Bored Piles Imperfection Detection Using Optical Fibre Sensor: Laboratory Simulated

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Abstract. Actual experimentation of the bored pile imperfection detection is infeasible to be conducted since the issues of limitation in imitating the actual bored pile construction and absent of practical observable condition during monitoring activity. Through this study, the bored pile is idealized to a reinforced concrete column (RC column) to ease the laboratory simulation and pile damage determination. Distributed Optical Fibre Strain Sensing (DOFSS) through Brillouin Optical Time-Domain Analysis (BOTDA) is used to detect the imperfection. The objectives of this study are to measure the effect of imperfection of bored pile through load column test and to compare the optical fibre sensor reading with conventional instruments. Firstly, the RC columns were designed and the sensors are embedded into the RC column which then loaded by few loading stages. Subsequently, the BOTDA analyser and the conventional sensors reading unit will read the strain of the RC column. After the experimentation conducted, it is proven that the fibre optic sensor is reliable and good in consistency for strain measurement compared to other conventional sensors, and the effect of imperfection of bored pile through load column test able to be measured.

1. Introduction
Substructure consists of shallow and deep foundation. It is favourable to employ deep foundation for conditions such as low bearing capacity, deep rock layer and structure with high load intensity. Deep foundation is defragged into different type of piles ranging from steel pile, timber pile, concrete pile, composite pile and drilled shaft [1]. Drilled shaft also known as the bored pile is a famous and widely used type of deep foundation in the construction industry. This is due to its exclusive characteristics such as low disturbance to the adjacent structure and flexible dimension.

Although, the construction of this type of foundation required high coordination and precautions to prevent any damage. The damages may lead to a reduction of pile strength and may induce catastrophes. The damages that normally experienced during bored pile construction are concrete contamination due to soil imposition where the concrete is mix with the earth, bulging due to the cavity on the side surface of the shaft and necking [2].

Since the inventions of the bored pile, the experts have been working in detecting the damage in the bored pile using numerous methods including fibre-optic sensor method. The method can be divided into discrete point, long-gauge sensors and continuous measurement. The discrete point measurement implies vibrating wire strain gauge (VWSG) and metal foil strain gauge, and fibre optics using Fibre Bragg Grating (FBG) technology. While, long-gauge use SOFO Interferometric sensors (SOFO) and continuous measurement use distributed sensor such as Brillouin Optical Time-Domain Analysis (BOTDA)[3].
However, actual experimentation would be infeasible to execute due to few reasons such as limitation in imitating the actual bored pile construction and monitoring it in a practical observable condition (lab condition). The most highlight issue is that the imperfection underground cannot be observed with the naked eye. Most of past studies made assumption on the type of damage happened to the underground bored pile as refer to the strength-strain data [2]. Thus, this study proposes to replicate the bored pile with a reinforced concrete column (RC column) to make the observation feasible to be performed. This is because both structures comprehend the closes role in a civil structure.

Distributed sensor through Distributed Optical Fibre Strain Sensing (DOFSS) was chosen as the strain monitoring method. Brillouin Optical Time Domain Analysis (BOTDA) or Brillouin Optical Time Domain Reflectometry (BOTDR) is one of the techniques in DOFSS beside Raman Scattering Sensors and Rayleigh Scattering Sensors. BOTDA is a system to read the strain using the single mode optic fibre where the analyser emits the pulse from one end of the fibre, and it travels along it. Some of the travel light travel back (backscattered) which enables it to measure the strain[4]. Besides, it is the best and effective technique for strain measurement.

The objectives of this study are (i) To investigate strain distribution of axially loaded RC column under various state of imperfection correspond to bored piles problem (i.e. cross-section reduction, concrete contamination and honeycomb), and (ii) To verify the measurement performance of the fibre optic sensor by comparing the results with conventional instrumentation and theory.

2. Literature review

2.1. The problem in bored piles
Despite all the benefits offered by the bored pile technology, it did carry a few problems. The problems are derived from few sources which may be classified into few classes namely force majure source, insufficient soil study, mislead pile testing, operation loading and construction [5]. This study would like to focus on the construction problem since it will show odd strain data [2]. The incident that typically happened during construction either under control or unavoidable condition are a soft toe on bored piles due to insufficient base cleaning, defects within the shaft of bored piles, insufficient founding conditions, ground movements induce due to drilling, excavation and dewatering effects, especially with remedial piling projects and excessive driving of preformed piles [5]. Next, the imperfections that induced by the construction activity could be classified into structural damage or geotechnical damage. Structural damage mostly covers the dimension and strength which differs to the designed value. Necking and bulging are examples of structural damage. Misinterpretation of the site condition corresponds to the construction sequence would lead to geotechnical damage. This can be seen during difficulty in withdrawing the casing and lack of monitoring during bentonite use in drilling activity.

