STRUCTURE-INTEGRATED FIBER-OPTIC STRAIN WAVE SENSOR FOR CONCRETE PILE TESTING AND MONITORING

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Reinforced concrete piles are used in case of structures that are constructed on soft ground to transfer the loads into deeper strata with sufficient bearing capacity. In order to determine the pile's behavior and possible damage, static and dynamic pile tests are carried out. Dynamic measurements taken from the pile head can show the bearing behavior and structural integrity by using the theory of wave propagation. In order to receive more precise information about the pile features, now, a string of sensors is embedded at different levels of the pile. A fiber optic strain wave sensor, based on the extrinsic Fabry-Perot interferometer (EFPI), has already been developed and tested in full-scale field tests by Schallert (2010). It was possible to detect the introduced deformation caused by the static load and the dilatational wave during dynamic loading.

Although the full-scale tests were successful, the engineering design of the sensor body left room - from the economical point of view - to be optimized. After laboratory tests with the optimized sensor, a cast-in-situ bored pile has been built at the BAM Test Site Technical Safety in Horstwalde, South of Berlin. Additionally to the EFPI sensors, fiber Bragg grating (FBG) sensors, temperature sensors and resistance strain gauge (RSG) sensors are embedded in order to compare the signals with each other. In this paper, the modified sensor and the setup of the cast-in-situ bored pile along with results of dynamic tests are shown.

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STRUCTURE-INTEGRATED FIBER-OPTIC STRAIN WAVE SENSOR FOR CONCRETE PILE TESTING AND MONITORING

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ABSTRACT: A highly resolving fiber optic sensor based on an extrinsic Fabry-Perot interferometer (EFPI) was developed for integration into concrete piles. The embedded sensors are arranged as a string of sensors at different levels of the pile. The purpose of this setting along the whole pile is to receive more and precise information during static as well as high-strain and low-strain dynamic pile testing. Commonly, sensors are installed on the top of or embedded near the pile head. The paper presents an optimized sensor design to record strain waves in concrete; first results of large-scale model pile tests are described.

1 MOTIVATION

Reinforced concrete piles are used in structures that have to be constructed on soft ground. The loads have to be transferred into deeper strata with sufficient bearing capacity. In order to determine the pile's bearing behavior and detect damage, static and dynamic pile tests are usually carried out. Dynamic measurements taken from the pile head can show the bearing capacity and structural integrity by using the theory of one dimensional wave propagation. In order to receive more and precise information about the pile characteristics, now, a string of fiber optic strain wave sensors can be embedded at different levels of the pile. Such a fiber optic strain wave sensor in a first design version was already developed and tested in full-scale field tests by Schallert (2010) and Schallert et al. (2010, 2008 and 2007). It was possible to detect the introduced deformation caused by the static load test and the dilatational wave during dynamic loading. Although the full-scale tests were successful, the engineering design of the sensor body left room - from the economical point of view - to be optimized.

The optimized sensor design and a first large-scale model-pile test including results of dynamic pile tests are shown in this paper.

2 DESIGN AND CHARACTERISATION OF THE OPTIMISED SENSITIVE ELEMENT

Based on the successful field tests with the measurement method developed by Schallert (2008), the sensor design had to be transferred into a prototype sensor for industrial manufacturing application. The future manufacturer and deliverer, Gloetzl Company in

South Germany, formulated high demands on the economy of the measurement system. In order to reduce the material costs and the very high tool wear, the originally used material for the sensor cage (steel 1.4301) was replaced by nickel silver. Nickel silver was chosen because of its resistance to the high-alkaline concrete environment and its modulus of elasticity similar to concrete.

Another point of optimization concerned the small gauge length of the EFPI sensor. In the stiff version, usually gauge lengths from 3 mm to 10 mm are used. These short gauge lengths cause only very low signal changes when small deformations occur. In order to increase the signal response, the deformation of the whole sensor cage must be transferred into the short sensitive element. Therefore, a flexure was added in the sensor cage and a flexible EFPI (Figure 1) was applied onto the flexure.

