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Li, J, Correia, RP, Chehura, E et al. (5 more authors) (2009) Field monitoring of static, dynamic, and statnamic pile loading tests using fibre Bragg grating strain sensors. Proceedings of SPIE - The International Society for Optical Engineering, 7503. 75034O. ISSN 0277-786X

https://doi.org/10.1117/12.835360

Field monitoring of static, dynamic and statnamic pile loading tests using fibre Bragg grating strain sensors

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ABSTRACT

Pile loading test plays an important role in the field of piling engineering. In order to gain further insight into the load transfer mechanism, strain gauges are often used to measure local strains along the piles. This paper reports a case whereby FBG strain sensors was employed in a field trial conducted on three different types of pile loading tests in a glacial till. The instrumentation systems were configured to suit the specific characteristic of each type of test. Typical test results are presented. The great potential of using FBG sensors for pile testing is shown.

Keyword List: Pile loading test, Static, Dynamic, Statnamic, Strain gauges, FBG

1. INTRODUCTION

As it is difficult to predict with accuracy of the performance of a pile due to many uncertainties inherent in its design and construction, pile loading tests are therefore conducted to verify the load-settlement behaviour and the load capacity of the pile [1]. There are broadly three categories of tests commonly used, namely, static, rapid and dynamic pile loading tests. The static test has traditionally been considered as the most reliable method as it replicates the long term sustained load conditions. An increment of load is applied and maintained to the head of the pile for a minimum specified time and until a specified rate of settlement criterion is satisfied. However, it is relatively expensive and time consuming, as a result of the need for a suitable reaction system, and takes a minimum of 19 hours [2]. In a dynamic test, a falling mass strikes the pile, delivering a short duration impulse (5-10 milliseconds). The force and velocity are derived from the gauges attached to the pile top and an equivalent static pile capacity can be determined [2]. In a rapid or statnamic test, a pressure chamber and a reaction mass are placed on top of the tested pile. Solid fuel is injected and burned in the chamber to generate an upward force on the reaction mass, which in turn imparts an equal and opposite load on the tested pile. The pile load increases to a maximum and is then reduced when exhaust gases are vented from the pressure chamber. The load duration is substantially longer, usually 100-200 milliseconds, and the static load settlement curve equivalent is then derived from the displacement and the induced force measured at the pile head [3].

Conventional strain gauges, either electrical resistance or vibrating wire, are often used to instrument piles and measure local strains, which can help establish the load transfer mechanism of piles under loading, e.g., the distribution of load, development of shaft resistance and end-bearing resistance. However, they have their own limitations [4]. In recent years, fibre Bragg grating sensors have investigated for use in foundation piles, e.g., static loading tests [5, 6] and condition monitoring during the construction of its superstructure [7]. The operation of these sensors is based upon the fact that the FBG wavelength is intrinsically strain and temperature dependent [8]. In particular, its durability and accuracy, immunity against electromagnetic interferences, multiplexing capability, and miniaturized size render the FBG a promising alternative for strain measurement for both pile loading tests and in-service performance monitoring over their design life.

This paper reports a field study where 3 nominally identical reinforced concrete piles were each instrumented with an array of FBGs acting as structurally integrated strain sensors. Each of the piles was subjected to a different loading test – static, dynamic and statnamic. The FBG sensor arrays and FBG demodulation systems used to monitor them were chosen to match the characteristics of the particular test used. The paper will discuss the practical issues associated with the field trials, and present typical results obtained.

20th International Conference on Optical Fibre Sensors, edited by Julian Jones, Brian Culshaw,
Wolfgang Ecke, José Miguel López-Higuera, Reinhardt Willsch, Proc. of SPIE Vol. 7503, 75034O
 · doi: 10.1117/12.835360

2. PILE CONSTRUCTION

The field tests were conducted in a glacial till, a typical type of soil mostly encountered in the UK and details about the site and soil characteristics can be found in [9]. A total of six tested piles were constructed for different types of pile test. The tested piles were 10.15 m long, 600 mm nominal diameter bored piles. The prefabricated 440 diameter reinforcement cage was comprised of 6 longitudinal rebars of 25 mm diameter with spiral of 10mm at spacing of 225 mm throughout. Given the tight time schedule for the construction of the piles, uncoated FBGs were used as strain sensors. This also provided flexibility to cater for the practical uncertainties associated with deployment in the field environment. The arrays used for the static and statnamic testing consisted of 4 wavelength-division multiplexed FBGs each of length 5mm, with centre wavelengths around 1300nm, written in Fibercore PS1250 photosensivive optical fibre. Adjacent FBGs were physically separated by 3m. For the dynamic tests, each FBG was fabricated in a separate fibre to allow the use of spatial division multiplexing and an edge filter to demodulate the FBGs.

