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Distributed Optical-fibre Strain Sensing in Reinforced Concrete Structures

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Graphical abstract

Brillouin Optical Time Domain Reflectometry (BOTDR) for concrete structure health monitoring

Abstract

An innovative technique based on optical fibre sensing that allows continuous strain measurement has recently been introduced in structural health monitoring. Known as Brillouin Optical Time-Domain Reflectometry (BOTDR), this distributed sensing technique allows measurement of strain along the full length (up to 10 km) of a suitably installed optical fibre. The sensors can be wrapped around or embedded in structures, where a single optical fibre potentially replaces a very large number of point sensors. The installation of optical fibres in concrete structures involved several procedures such as pre-tensioning of cables, spot-glued or end-clamped onto steel rebars, and the use different types of commercially available optical cables. Such instrumentation techniques must be validated in terms of their measurement performance, which is the aim of this research. This was done through a series of well-instrumented uniaxial load tests of concrete columns. The loading of the structures were performed within the elastic range and later loaded up to failure. The test results revealed that all sensing cables of various types used in this study measured strains of about the same values (within the BOTDR accuracy of 30 microstrains) and were comparable with other independent instrumentation devices. Strain data from the two methods of attachment (spot-glued or end-clamped), either pre-tension or without pre-strain, generally did not indicate any dissimilarity between them. These findings have enabled the establishment of the best practice of field instrumentation consisting fibre optic sensors in the current exploration the use of end-clamping technique.

Keywords: Smart structures; monitoring; fibre optics; strain; geotechnical; concrete columns; BOTDR

■1.0 INTRODUCTION

Structural integration of fibre optic sensing systems represents a new branch of engineering which involves the unique marriage of: fibre optics, optoelectronics and composite material science[1,2]. In this study, we used a distributed strain measurement system known as Brillouin optical time-domain reflectometry (BOTDR) that employs a standard single-mode optical fibre on the basis of the reflective technique[3,4]. When an optical pulse is launched from the BOTDR analyzer to one end of an optical circuit, it travels along the fibre and a small fraction of the light is backscattered, one of the components of which is that of the Brillouin. Because the frequency of Brillouin scattering is linearly proportional to the applied strain[5], it is possible to obtain the strain distribution from the scattering locations by resolving the back-scattered signal for both frequency and return time of the signal.

Depending on how the measurement of the BOTDR analyzer was set, the system used in this study can measure strain with an accuracy of up to ±30 microstrain along the full length (up to 10 km) with spatial averaging of 1 m. BOTDR can be used with standard inexpensive telecommunication optical fibre cables, wrapped around or embedded in structures, such that a single optical fibre potentially replaces a very large number of closely spaced point sensors. Hence, it provides an economic and effective solution and has considerable potential as a system for performance monitoring.

The suitability of distributed strain measurement using optical fibre sensors has been demonstrated in a number of geotechnical field trials for various types of tunnel monitoring[6,7], pile foundations[8,9] and earth retaining structures[10]. A number of techniques were developed to suit the practicality of installation inside concrete piles[11]. These include the need to pre-strain the cables and attaching them on the reinforcing bars by equally spaced spot-glue or by simple end-points clamping[12]. It is however uncertain whether the variation in the installation techniques would have any influences to the strain data obtained. Moreover, fibre-optic cables may come from various shapes and sizes and coated with different materials, in which it is necessary to investigate their strain sensing performance before it can be properly deploy in the field.

Therefore, this paper aims to investigate the performance of different types of optical cables as well as variation in the attachment methods used in concrete pile instrumentation. A total of three reinforced concrete columns equipped with fibre optics and conventional sensors were axially loaded using a hydraulic machine in a control laboratory environment. For convenience, brief presentation of the experimental procedure and data interpretation are given in the followings.

