Structure-Integrated Fibre-Optic Strain Wave Sensor for Pile Testing and Monitoring of Reinforced Concrete Piles

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ABSTRACT

Reinforced concrete piles are used when structures are constructed on soft ground, because it is necessary to transfer the loads into deeper strata with a sufficient bearing capacity. Usually, static and dynamic pile tests are carried out in order to determine the pile's behaviour and possible damages. The dynamic measurements can show the bearing behaviour and the structural integrity by using the theory of one-dimensional wave propagation. Commonly, the sensors are installed on the top of the pile head or embedded near the pile head. With the purpose of receiving more precise information about the pile features, now, a string of sensors is embedded at different levels of the pile.

A fibre optic strain wave sensor has already been developed by Schallert [1]. The sensor is based on the principle of the extrinsic Fabry-Perot interferometer and was already tested in laboratory and full-scale field tests with precast driven piles. It was possible to detect the introduced deformation caused by the static loading and the dilatational wave during dynamic low-strain as well as high-strain loading. Although the full-scale tests were successful, the high demands on the economy of the sensor required the optimisation of the sensor design. After laboratory tests with the optimised sensor, a cast-in-situ bored pile has been built at the BAM Test Site Technical Safety in Horstwalde, South of Berlin. In order to enable the comparison of the signals, additional fibre Bragg grating sensors, temperature sensors and resistance strain gauge sensors are embedded into the pile. In this paper, the optimised sensor and the setup of the cast-in-situ bored pile along with results of the conducted pile tests are shown together with an outlook on further field-tests in progress.

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INTRODUCTION

When structures have to be constructed on soft ground, reinforced concrete piles are used to transfer the loads into deeper strata with sufficient bearing capacity. Usually, static and dynamic pile tests are carried out to determine the pile's bearing behaviour and to detect damage. The bearing capacity and the structural integrity are generally determined from the dynamic measurements taken at the pile head by using the theory of one dimensional wave propagation. By embedding a string of fibre optic strain wave sensors at different levels of the pile, additional and more precise information about the pile characteristics can be received. Schallert [1] and Schallert et al. [2, 4 and 5] already developed a first design version of such a fibre optic strain wave sensor and tested it in full-scale field tests. In these tests, the introduced deformation caused by the static load test and the dilatational wave during dynamic loading were successfully detected. Nevertheless, the engineering design of the sensor body left room - from the economical point of view - to be optimised.

After laboratory tests with the optimised sensor, cast-in-situ bored piles have been built at the BAM Test Site Technical Safety in Horstwalde, South of Berlin. Other precast driven piles have been casted in the factory of our project partner, Centrum Pfähle GmbH, Hamburg/Germany, and were driven and tested on one of their big construction sites. In order to verify the performance of the newly designed strain wave sensors, additional fibre Bragg grating sensors, temperature sensors and resistance strain gauge sensors are embedded into the piles. In this paper, the optimised sensor and the setup of the cast-in-situ bored pile along with results of the conducted pile tests are shown together with an outlook on further field-tests in progress.

DESIGN OF THE OPTIMISED SENSITIVE ELEMENT

Based on the successful field tests with the measurement method developed by Schallert [3], the sensor design had to be transferred into a prototype sensor for industrial manufacturing application. High demands on the economy of the measurement system were formulated by the future manufacturer and deliverer, Gloetzl Company in South Germany. The steel 1.4301 used for the sensor cage had to be replaced in order to reduce the material costs and the very high tool wear. The need of resistance to the high-alkaline concrete environment and the modulus of elasticity similar to concrete were the criteria for the choice of nickel silver.

The small gauge length (usually between 3mm to 10 mm) of the extrinsic Fabry-Perot interferometer (EFPI) sensor was another point for optimisation. When small deformations occur, they are measured over the short gauge lengths and cause only very low signal changes. In order to increase the signal response, the deformation of the whole sensor cage must be transferred into the short sensitive element. Therefore, a flexible EFPI (Figure 1) was applied onto an additional flexure in the sensor cage.

