination of temperature coefficient

The calibration of the temperature coefficient is done in the laboratory, with the aid of a water bath. The water is heated in increasing steps of 5 °C to a maximum temperature of 60 °C and decreasing steps of 5 °C cooled down to 0°C. The average Brillouin frequency and average temperature along the tested section of 10m are plotted for temperatures varying between 0° and 25° in Figure 4. A linear trend over the first 25° is used to derive a temperature coefficient of 2 Mhz/°c.

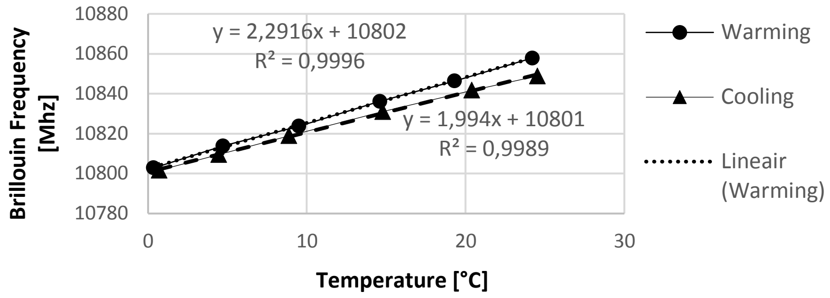


Figure 4. Relationship between temperature and Brillouin frequency (temperatures between 0 and 25°).

3.3 *Determination of strain coefficient*

By applying a well-known strain variation to a FO at a constant temperature in the laboratory, the variation of Brillouin frequency versus strain can be plotted (see Figure 5). For this test a 4,77 meter length was stretched in incremental steps of 5mm till 50mm was achieved. The highest stage delivers 10482 µstrain or 1.0482% extension. Afterwards, the fiber was relaxed to zero in the same steps. To determine the strain coefficient only the values how are not influenced by the deformation are taken. A strained coefficient is determined as 470Mhz/%.

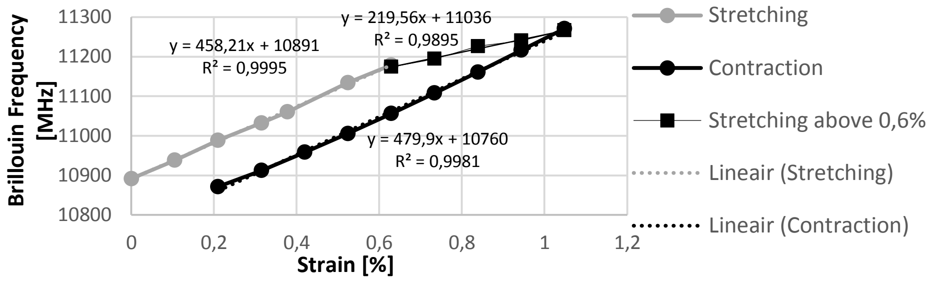


Figure 5. Determination of strain coefficient based on strain – Brillouin measurements

4 DATA MEASUREMENT AND ANALYSES

4.1 *Interpretation of the data during concreting*

After installation of OV4 and OV5 a lot of measurements were made during concreting.