■2.0 OPTICAL FIBRE SENSING CABLES

Four types of strain sensing cables used for BOTDR are shown in Figure 1. The simplest type is shown in Figure 1a. It has an external diameter of 0.9 mm with a single optical fibre placed in the middle. The plastic coating and the inner glass core are fixed together so that the strain applied externally is transferred from the coating to the inner core. This low cost (~US$0.20/meter) cable is fragile and care must be taken when installing it. A sensing cable with multiple optical fibres in the shape of a ribbon such that as shown in Figure 1c is also inexpensive and provides redundancy in case one of the fibres breaks. Extra layers of protection are often placed around more than one fibre to form a cable. Special types of optical cables are also available for direct bury application. Examples of such fibres are shown in Figures 1b and 1d. These cables are reinforced by steel wires (Figure 1b) and Kevlar yarns (Figure 1d) and hence are more robust, but still transmit the strain applied through to the glass optical fibre and allow the strain to be measured. Although they are considerably more expensive (up to US$20/m), their installation time is relatively short as gentle handling is not an issue (like for cast-in-place piles).

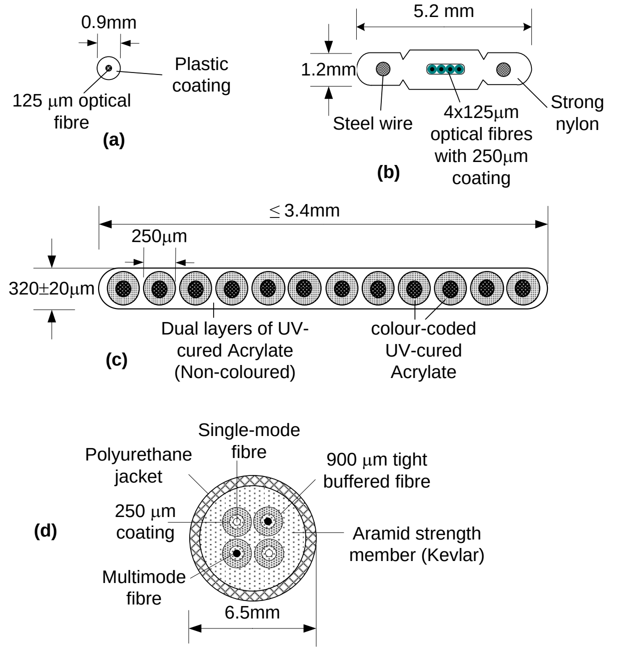

Figure 1 Cross-sectional view of strain sensing optical cables (a) Single fibre, (b) Reinforced ribbon fibre, (c) 12-ribbon fibre, and (d) Sensornet cable

■3.0 INSTALLATION METHODS

The procedure of optical fibre installation of cast-in-placed piles as mentioned in the literature is to pre-tension the cables before attaching them onto the host rebar. This is to ensure that the fibres would not go slack but correctly measures compressive strain by reduction in the tensile strain. Figure 2 demonstrates the two attachment techniques implemented in our experiment consisting of Point Fixing (Spot-Glued) and Two-point Fixation (End-Clamped). The cables were pre strained to about 1500–2000 microstrain by manually hand-pulling each cable at one end whist the opposite end is clamped onto the rebar. Once the desired strain is achieved (this is checked by connecting the cable to the BOTDR analyzer), the two ends are epoxy glued using rapid curing adhesive. Gluing only the two ends is mimicking the end clamping technique conducted in the field**[10]**. In the case of the spot-gluing method, the glue is applied at every 15–20 cm along the rebar**[4]**. The former method (end-clamp) is more feasible in the field because the cables can be installed during the insertion of pile steel cage into the borehole prior to casting of concrete. The latter method on the other hand requires considerable installation time and space access, but allows gentler handling of the cables.

A total of eight rebars were used to construct the cage for each column (Figure 2). Each rebar was attached with a certain type of optical cable and method of attachment. A generic-type of strain gauges suitable for steel surface attachment was also used in the experiment for comparison purposes.

■4.0 CONCRETE COLUMN LOAD TESTS

Compressive load tests on three reinforced concrete columns were performed to study the effect of variation in the installation techniques conducted for recent instrumentation of cast-in-situ piles**[8]**. Due to the spatial averaging effect of BOTDR measurement (i.e. 1 m spatial resolution), the columns were designed to be long enough so that the true strain of the system can be correctly measured, that is, somewhere at the mid-height of the column. The columns were named as Prototype, Column II, and Column III. The Prototype column has a length of 1.2 m while Columns II and III are 1.8 m long. These columns were designed to be stocky (i.e slenderness ratio of less than 8), have better loading stability and less likely to buckle. The reinforcements of the three columns were designed in accordance with BS ENV 1992-1-1.