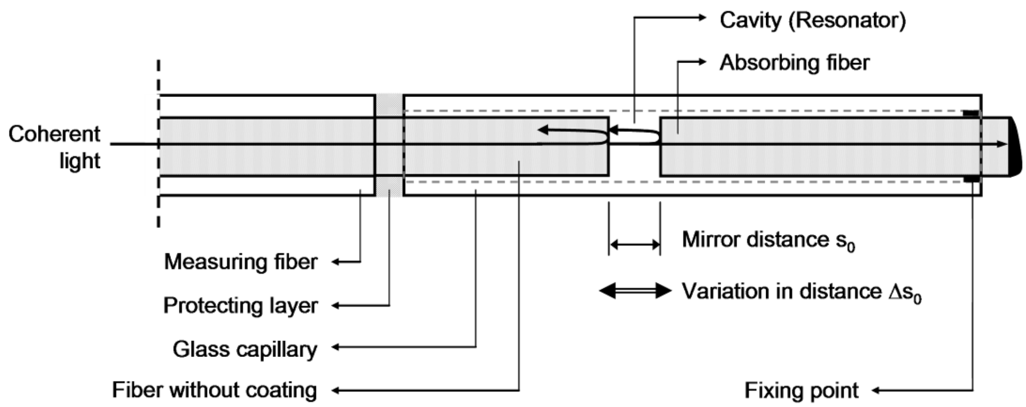

Figure 1. Flexible EFPI sensor.

The difference between a commonly used stiff EFPI sensor and a flexible EFPI sensor is that the measuring fibre (connected to the recording device) is not fixed to the capillary anymore, but able to move freely in it. The measuring fibre is applied to one end of the flexure and the absorbing fibre with the capillary is glued to the other end (see Figure 2).

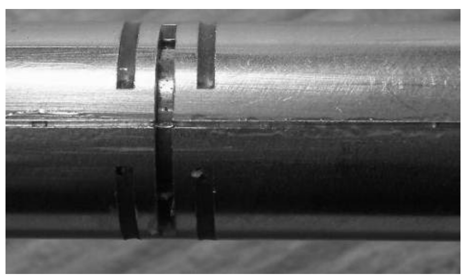

Figure 2. Flexure with applied flexible EFPI sensor.

Because of the soft nature of the sensor cage, deformation applied on the sensor cage is directly transferred onto the flexure. As a positive result, the gauge length is not only the length of the flexure but the length of the whole sensor cage, resulting in an amplification of the signal changes. At the same time, the gained flexibility of the sensor cage is also a disadvantage because shear forces or bending can easily damage the sensor. Therefore, a steel rod, which is mechanically decoupled from the nickel silver sensor cage, reinforces the flexure. Additionally, influences on the movement of the flexure along the axis of deformation can be prevented. In order to integrate the complete sensor into the concrete pile, the sensor is fixed at the reinforcement cage. But it was necessary to separate the sensor cage from the reinforcement cage of the pile, because bending of reinforcing steel elements could occur while the pile is constructed. For this reason, the already mechanically decoupled steel part of the sensor was suited as mounting. With an increase of the length of the steel rod and a steel plate welded at the end of the steel rod, the complete sensor can be installed by welding the steel plate on the reinforcement elements.

It was also necessary to apply the fibre sensor outside instead of inside the sensor cage because of the flexure. Therefore, the sensor cage is covered with a protective shell in order to protect the fibre. The complete sensor is shown in Figure 3.

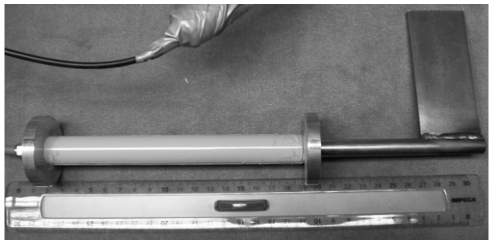

Figure 3. Complete sensor.

Two important deformation values had to be considered in order to dimension the measurement range of the sensor appropriately: a) deformation range during the curing process of the concrete (shrinkage), and b) deformation values expected during the static and dynamic loading. Otherwise, the applied strain will not be measured anymore when the mirrors of the sensor touch each other. Therefore, the optimal mirror distance for the flexible EFPI was concluded from a) the results of laboratory tests where small-scale sensors were embedded into concrete specimens, and b) the field tests made with the previously developed sensor design.