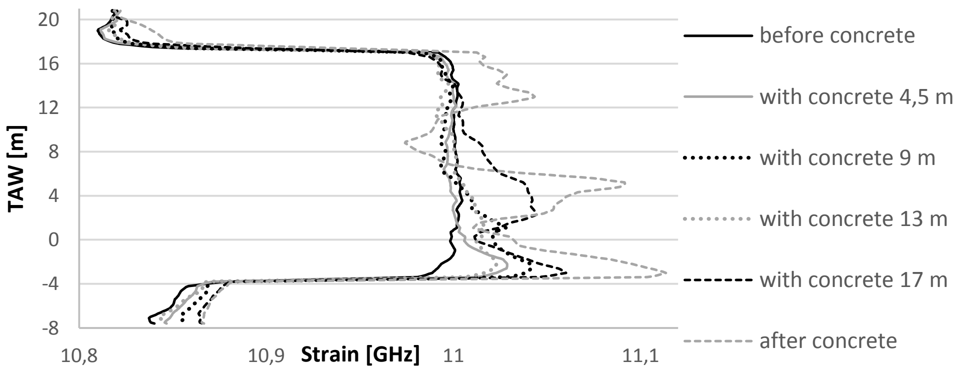


Figure 6. Strain during installation of OV4

The first reference measurement was made after lowering the cage in the bentonite slurry and before concreting. While filling the trench with concrete different measurements were taken at following heights of concrete: 4,5 m, 9 m, 13 m, 17 m and after complete concreting. The concrete is developing a horizontal and vertical pressure on the fiber, resulting in a higher pretention in some areas of the fiber. As a result of the concreting, the pretention in the fiber optic is not equally distributed along the fiber. The variations in the pretention sometimes result in local strain peaks, which makes it harder to interpret the data.
Obviously, due to the large influence of the installation on the pretention, it is required that the reference measurement is taken after concreting. This implies that, when this measurement is made shortly after concreting, large temperature difference need to be taken into account (see figure 7).

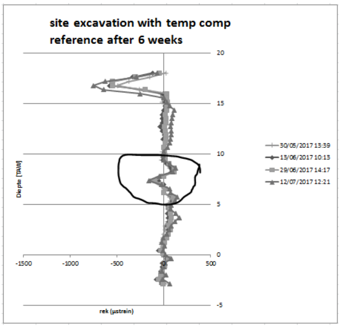
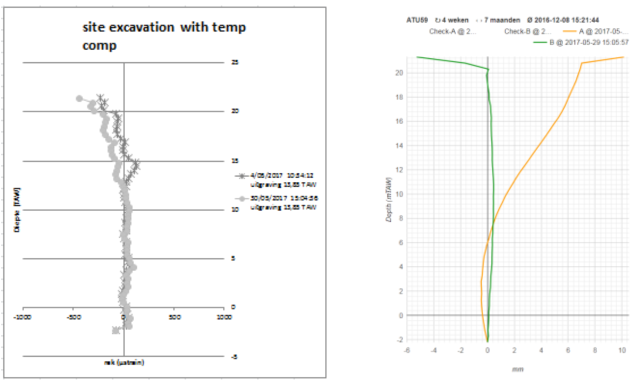


Figure 7. Strain of OV4 with reference after 6 weeks

To avoid large temperature changes compared to the reference measurement, and to make a good comparison with the inclinometer measurements, a reference measurement +/- 1 month after installation and before excavation was chosen.

4.3 Interpretation of the data between fiber optics and inclinometer

A first comparing can be made between OV2 and the inclinometer. These two measurement techniques are placed in the same steel tube. In figure 8, a comparison is made between the movement, obtained from the inclinometer and the strain (~forces) which is measured with the fiber optics. A direct comparison is difficult and further analysis is required to compare the bending moments (deduced from the fiber optics) and the displacements (deduced from the inclinometer measurements).



a b

Figure 8. a) measurement with fiber optic; b) measurement with inclinometer

4 CONCLUSION

Different installation techniques for fiber optics in diaphragm walls were tested, with fibers placed directly on the reinforcement cage or in hollow rectangular tubes. The conclusions of the installation directly on the cage are:

1) Installation in a diaphragm wall is possible with not too much time delay
2) with the right protection at the bottom and the top there is a high % of success rate
3) Taking measurements during concreting is indispensable to interpret the final pretension. Whether the installation method and pretension has an influence on the final result will be investigated during excavation.
4) concreting develops turbulence and currents that influence the pretention in the FO

The influence of the installation method on the final result will be investigated during excavation. After several installations preparation, installation and protection techniques were improved.

Finally, the comparison of strain, bending moment and displacement will be made, based on the measurement of the fiber optic and the inclinometer. The aim is to compare measurements with the predictions obtained in the design.

At this stage, even though the fiber optic measurements result in a rather straight forward deduction of the bending moments in the excavation wall, we believe that the optical fiber technique cannot yet be used as a standalone measurement technique and still requires a comparison with more traditional techniques.

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