The uniaxial loadings on the columns were firstly done within the ‘elastic region’ (consisting of a single loading-unloading cycle) before loaded up to failure. Thus additional tests on the elastic properties of the concrete and steel reinforcement were conducted to estimate the elastic limit of the column. The concrete secant Young’s modulus was measured from concrete cylinder test which can also be compared to the suggested values given in EN 1992-1-1 based on the concrete cube test**[13]**. The secant value of modulus of elasticity was measured for compressive stress applied between 0 and $0.4f_{cm}$ (i.e. up to 40% mean value of concrete cylinder compressive strength).

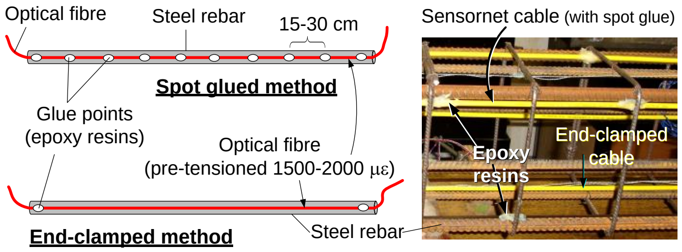

Figure 2 Attachment methods of optical cables

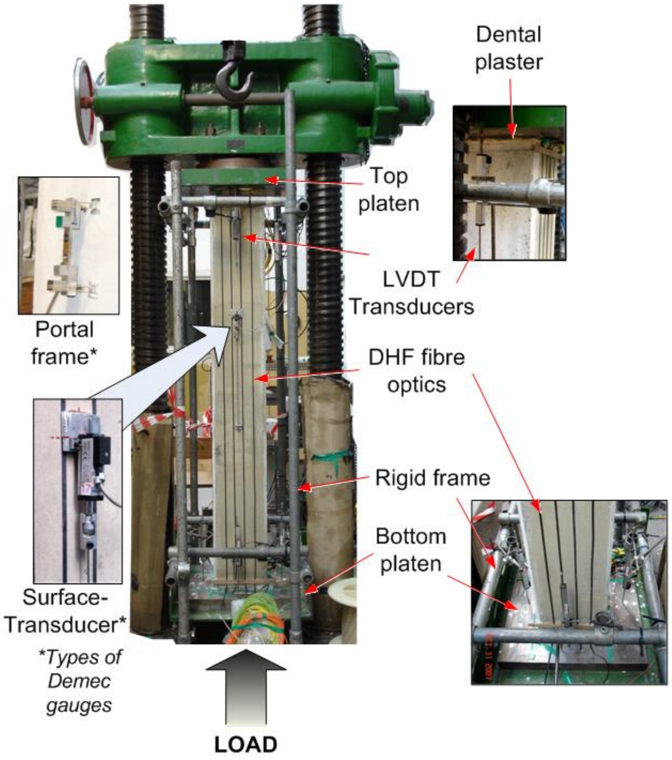

Figure 3 Experiment configuration for load test

A servo-controlled hydraulic machine (Amsler) with a capacity load of 5000 kN was used to apply axial compression loads onto the concrete columns as illustrated in Figure 3 through a hydraulic jack at the bottom platen. The load is carried to the concrete structure towards the top platen where it is anchored to the ground by two piers. The top platen consists of a bearing system which allows rotation for self-adjustment. Thus, it requires load as much as 50 kN to counter the self weight of the top platen and eliminate any bedding movement. It is usual that baseline of strain measurements are made after applying this pre-loading to the column first.

Special attention was made during the erection of the column so that the structure stands vertically upright. The adjustment of the column standing was made using dental plaster pastes applied at both ends (platens). In order to detect any possibility of errors caused by differential movement or beddings, four LVDT transducers were installed at the top and bottom platens at four sides of the column. This also enabled an independent external displacement measurement of the structure. Demountable mechanical strain gauges (Demec) and transducers were mounted on the concrete surface at the middle section for surface measurements. Demec gauges were installed on all four directions of Prototype column. Surface transducers, which measure displacements over a longer extension of gauge length (100 mm), were installed on two opposing sides of Column II and Column III.

In addition, fibre optic surface measurements were made by the inclusion of prototype self adhesive fibres attached along the concrete surface (outputs are not covered in this paper). All of the cables installed inside the column were connected together to form one continuous fibre. Slack (loop) sections outside the specimens were formed after each attachment inside the rebar to provide jointing points of two different fibres and a section of reference so that temperature compensation technique can be applied.