On each pile, two arrays, each containing four FBG sensors, were attached using an epoxy resin onto the longitudinal rebars of the pile cage at different levels. FC fibre connectors were used to terminate the fibre outside the pile head. A schematic view of the sensor locations is shown in Figure 1, while Figure 2 shows the reinforcement cage. The tested piles were constructed by continuous flight auger (CFA) method. In this system, the bore was formed using a continuous flight auger and a high slump concrete mix was pumped in through the hollow stem as the auger was withdrawing from the bore until ground level. The instrumented cage was then placed in the bore with a cap placed exclusively for conducting the test. A built pile can be seen in Figure 3. The robustness of the packaging/protecting measures had been proven in the field by surviving all the construction stages. Testing was carried out more than 1 month later, when the concrete curing was completed.

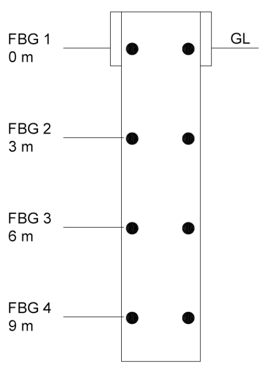

Fig. 1 Pile instrumentation diagram

Fig. 2 FBG instrumented reinforcement cage

Figure 3 Constructed pile

3. PILE TESTING

3.1 STATIC TESTING

Given the relatively long duration of this test, a demodulation unit based upon a fibre Fabry Perot Tunable filter, with a scan rate of 100Hz and wavelength range of 66 nm centred at 1318 nm, was used to interrogate the wavelength division multiplexed FBG array. Data were recorded at 1 Hz interval with a burst of 10 files to facilitate data averaging. A temperature stabilised grating was also provided as reference in the system. A lorry based system with package capacity of 3MN was used to undertake the maintained load test (Figure 4). Loads were applied incrementally and maintained by a hydraulic jack pressing against a reaction beam system which was secured in place by anchor piles. A total of two loading and unloading cycles were conducted sequentially.

A typical of local strains for one test cycle is plotted as a function of time together with the applied loads in Figure 5. Clearly, it can be observed that the mobilised strains in the pile followed each increment/decrement of the loads and varied slightly over the load maintaining periods, as observed similarly in [5]. Typical load distribution curves in the pile under certain load levels are plotted in Figure 6. The redistribution of the load down the pile shaft can be seen as load transfers progressively downwards in line with the increase of the applied load, which is also evident in [6].

Figure 4 Static testing system

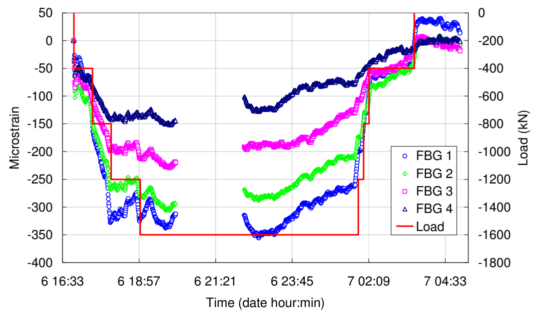

Figure 5 Strain vs. time calculated from the measured wavelength shifts

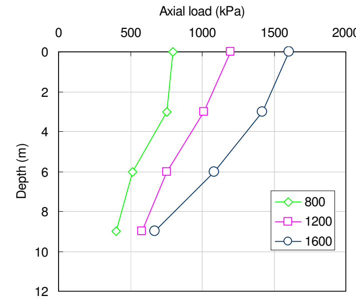

Figure 6 Load distributions in the pile under various applied loads

3.2 DYNAMIC TESTING

To make measurements over the short duration of the loading pulse experienced in dynamic loading, spatially multiplexed FBGs were each demodulated using an edge filter and detector. A drop weight of 4t was raised to various heights by a crawler crane. It was then released and allowed to free fall onto the pile head along its guided assembly (Figure 7). A total of thirteen strikes were carried out. A typical example of local strains monitored during a loading event is plotted as a function of elapsed time in Figure 8. It can be observed that the transient compressive strain was developed rapidly within the pile, which propagated down the pile with well resolved peaks recorded at each location. The initial strain pulse was followed by a damped signal, with tension strains developed at some locations. The small physical length of the FBGs ensured strain pulse was temporally resolved, which can be difficult with longer gauge length sensors.

