Malaysian Journal of Civil Engineering 29(2):132-144 (2017)

DISTRIBUTED FIBRE OPTIC AS SENSOR FOR CORROSION DETECTION IN STEEL REINFORCEMENT

Lew Shong Wai & Mohammad Ismail*

Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM, Johor, Malaysia

Corresponding author: mohammad@utm.my

Abstract: Previous studies indicated that problems with the application of distributed fibre optic sensor remain unresolved despite considerable effort in the last few decades. This research describes the work conducted to develop the use of BOTDA, as a distributed strain sensing technology, to identify the presence of corrosion in steel reinforcement in concrete structures. BOTDA is capable of measuring relative strain at any point along a standard optical cable. A properly installed cable can replace multiple closely-spaced strain sensing gauges and is considered cost-effective in this context. In corrosion monitoring, the presence of corrosion can be monitored by many means such as fibre optic sensing technique. The application of distributed fibre optic in corrosion detection seems to be a potential for research. The location of corrosion in steel reinforcement in concrete is expected to be detected from the occurrence of spike in the relative strain profile obtained from a single optical fibre. There are many implementations that require careful consideration and hence are examined in this research. Specimens were casted and installed with standard fibre optic cables along the steel reinforcement. Reinforcement were grinded at predetermined locations to reduce its cross sectional area to simulate cavity due to corrosion. Relative strain profiles were obtained from BOTDA when the specimens are loaded. Further investigation is recommended to make better sense of the results obtained.

Keywords: *Corrosion, steel reinforcement, distributed fibre optic sensor, Brillouin optical time domain analysis (BOTDA)*

1.0 Introduction

There are many applications of distributed fibre optic sensor. Distributed fibre optic sensor has been regarded as a way to overcome the shortcomings of point-based sensors such as the fibre Bragg Grating (FBG) sensor. The Brillouin Optical Time-Domain Analysis (BOTDA) sensor is an example of a distributed fibre optic sensor which has been used for long distance sensing. Its application in corrosion monitoring has not been comprehensively developed (Sidek *et al*., 2011).

2.0 Corrosion of Steel Reinforcement in Concrete Structures

Corrosion of steel reinforcement in concrete is a problem and has huge economic as well as social implications. Steel corrosion is a dominant factor for the degradation of concrete structures. Reinforced concrete make up large portion of the physical infrastructure of the world, and their durability is an issue of concern (Leung *et al*., 2008). Deterioration of concrete structures due to harsh environmental conditions leads to performance degradation of reinforced concrete structures, and premature deterioration of structures before completing service life is a major concern for engineers and researchers (Verma *et al*., 2014)

The main factor causing corrosion of steel reinforcement is the ingress of chloride ions and carbon dioxide to the reinforcing steel surface. This may cause pitting, where cavity will be formed in the steel or rust formation, where deposit will be formed around the steel surface. Pitting can be more dangerous than uniform corrosion as it is more difficult to detect, predict and design against. One of the ways to detect this is by using the fibre optic system (Song & Saraswathy, 2007).

3.0 Fibre Optic System

Generally, a fibre optic system consists of a light transmitter, a receiver, an optical fibre, a modulator element, and a signal-processing unit. Optical fibre is normally made from silica glass or polymer material, which either acts as a sensing element itself or carries the light from the source to the modulator element. In the occurrence of strain or temperature variation, the surface-mounted or embedded optical fibre sensor in the structure will expand or contract. In accordance with the change of the length of the optical fibre, the optical fibre sensor modulates the light and reflects back an optical signal to the analytical unit for deriving the concerned physical quantity of the structure (Annamdas, 2011; Afzal *et al*., 2012 & Ye *et al*., 2014)

3.1 Brillouin Optical Time Domain Analysis

Distributed optical fibre sensors, named Brillouin Optical Time Domain Analysis (BOTDA) is another optical monitoring technology developed in the last decade. It is also known as Brillouin Optical Time Domain Reflectometer (BOTDR). They can achieve synchronous strain monitoring of structures both in multi-environment and multi-dimensional space. It was demonstrated that BOTDA is feasible in monitoring durability it can accurately measure the strain values and identify the crack locations of the simulated reinforced concrete column. BOTDA has limited spatial (Mao *et al*., 2015)

4.0 Issues on Optical Fibre Corrosion

Structural health monitoring (SHM) is scarcely used on real structures. An efficient approach for implementation of SHM has not been developed yet, which is in part due to the current inefficient fragmented approach to SHM in research activities, in practical applications and in education (Sigurdardottir & Glisic). Interest on non-electrochemical embedded sensor was scarcely found in literature. There is a need to study the use of distributed fibre optic sensing technology for monitoring corrosion. Past researches have been too complicated and have been unable to demonstrate the applicability of BOTDA in structural health monitoring for practical purpose. There is a need to develop a practical and applicable method for corrosion detection in structural health monitoring (Abdul Rahman *et al*., 2012)

The problem of optical fibre corrosion detection is still current despite considerable effort during the past few decades. The basic principles and achievements have remained much the same for the past few years and the problem of optical fibre corrosion detection is far from resolved. Study conducted has shown that an approach based on distributed measurements of fluorescence excited through the evanescent field in an optical fibre sensor has great potential for corrosion detection. However, an optimal optical fibre sensor construction remains the main challenge (Sinchenko, 2013).