■5.0 RESULTS

In this paper, results of the experiments are summarised into four categories as described herein. Details of the full experimental results can be referred from the doctoral thesis of the first author[14]. For ease of explanation, only the loading part of *elastic* load-unload tests are shown in Figures 4 to 6. These data were compared with averaged strain gauge readings, and theoretical calculations of ENV 1992-1-1 Eurocode 2: Design of concrete structures - Part 1-1.

5.1 Comparison of Different Types of Optical Cables

Figure 4a compares the performance of cables between Reinforced ribbon, 12-ribbon and Single fibre conducted in Column II using spot-glued method. The figure shows strain linearly increases with loading. Close agreement can be observed between different types of optical cables. In this case, the averaged standard deviation of strain from a given load is 18.4 microstrain. (Note that the accuracy of BOTDR reading using Yokogawa AQ8603 is ±0.004% at two times standard deviation). Similar patterns are also observed from tests conducted in Column III where comparisons being made between Sensornet and Reinforced-ribbon cables as shown in Figure 4b. Both cables using the same attachment technique (spot-glued) recorded strain of the same magnitude (i.e. Sensornet II and Reinforced ribbon). It should be noted that response of another Sensornet cable attached on a different rebar agreed with the strain gauge reading. The averaged standard deviation of the three cables (Figure 4b) is 27.7 microstrain, which is still within the accuracy of BOTDR measurement.

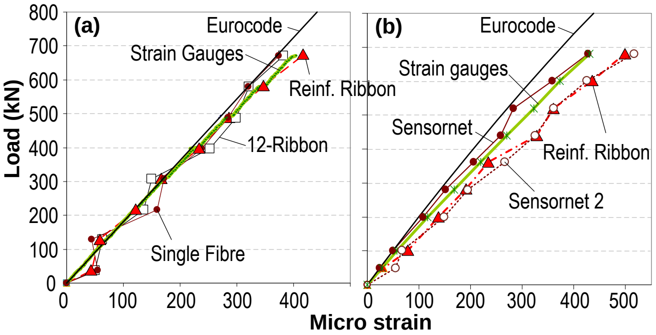

Figure 4 Variation in types of optical cables installed in (a) Column II and (b) Column III, both using spot-glued method

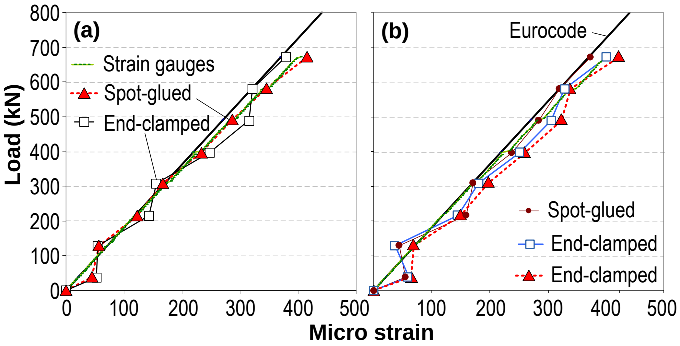

Figure 5 Variation in method of attachments in Column II using (a) Reinforced ribbon cables, and (b) Single fibre cables

5.2 Comparison Between End-clamped and Spot-glued

Examples of data showing variation in attachment techniques in Column II are shown in Figure 5. The experiment consisting of Reinforced ribbon cables (Figure 5a) indicates outcomes from both methods that of spot-glued and end-clamped, are similar and consistent with that of strain gauges. Similarly in the case of Single fibre (Figure 5b), the end-clamped fibres recorded strain differences of less than 15 microstrain in comparison to the spot-glued method. Other cables with variation in attachment techniques made in Prototype Column consisting of 12-ribbon fibres and Sensornet in Column III (not shown here) also do not exhibit any deviation in the strain readings, all of which but broadly agree with electrical based strain gauges. In general, it can be concluded that varying the attachment method between spot-glued and end clamped does not affect fibre optic strain measurement embedded in concrete.