2.2. Pile imperfection correspond to Young’s modulus theory
Pile imperfections as mentioned before can be explained theoretically by manipulation of Young’s Modulus theory. This theory explains by [6] as the value that describes the stiffness or stretchiness of a material. Other than that, Young’s modulus can be represented as the ratio of stress and strain of a material.

\[ E = \frac{\sigma}{\varepsilon} \]  \hspace{1cm} (1)

where, \( E \) = Young’s modulus, \( \sigma \) = stress and \( \varepsilon \) = strain. Strain is the change of length of an object as force is applied to it either compression or tension and the value is respected to the object’s material instead of the object’s dimension. Then, stress is the amount of pressure applies onto a surface area of materials. The unit used is Pascal (Pa) which the same unit used to define pressure. The equation is as follows:

\[ \sigma = \frac{P}{A} \]  \hspace{1cm} (2)
where, $P = \text{pressure}$ and $A = \text{surface area}$. Substitutes equation (2) into (1),

$$
\varepsilon = \frac{P}{EA}
$$

(3)

Corresponds to bore pile imperfections, the change of material stiffness ($E$) happened when concrete strength reduces as the soil intrusts into the concrete during construction activity and honeycomb formation during the post-concreting process, which cause pile stiffness imperfection. While, the change of surface area ($A$) occurred as the piles experience necking or bulging, which cause surface area imperfection. As the stiffness and surface area imperfection happened, it does affect the strain of the bored pile either increase or decrease, as the force introduces to it. These conditions clearly portrayed by the manipulated Young’s Modulus theory throughout this section.

2.3. BOTDA method

BOTDA method was invented after the first introduction of Raman Scattering in the 1980s. The idea of the invention is to expand the DOFSS technology and strain-temperature measurement [3]. BOTDA using a standard communication optical fibre (single mode type) which widely available on in today’s market. The light pulse is emitted from one end of the optic fibre connected to the analyser to another end where it propagates along the cable and some pulse are backscattered [7]. The backscattered light is Brillouin scattered light in which according to [8] the Brillouin frequency is relative to the occurrence strain. Since then it enables the BOTDA to measure the strain from scattering location by read the backscattered pulse for both parameter, frequency and return time [7]. The optical fibre may be installed either mounted on the structure surface or embedded in the structure.

Temperature and strain are the possible parameters that can be measured by the BOTDA. The reading happened when the light propagates through the optical fibre, most of the light pass and some may travel back. This travel backlight known as backscatter light and portion of it is Brillouin scattering. According to [9] stated that “Brillouin scattering occurs because of an interaction between the propagating optical signal and thermally excited acoustic waves in the gigahertz range present in the silica fibre, giving rise to the frequency-shifted components. It can be seen, as the diffraction of light on a dynamic grating generated by an acoustic wave (an acoustic wave is actually a pressure wave that introduces a modulation of the index of refraction through the elasto-optic effect)” (as cited in [3]).

The light that had been diffracted propagates in the fibre at the acoustic velocity. This phenomenon calls Doppler shift. The density of the medium that temperature and strain dependent, and the acoustic velocity is directly proportional to each other [3]. Through this concept, the temperature and strain data are able to be measured.

BOTDA consists of hardware that helps it to serve its function. Optical fibre cable and reading units are the prime hardware use in BOTDA technologies besides others. Optical fibre cable use in BOTDA is normally a standard communication cable consist of core-cladding and the buffer layer. The core layer is made up of glass with refractive index (RI) 1.5 [4] and the core size normally 8µm. The cladding layer’s RI must be lower than the core in order to enable the clean light propagation.

There are two types of cables available in the market which are single mode and multi-mode. The single mode which also known as fundamental or monomode is normally used in telecommunication while the multi-mode can be found in data communication service line. The relative size and optical performance are the major differentiation among the cables. Besides, the single mode cable only enables one light to travel along it while multi-mode allows numerous lights to pass through it.

Then, there is a wide range of available reading units offer in the market by specialist company such as Omisens, SMARTEC, Sensornet, ANDO and Nubrex. The typical spatial resolution is 1 m which may go up to 20 m [10]. Multiple fibre optical cable is able to be connected to the lodger.