LARGE-SCALE MODEL PILE TESTS

A large-scale cast-in-place bored model pile of 10 m length and 0.75 m diameter was constructed at the BAM Test Site Technical Safety in Horstwalde, South of Berlin. It is part of a setting of five piles where a number of new and innovative NDT technologies are investigated (see Figure 4, pile in the centre).

Figure 4. Pile Setting; the pile in the centre of the picture is equipped with fibre optic sensors.

The pile has three measurement levels (ML) at 1.5 m, 5 m and 8.5 m. At each level, the reinforcement cage is equipped with three fibre optic EFPI sensors which are displaced by 120°. A commercially available fibre Bragg grating (FBG) sensor (Figure 5, left), a temperature sensor and a resistance strain gauge (RSG) sensor (Figure 5, right) were added at every measurement level.

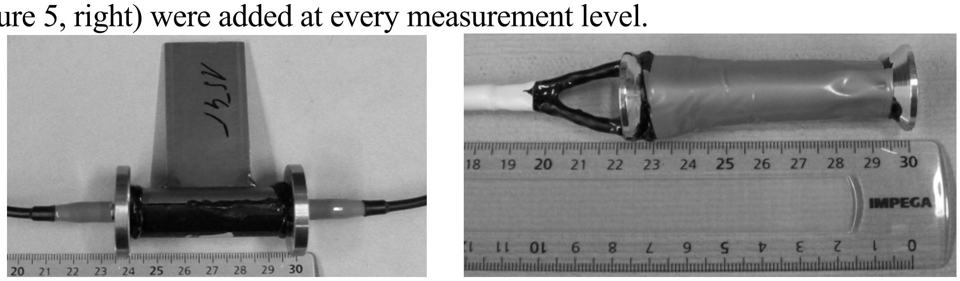

Figure 5. FBG sensor (left) and RSG sensor (right).

There are also two additional RSG sensors at the second level next to the fibre optic EFPI sensors to compare the measured signals in plane. In total there are nine fibre optic strain wave EFPI sensors, three FBG sensors, five RSG sensors and three temperature sensors installed in the reinforcement cage. The measurement level setup is shown in Figure 6, left.