5.3 Effect of Cable Pre-tensioning

Compressive strains are usually measured by deducing the reduction of tensile strains from BOTDR baseline reading. It is unknown whether pre-tensioning of optical cables is required inside the concrete since it is unlikely that they would become slack or crimple. Figure 6 shows the result of strain measurements of two types of cables installed under pre-tension and without pre-strain conducted in Column III. It can be seen that Reinforced-ribbon behave consistently either pre-strained or without pre-strained. On the other hand, there exists a large discrepancy in the Sensornet cable when the cable is pre-strained. This cable was actually pre-tensioned to about 2000 microstrain. The high pre-stress applied to the fibre somehow had caused the cable to strain less under 400 kN (300 microstrain) but showed much higher values for higher load range.

One explanation of such non-linear behaviour depicted by the pre-strained Sensornet cable is attributable to the fabric bonding effect of the Kevlar yarn located underneath the thick-coated buffer. The stored pre-strained energy within the Kevlar may had initially "locked" minor stresses imposed but later dissipated or slipped as more shear force was transferred from the outer jacket. Changes in the shear stress of the cable's jacket in this case were not proportionally transferred to the optical fibre and thus giving the non-linear effect. Further investigation however is needed to confirm this finding.

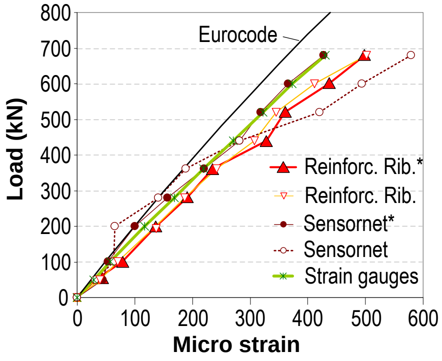

Figure 6 Effect of pre-tensioning of cables. (* without pre-tensioing)

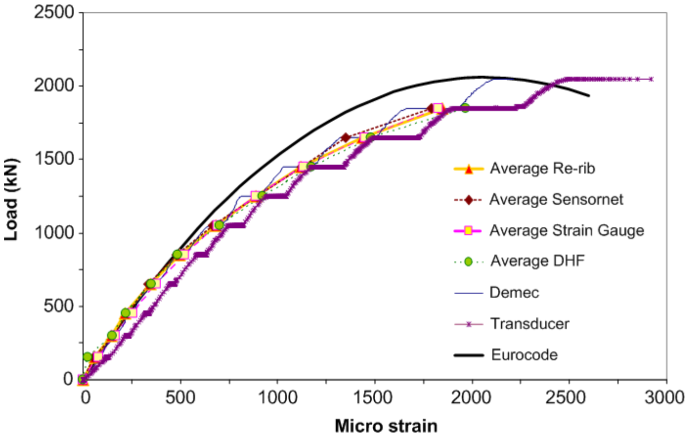

Figure 7 Loading to failure of Column III

5.4 Performance of Cables Under High Compressive Load

Strain measurements of Column III from all instrumentation during the ultimate load test are presented in Figure 7. The transducers recorded highest movements (upper-bound). This is expected because of the bedding error where external measurement is usually higher than internal measurement (only part of the external strain is detected by the internal system). Excellent agreement is seen between the surface-mounted gauges such as Demecs and the embedded sensors consisting of strain gauges, Reinforced ribbon and Sensornet cables. The Eurocode curve on the other hand provides the lower-bound. This is because the analysis did not take into account the loading rate used in the tests. Note that concrete creep occurred at each loading stage when the load was held constant (this process was required to allow BOTDR eight minutes acquisition time). Thus, it can be seen in Figure 7 that the structure failed at a lower ultimate value than the predicted value.

■6.0 CONCLUSIONS

In this study, the variation in the installation techniques of optical fibre sensing in concrete structures are described and validated through laboratory concrete column load tests. The results indicated no distinction of measurement performance when using different types of sensing cables. These cables were tested because they were previously adopted in the field. There was also no major variation in the strain readings when the cables were installed either as spot-glued or end-clamped. Hence, the end-clamp installation method is recommended in the future field instrumentation because of its fast and simple attachment procedure. The act of pre-tensioning of cables may be used during fibre installation. However, caution should be exercised in case of the Sensornet cable as the cable appeared to behave non-linearly under high pre-strain. In general, the performances of fibre optic sensing were consistent with other instrumentation devices, albeit during structural working load or during the state of structural failure.

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