Despite its advantages, fibre optic network marks three challenges. The first is the need to increase the number of sensors that can be multiplexed on a single network while ensuring good signal quality. The motivation for multiplexing fibre optic sensors is the cost. The second demand is to ensure service continuity in the event of point failure on the network. The continued operation of the sensor network after accidental or malicious damage is of increasing importance when the structure being monitored is of high value, where human safety is at risk or when perimeter security is a concern. The third is to enable the possibility of remote sensing (Fernandez-Vallejo & Lopez-Amo, 2012).

This research was conducted to investigate the applicability of BOTDA as a distributed fibre optic approach to accurately detect the location of corrosion of steel reinforcement in concrete. The hypothesis is that the presence of corrosion can be detected based on occurrence of spike in the strain profile where defects are located.

5.0 Methodology of Research

The research laboratory works was carried out in Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM). M25 grade concrete with the mix proportion of the concrete as shown in the following table was used to cast the concrete specimens. The cement used is Ordinary Portland Cement (OPC). The fine aggregate used is medium sand and the coarse aggregate used is of 10mm size. The water - cement ratio adopted is 0.5 to obtain high workable concrete and to reduce vibration of concrete required.

Table 1: Concrete Mix per Cubic Meter of Concrete by Weight Batching

Constituents	*Weight (kg/m3)*
Cement	360
Coarse Aggregates	1150
Fine Aggregates	600
Water	180

Concrete is mixed in accordance to BS 1881-125:2013 Testing Concrete: Methods for mixing and sampling fresh concrete in the laboratory. According to the code, the quantity of concrete in each batch is at least 10% more than that required for the proposed tests. The steel reinforcement used in this study is a high yield steel bar of 12mm diameter. The steel reinforcement is grinded at per-determined locations to simulate cavity due to corrosion. The steel reinforcement is cleaned and grinded as described in Table 2.

Four numbers of specimens are made. The dimensions of the specimens are 150mm x 200mm x 1.2m. One will be the control specimen while the other three will be used for corrosion detection. The control specimen is cast without any deformation induced to its steel reinforcement through grinding. The steel reinforcement of the remaining three concrete column specimens will be grinded at 25% of its length, at 50% of its length and 75% of its length to reduce their diameter from 12mm to 10mm to simulate presence of mass loss due to corrosion. The type of fibre optic cable used is similar to the fibre optic communication cable used in the local communication service.

Table 2: Description of Specimen

Specimen	*Description*
Specimen 1	Control sample: Original rebar diameter
Specimen 2	Reduction of reinforcement diameter from 12mm to 10mm at a distance of a quarter of beam length
Specimen 3	Reduction of reinforcement diameter from 12mm to 10mm at middle of beam length
Specimen 4	Reduction of reinforcement diameter from 12mm to 10mm at a distance of one quarter and three quarter of beam length