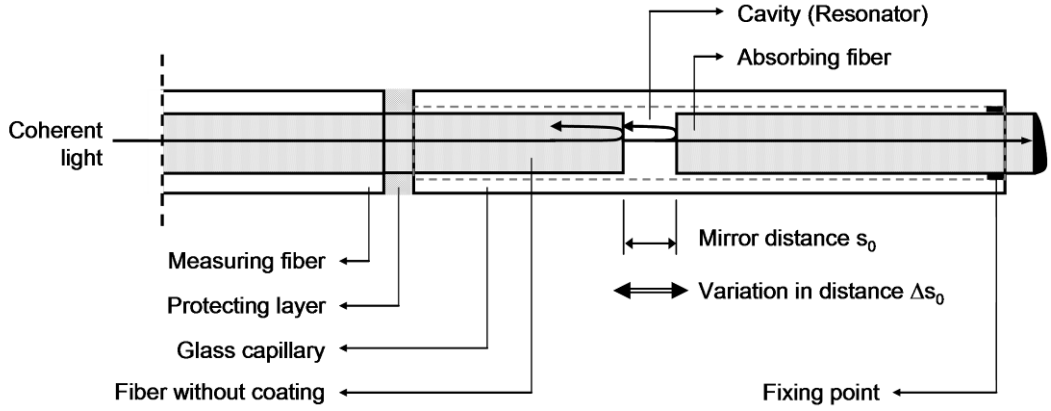


Figure 1. Flexible EFPI sensor.

The flexible EFPI sensor differs from the stiff one because the measuring fiber (connected to the recording device) is not fixed to the capillary anymore but able to move freely in it. In order to apply the flexible EFPI, the measuring fiber is glued to one end of the flexure, and the absorbing fiber with the capillary is glued to the other end (see Figure 2).

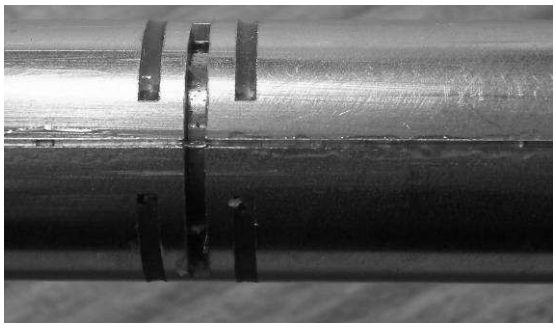


Figure 2. Flexure with applied flexible EFPI sensor.

Deformation applied to the sensor cage is directly transferred onto the flexure because of its soft nature. As a positive result, the gauge length over which the deformation is measured is not only the length of the flexure but the length of the whole sensor cage.

However, the gained flexibility of the sensor cage is also a disadvantage. The sensor can easily be damaged by shear forces or bending. Therefore, the flexure is reinforced with a steel rod that is mechanically decoupled from the nickel silver sensor cage. This prevents influences on the movement of the flexure along the axis of deformation. Generally, the complete sensor is fixed at the reinforcement cage. But because bending of reinforcing steel elements could occur, it was necessary to separate the sensor cage from the reinforcement cage of the pile. For this reason, the already mechanically decoupled steel part of the sensor was suited as mounting. Therefore the length of the rod was increased and a steel plate was welded at the end of the rod. The complete sensor can be fixed at the reinforcement cage by welding the steel plate on the reinforcement elements.

The flexure made it necessary to apply the fiber sensor outside instead of inside the sensor cage. In order to protect the fiber, the sensor cage is covered with a protective shell. The complete sensor is shown in Figure 3.