2.4. Performance of BOTDA method

Zeng et al. [11] once wrote that BOTDA is an operative mechanism to supervise the structures’ health in wide scale since it proved form the result of laboratory bending test on the beams and steel pipes as example which equivalent with the precise spatial resolution of conventional strain gauges as cited by
[4]. BOTDA is a distributed type of sensor which possible to measure up to 30 000 points in one line. This capacity made BOTDA an economic and efficient way of strain and temperature reading. BOTDA technology able to measure those mention parameters, strain and temperature at the accuracy of 20 µε and 0.2 °C respectively [3]. This fibre has the ability to read 30 km to 150 km with a range of extenders.

3. Methodology

The methodology carried out started by designing the RC column in a rectangular shape with 150 x 150 x 1250 mm dimension and casted with 20 MPa concrete strength of conventional concrete. There are 6 conditions of the columns namely control, with rebar lapping, cross-section reduction, localized reduction of cross section, concrete contamination and honeycomb. Prior to concrete casting, 2 type of sensors were embedded into the concrete namely optical fibre and strain gauges. Then, the RC columns were cured for 28 days. Upon the testing period, there were 3 types of instrumentation had been set up as detailed in Table 1. Details of the methodology as following subsection:

**Table 1. Type of instruments.**

| No. | Parameters                  | Instruments                                                      |
|-----|-----------------------------|------------------------------------------------------------------|
| 1   | Load                        | Universal Testing Machine Dynamic Machine 500kN                  |
| 2   | Displacement                | Linear variable differential transformer (LVDT)                  |
| 3   | Strain sensor: embedded into the RC column | BOTDA and electric strain gauge                               |

3.1. Design and fabrication the RC column

Foundation design may need to consider geotechnical and structural aspect [4]. However, this study will not consider the geotechnical element since it will be carried in the laboratory. Therefore, Section 2.6 Load test and tests in experimental models from BS EN 1997-1:2004 Eurocode 7: Geotechnical Design – Part 1: General Rules were applicable. Moreover, the column design also conformed to the BS EN 1536:2000 Execution of special geotechnical work – bored piles.

The RC columns were designed with dimension which specifies in the following section. The columns were made up of concrete with reinforcement. The reinforcement detail is specified in the below section.

3.1.1. Design the RC column dimension

There are six typical imperfection happened on the bored piles whereas there were six RC columns constructed to imitate the imperfection conditions (Figure 1). The column dimension was designed to be stocky enough which the slenderness ratio is less than 15 [4]. This concern was to maintain the column before it fails in buckling which is not favourable in column design.

Moreover, the dimension was also being designed to cater the loading from the loading machine correspondent to concrete capacity 20 MPa. The concrete capacity will be detailed in the casting section. Other than that, the height of the column was limited to 1250 mm due to the limitation of the available headroom under the loading machine in the laboratory. The conceptual drawing of the columns is portrayed in Figure 1 below.

3.1.2. Fabricate the reinforcement cage and formwork

The reinforcements of the column were made of steel Y type - hot rolled deformed high yield steel reinforcement with characteristic yield strength of 500 N/mm³. The bar size was varied correspond to its location. 8 mm diameter bar used for main bar and 6 mm diameter bar used for link. 25 mm of concrete cover was provided and the length of four main rebars is 1200 mm. The shear link spaced at 120 mm. The formworks for the RC column were made up of plywood and 2 x 1 in timber. The dimension and design of formwork were corresponding to the RC column dimension (150 x 150 x 1250 mm) and designs.
Figure 1. RC column drawing: A) control, B) with rebar lapping, C) reduction of cross-section, D) localised reduction of the cross section, E) concrete contamination and F) honeycomb.

Figure 2. Rebar and fibre optic arrangement.

Figure 3. Loading test arrangement.

3.2. Installation of sensors

There are 2 types of sensors that were installed on the reinforcement, the main sensors is the fibre optic and the secondary sensor (conventional) is the strain gauge. The idea of utilization of two sensors was to have a better reading/result and to cross check each other. The installation detail as per the following sections.

A single mode type of fibre optic was chosen to be used in this study. The installation was done by continuously aligned the cable along the four main bar by looping at end before free end. Figure 2 shows the layout of fibre optic in the column. The cable ties were used to attach the cable to the reinforcement bar. About 1 meter of the cable was kept as an extra allowance for splicing it with a pigtail to be connected to the logger later during the testing stage. After the installation was done, the fibre optic was tested by projecting a laser beam into one end of the cable and the beam is shown at other cable’s end to validate the functionality of the sensor.

A 30 mm length of strain gauge was used in this study. The sensor is manufactured by a Japanese company, Tokyo Sokki Kenkyujo Co., Ltd. and having gauge resistance 120 ± 0.3 Ω. According to [9], the strain gauge arrangement will be at the top, middle and low part of the RC column.