Figure 7 Dynamic testing device

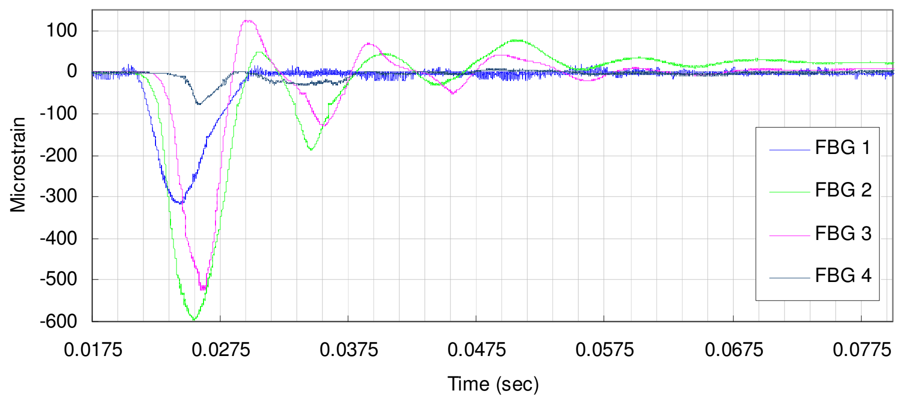

Figure 8 Strain vs. time calculated from the measured wavelength shifts

3.3 STATNAMIC TESTING

Given the timescale of the loading event associated with the statnamic test, a SANTEC HSL 2000 high speed scanning laser, with a scan rate of 20 KHz and wavelength range of 114 nm centred at 1330 nm, was used to interrogate the wavelength division multiplexed FBG array. The statnamic tests were carried out by utilising a 3 MN Statnamic device of 18 t weight pack (Figure 9). Solid fuel was burned in the combustion chamber to generate the target load to the pile against a travelling reaction mass. A total of five load cycles were carried out with various target levels of statnamic loading. A typical example of local strains recorded for one test cycle is plotted as a function of elapsed time in Figure 10. It can be seen, over the test duration of 130 ms, the compressive strains increased first until reaching their peaks and then declined to zero for measurements at all locations. The peak strains in the pile were recorded as 200 με for FBG 1, diminishing down the pile shaft until reaching 56 με at FBG 4. These were also used to calculate load distribution in the pile [10]. Figure 11 shows load distribution together with a simplified analytical approximation [11]. It can be observed that the FBG measurements generally agree well with the pattern of the model, however smaller. It should be noted that there are a few assumptions made in this approximation, e.g., pile being elastic and sufficiently long. Furthermore, as the rate effect was not being taken into account, the model might substantially overestimate the axial load mobilised in the pile for this type of soil.

Figure 9 Statnamic testing device

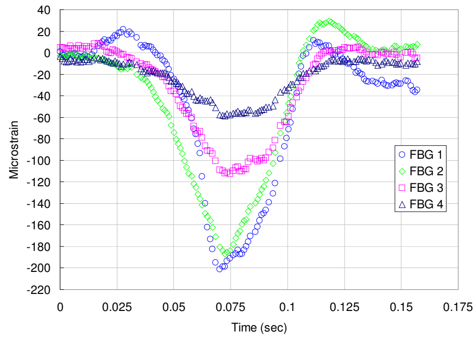

Figure 10 Strain vs. time calculated from the measured wavelength shifts

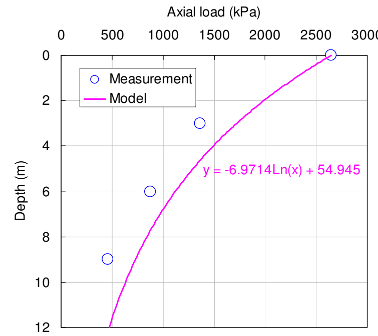

Figure 11 Load distribution at peak loads

4. CONCLUSIONS

FBG strain sensors were successfully deployed in a field pile testing trial involving three different types of testing techniques: static, dynamic and statnamic. The instrumentation systems were configured to suit the specific characteristic of each type of test. Practical issues and typical test results for each technique are presented. It has been further proven that the FBG strain sensor offers promise for pile testing applications.

ACKNOWLEDGEMENT

This research project was funded by the Engineering and Physical Sciences Research Council (Grant No. EP/D506654/1). The authors are grateful to all of the consortium members of the Technology Strategy Board funded RaPPER project for funding the installation and testing of the piles. Stent foundation ltd. constructed all the tested piles. PMC, Stent and Profound BV (NL) undertook the static, dynamic and statnamic tests respectively. Their assistance on the site is much appreciated.

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