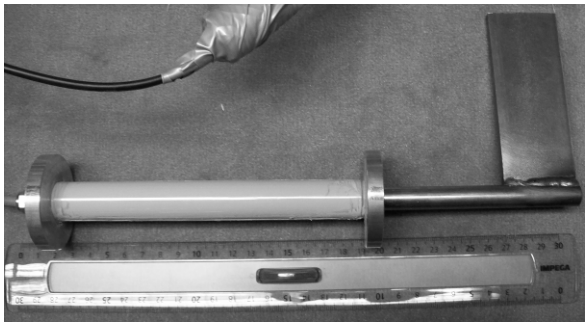


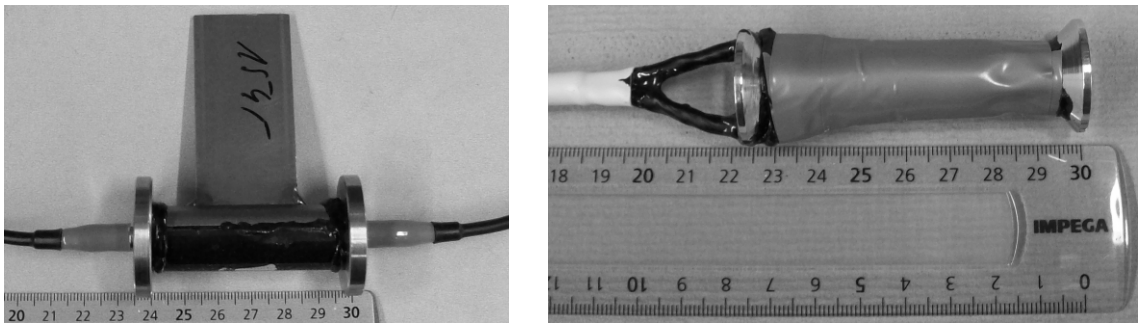
Figure 3. Complete sensor.

In order to dimension the measurement range of the sensor appropriately, two important deformation values had to be considered: a) deformation range during the curing process of the concrete (shrinkage), and b) deformation values expected during the static and dynamic loading. Otherwise, the mirrors of the sensor will touch each other and the applied strain will not be measured anymore. Therefore, the right 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.

3 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 fiber optic sensors.



(a) (b)

Figure 5. FBG sensor (a) and RSG sensor (b).

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 fiber optic EFPI sensors which are displaced by 120°. A commercially available fiber Bragg grating (FBG) sensor, a temperature sensor and a resistance strain gauge (RSG) sensor were added at every measurement level. There are also two additional RSG sensors at the second level next to the fiber optic EFPI sensors to compare the measured signals in plane. In total there are nine fiber optic strain wave EFPI sensors, three FBG sensors, five RSG sensors and three temperature sensors installed in the reinforcement cage. The FBG sensor and RSG sensor are shown in Figure 5, the measurement level setup is shown in Figure 6.

The temperature sensors show that there is a significant temperature drop between the measurement levels, e.g. from 14.1°C at ML1 to 12.7°C at ML 2 and 10.0°C at ML3, which needs to be known to compensate for the temperature-induced apparent strain in the FBG sensors. Further monitoring of the temperature showed that the temperature of ML1 varies strongly with the season. Therefore, the first measurement level will be located more away from the pile head for the field tests.

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 7 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.

Figure 6. Reinforcement cage with installed EFPI sensors (E), FBG sensors (F) and RSG sensors (R).