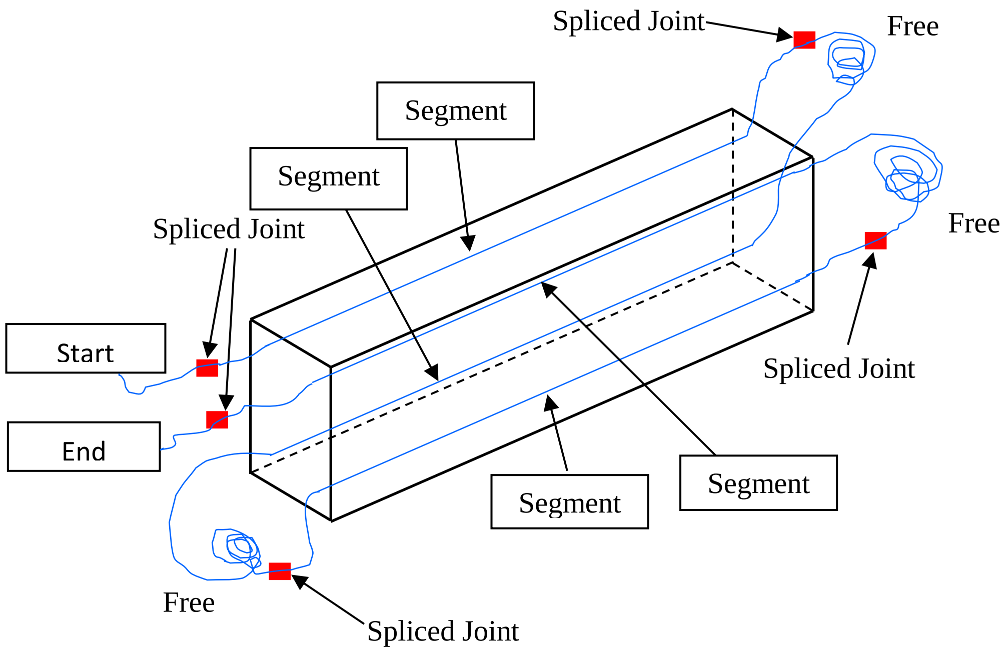

Figure 1: Details of Fibre Optic Cable Installation in Specimen

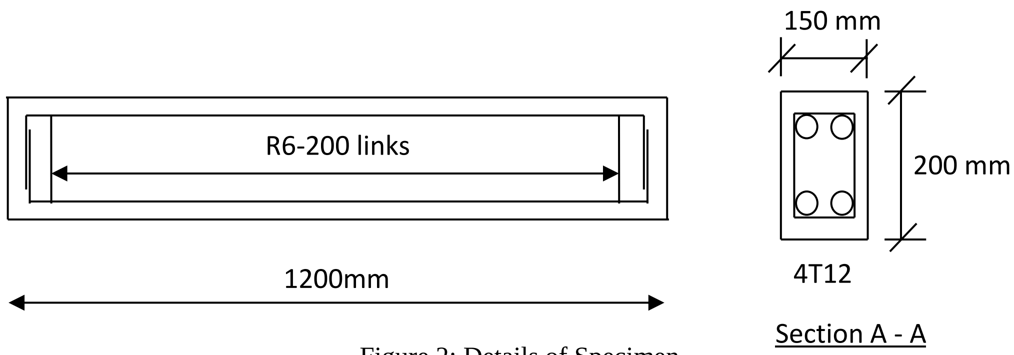

Figure 2: Details of Specimen

The fibre optic cables were carefully spliced and cleaved to ensure that the qualities of the results are not affected. The specimens were cast together with the optical cable which is attached to the reinforcement using cable tie. Concrete specimen is wet cured for 28 days. The optical cable is connected to the BOTDA analyser. The BOTDA Analyzer used in this research is from Oz Optics Limited. Data were obtained by loading the specimen. Section 7.0 presents the findings of this research.

6.0 Results and Discussion

Two sets of results are presented in this paper, one from the results of using pulse width of 1ns and another by comparing the results between different spatial resolutions. Section 7.1 discusses the relative strain versus distance graph for pulse width of 1ns and Section 7.2 discusses the comparison of output between different spatial resolutions of each specimen.

6.1 Relative Strain versus Distance Graph for 1ns

Figure 3 shows the output obtained from specimen 1. Table 3 provides a summary of the output. Specimen 1 is a controlled specimen. The expected strain profile for Specimen 1 is one without spike in strain readings. However, based on the graph, it can be seen that the strain readings is unstable and significant fluctuations are obtained. The fact that spikes are obtained at 3.0m, 6.5m and 10.0m is unable to be justified. Factors which had caused the spike could be due the loading or other factors. Further research is required to look into this.

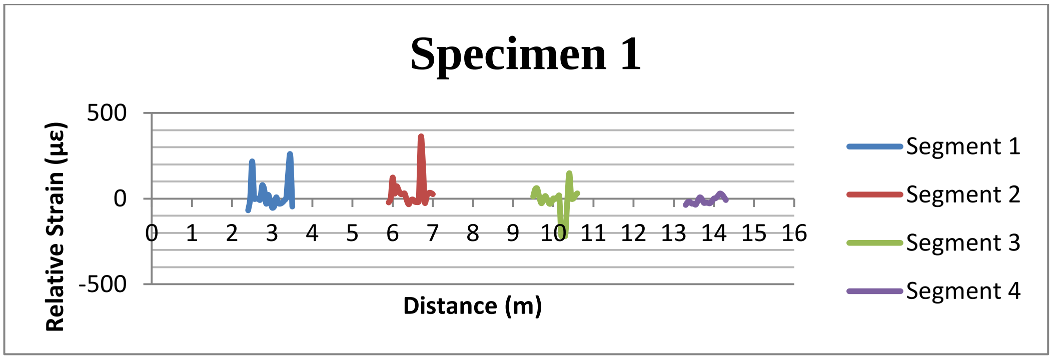

Figure 3: Strain Profile for Specimen 1

Table 3: Summary of Results for Specimen 1

Locations	*Spike Detected?*	*Remarks*
Segment 1	Yes	Detection of spike is unexpected
Segment 2	Yes	Detection of spike is unexpected
Segment 3	Yes	Detection of spike is unexpected
Segment 4	Yes	Detection of spike is unexpected