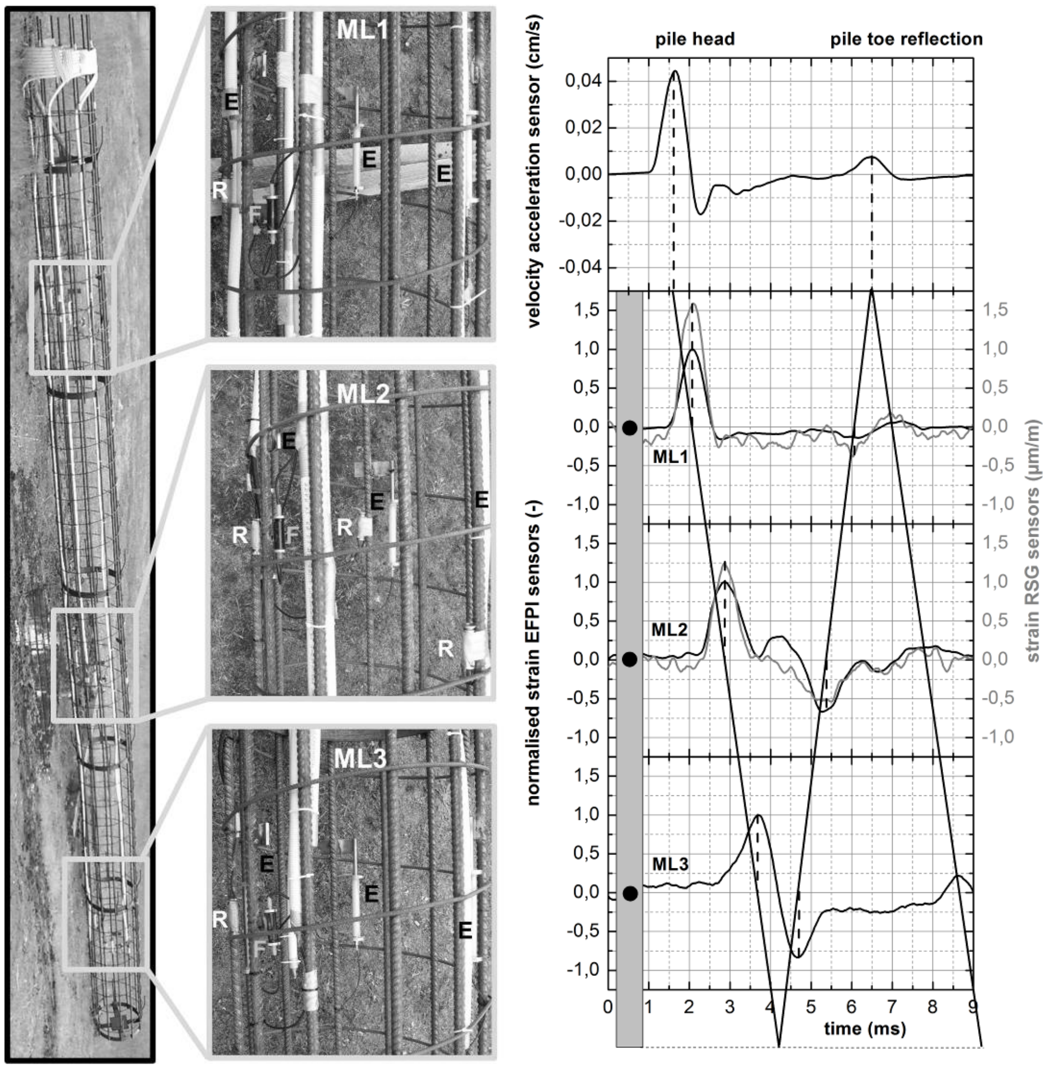

Figure 6. Left: Reinforcement cage with installed EFPI sensors (E), FBG sensors (F) and RSG sensors (R), right: wave propagation after low-strain impact.

The FBG sensors can be used to determine the load-independent deformation of the pile caused by the curing process. The axial deformation of the pile caused by shrinkage of the concrete during curing was approximately 350 µm/m. It is about half the strain measured during the laboratory tests and less than expected. Since the strain seems to vary along with the temperature, the data recording is being continued to get data from different seasons.

Figure 6, right, shows that the wave propagation can clearly be detected by the EFPI sensors and that the signal response correlates with those of the RSG sensors. Additionally, the EFPI strain signals were correlated to the installed accelerometer during the first dynamic tests, like it is common practice by low-strain pile integrity testing.

Another large-scale cast-in-place bored model pile of 10 m length and 0.88 m diameter was built recently (see **Figure 7**, left). This pile has also three measurement levels located at 0.9 m, 5 m and 8.75 m. Each measurement level is equipped with two EFPI sensors and one FBG sensor with temperature compensation (**Figure 7**, right), which are displaced by 120° as can be seen in **Figure 7**, middle. Additionally, temperature sensors, strain sensors and a load cell at the pile toe were installed by the BAM division 8.2 Non-destructive Damage Assessment and Environmental Measurement Methods and their project partners. This pile is scheduled for a static load test and dynamic low-strain tests.

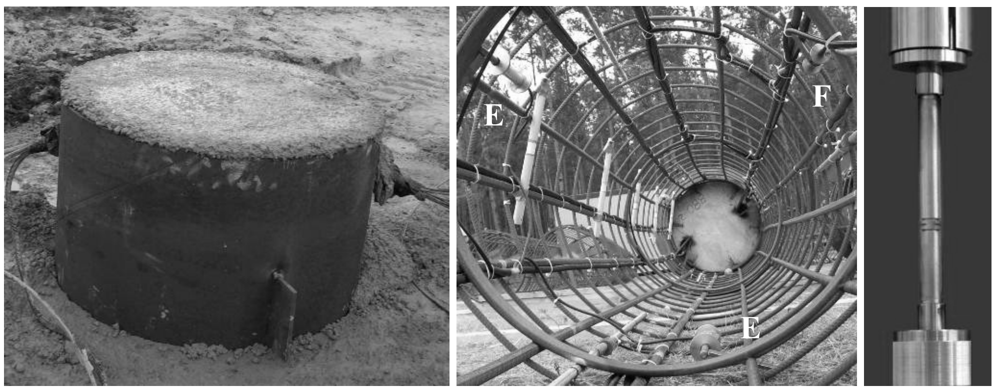

Figure 7. Left: Pile equipped with fibre optic sensors, middle: reinforcement cage with two EFPI sensors (E) and one FBG sensor (F) at each measurement level, right: FBG sensor with temperature compensation.