Nevertheless, for this study, the strain gauges were placed with three different types of arrangement. First arrangement is three levels of strain gauge for Column A and B, second arrangement is four levels of strain gauge for Column C, D and F, and third arrangement is two levels of strain gauge for Column E. The arrangement made to provide the strain reading at interest region corresponding to the column imperfection.
3.3. Casting the RC column
The RC columns were casted with normal concrete made up of standard Ordinary Portland Cement type of cement and maximum 20 mm crushed coarse aggregate. The characteristic strength of the concrete is 20 MPa achieve at 28 days. This was because the available testing machine only capable to test concrete with mentioned strength corresponds to the loading area of the RC column. Typically, bored piles concrete strength is ranging from 20 MPa to 40 MPa [4]. The slump of the concrete is 100 mm to allow good workability of the concrete during the casting process. After the casting process, the RC columns were cured to achieve design characteristic strength.

3.4. Testing the RC column
The casted RC columns were tested using a Universal Testing Machine Dynamic Machine 500 kN. The machine axially loaded a compression load onto the RC column from the top. The top of the column was fixed with steel plates, and the RC column standing was attuned by applying dental plaster [4]. Two linear variable differential transformers (LVDTs) were set up, and connected to the strain indicator and recorder, together with the strain gauges. Besides, the fibre optic reading unit was set up during the testing to continuously read the strain throughout the RC column. The measurement was using 10 MHz frequency and 5 ns or 0.5 m distance resolution. The testing arrangement depicted in Figure 3.

4. Result and discussion
In this section the strain profile of each column is discuss. This is to investigate the strain distribution of axially loaded RC Column under various state of imperfection. Should each of column portrays strain profile according to the assigned condition. There are 3 set of data presented in the figures that will be discussed in this section; average FO, average SG and theory value. Noted that the top and bottom part of the graph need to be discarded since it is the convolution region with respect to 5 ns of pulse width (spatial resolution). Convolution is the product of true strain profile in fibre optic cable and resolution function of BOTDA. The resolution function.corelated to the spatial resolution of the measurement system [4]. To ease the discussion some abbreviations were made up for strain gauge (SG) and fibre optic (FO). Below is the discussion for each column:

Column A was used as a learning and experience tools for this study. During the testing, the SG logger having error in data capturing which demand the test needed to be redone. Figure 4(a) shows the strain profile of the column after second loading cycle. Supposed the strain profile for this column should be flat without peak in the middle. This situation happened maybe due to the double cycle loading.

Then, Column B in Figure 4(b) show the rebar lapping condition. Suppose the rebar lapping condition will not affect the column’s stiffness as the design and fabrication done according to the requirement. This condition is clearly depicted in Figure 4(b) where the strain is approximately constant at 240 µm/m.

The column C (Figure 4(c)) imitate the cross-section reduction (necking and bulging) of bored piles. The strain value at middle of column where reduction happened is 282.814 µm/m and continue increase until reach 308.736 µm/m at distance 0.84 m. The increments happened due to the hair line crack during the experiment was conducted.

Next, column D imitates the localized reduction of cross section imperfection of a bored piles. The FO used is able to detect the imperfection as displayed in Figure 4(d). At nearly middle of the column (0.56 m) the strain value is the highest at 270.767 µm/m and the trend decreasing back before experiencing acute rise due to reduction area at nearly 0.8 m distance.

Besides, in column E concrete contamination causes the stiffness reduction. This condition is shown is Figure 4(e) where the strain profile show imperfection of contamination at the center of the column. This strain profile is corresponding to the casted column where 300 mm length of concrete contamination is in the middle. The highest strain in the contamination region is -606.653 µm/m having 384.433 µm/m different compared to strain at non-contaminated concrete region.

Lastly, in column F the honeycomb condition also decreases the structure stiffness. This situation depicted in Figure 4(f). The strain value is high (287.222 µm/m) at nearly middle of column (0.48 m) and decreasing at 0.68 m distance. Then, increase back at 0.84 m with 274.603 µm/m strain value.
5. Conclusion
At the end of this study, the imperfection of bored pile simulated through RC column was proven. Total of 6 RC Columns fixed with fibre optic and conventional sensors were tested with axial loading in laboratory. The strain reading from the sensors of each column was recorded and analysed. The following conclusions that can be drawn:

Figure 4. Strain profile of the column according to imperfection condition.
If the stiffness reduction happened onto the specimen, the strain reading will read high strain value and vice versa. This condition can be observed from column B, E and F. Similarly happened when the reduction of cross-sectional area of the specimen which was investigated through column C and D.

The fibre optic sensor able to detect the imperfection at any point along (continuously) the specimen instead discrete point provided by conventional sensor (strain gauge). This allow the acknowledgement of imperfection at specific point.

6. References

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