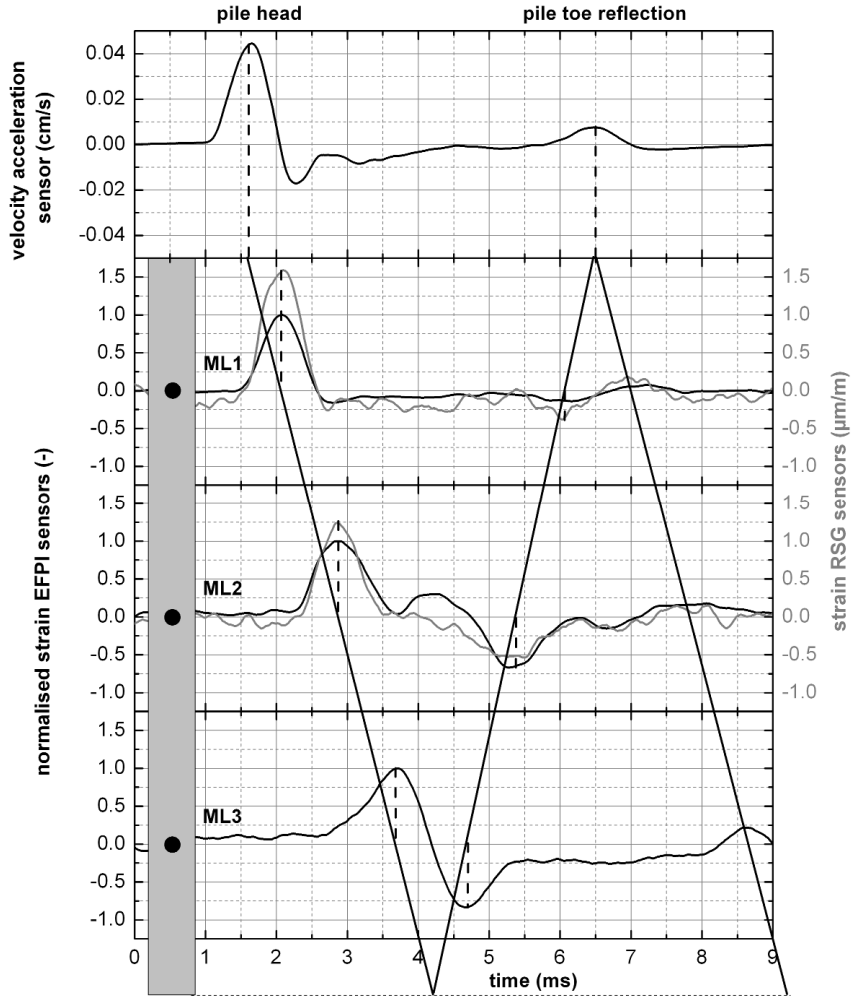


Figure 7. Wave propagation along the model pile after low-strain impact.

4 CONCLUSIONS AND OUTLOOK

Newly designed concrete embeddable fiber optic strain wave sensors were prepared for a large-scale dynamic low-strain test. The cured piles got covered with a reinforced concrete plate, which will allow static load tests (Figure 8). Additionally, dynamic tests with EFPI sensors as well as RSG sensors and measurements using FBG sensors to monitor the overall deformation can be carried out.

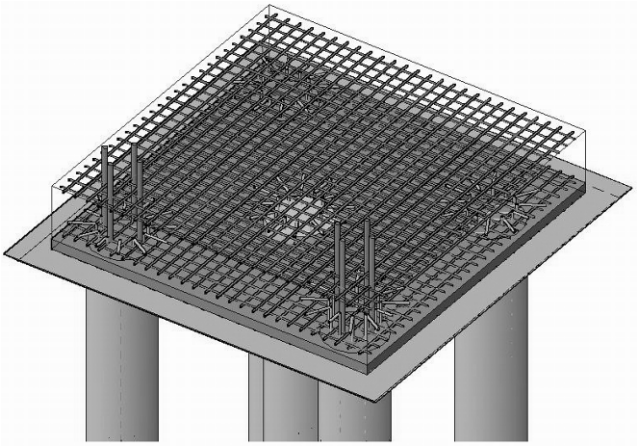


Figure 8. Reinforced concrete plate to cover the piles (3D-model: Dr. Niederleithinger, BAM 8.2).

In order to verify the results received from the large-scale test, field tests with cast-in-situ bored piles and precast driven concrete piles on regular construction sites are in preparation. The piles will be tested by the common high-strain and low-strain test technologies as well as by static load tests.

Another important task in developing this new monitoring technology is the development of an appropriate read-out technology and instrumentation to gain useful measurement information from the EFPI sensor signals. From the user's point of view, the deformation measured by fiber optic sensors must represent an absolute strain value that allows direct evaluation of the integrity or the load-bearing capacity of the tested pile. This requires repeatable zero-point referenced measurements over long periods of time without having the need of a continuously running system. Within the next months, the refined system will be tested during large-scale model pile tests and with real piles at big construction sites.

5 ACKNOWLEDGEMENTS

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