FIELD TESTS

In order to verify that the newly designed EFPI sensors would withstand the conditions during the use on a real construction site, two precast piles with a cross-section area of 35 cm x 35 cm have been fabricated (**Figure 8**, left). Pile 1 has a length of 15 m while pile 2 is a coupled pile consisting of a 15m upper pile and a 10 m lower pile. The four measurement levels of these piles are located at 2.5 m, 8.5 m, 11.5 m and 14.5 m from the pile head. At each measurement level one newly designed EFPI sensor and a second sensor are installed (**Figure 8**, right). Because of the limited space, this sensor, similar to the prototype EFPI sensor without a flexure, was built to contain the established sensing elements.

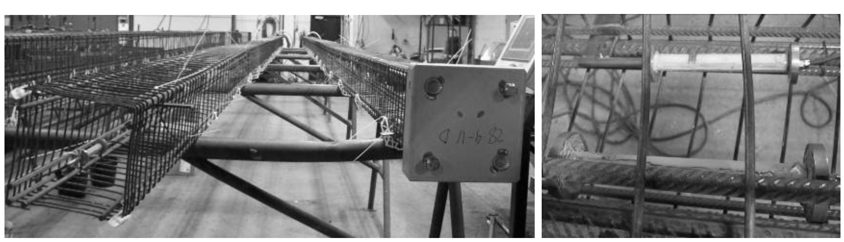

Figure 8. Left: Reinforcement cages of Pile 1 (left cage) and the upper pile of Pile 2 (right cage), right: EFPI sensor (upper sensor) and reference sensor (lower sensor).

The sensors at measurement level 2 and 4 are equipped with two resistance strain gauges, one stiff EFPI sensor and one FBG sensor while the sensors at measurement level 1 and 3 are equipped with only two resistance strain gauges.

After curing the piles for two weeks, they were driven at a big construction site of our project partner, Centrum Pfähle GmbH, Hamburg/Germany. **Figure 9** shows the driving process of pile 1 on the left and both piles after driving on the right. Dynamic low-strain and high-strain tests have been carried out and all sensors showed a corresponding response, but the analysis of the data has to be completed yet.

Figure 9. Left: Driving of pile 1, right: precast piles after driving.

CONCLUSIONS AND OUTLOOK

The newly designed concrete embeddable fibre optic strain wave sensors were prepared for laboratory specimens as well as large-scale cast-in-place model-piles at the BAM Test Site Technical Safety in Horstwalde, South of Berlin, and precast driven piles at the construction site of our project partner, Centrum Pfähle GmbH, Hamburg/Germany. Until now, dynamic low-strain tests were carried out with the cast-in-place model piles while dynamic low-stain and high-strain tests were carried out with the precast driven piles. Static load tests are in preparation for the cast-in-place model-piles while the dynamic strain tests with the precast driven piles will be repeated. In order to verify the performance of the newly designed strain wave sensors, additional sensors equipped with stiff EFPI sensors, RSG sensors and FBG sensors were integrated into the piles.

The development of an appropriate read-out technology and instrumentation to gain useful measurement information from the EFPI sensor signals is another important task in developing this new monitoring technology. From the user’s point of view, the integrity or the load-bearing capacity of the tested pile has to be evaluated from an absolute strain value that is represented by the deformation measured with the fibre optic sensors. Therefore, repeatable zero-point referenced measurements are required, which are carried out over long periods of time without having the need of a continuously running system. The refined system will be tested during the scheduled pile tests within the next months.

ACKNOWLEDGEMENTS

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