Figure 4 shows the strain profile obtained from specimen 2. In specimen 2, spike in the strain profile is expected to be at 2.9m (Segment 1), 7.2m (Segment 2), 10.3m (Segment 3) and 13.1m (Segment 4). Signals are obtained in Segment 1 and Segment 2 but very weak signals are obtained Segment 3 and Segment 4. The results obtained for Specimen 2 justified the occurrence of spike at locations where there is defect. However, there are fluctuations in the signal which is not consistent throughout the specimen. Possible factors affecting the results are discussed at the end of this section. Table 4 shows the summary of the results.

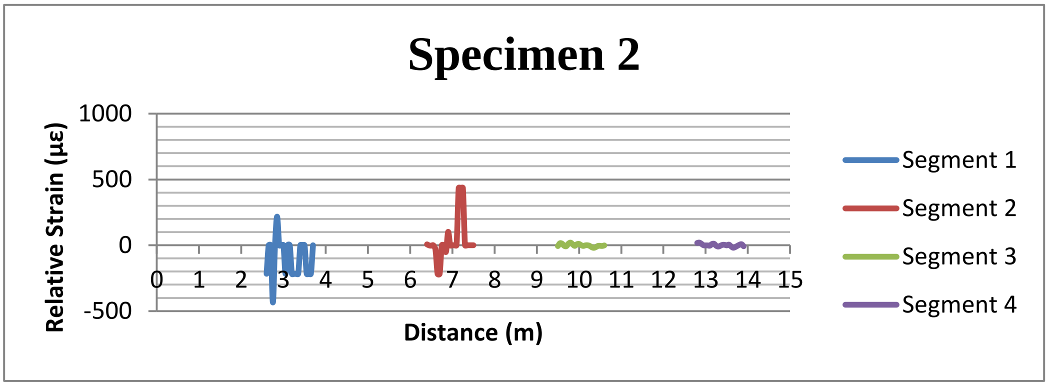

Figure 4: Strain Profile for Specimen 2

Table 4: Summary of Results for Specimen 2

Locations	*Spike Detected?*	*Remarks*
2.9m (Segment 1)	Yes	Unstable signal
7.2m (Segment 2)	Yes	Unstable signal
10.3m (Segment 3)	No	Unstable Weak signal
13.1m (Segment 4)	No	Unstable Weak signal

Figure 5 shows the output obtained from specimen 3. In specimen 3, the spike in the strain profile is expected to be at 3.35m (Segment 1), 7.15m (Segment 2), 10.65m (Segment 3) and 14.45m (Segment 4). From the graph, the spike at Segment 1 is at the predicted location. However, the signal is weak in Segment 2. The spike in Segment 3 and Segment 4 are not at the predicted location. There are also fluctuations in the signal which is not consistent throughout the specimen. Possible factors affecting the results are discussed at the end of this section. Table 5 shows the summary of the results.

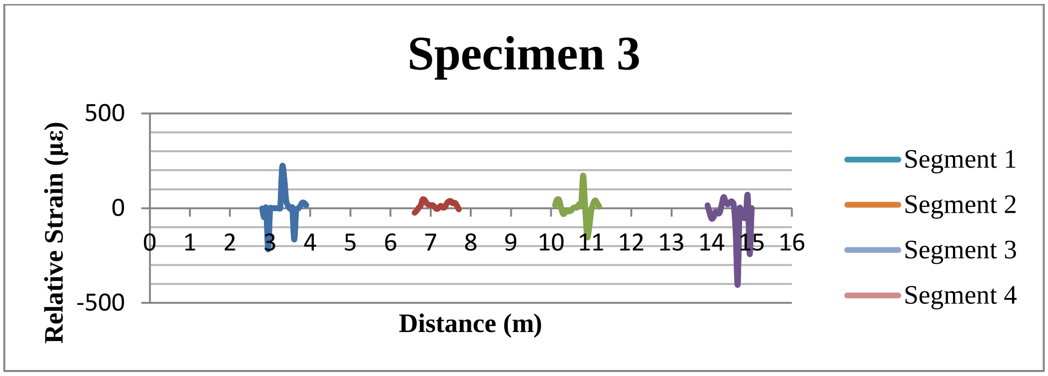

Figure 5: Strain Profile for Specimen 3

Table 5: Summary of Results for Specimen 3

Location	*Spike Detected?*	*Remarks*
3.35 (Segment 1)	Yes	Unstable signal
7.15m (Segment 2)	No	Unstable weak signal
10.65m (Segment 3)	Yes	Unstable signal
14.45m (Segment 4)	Yes	Unstable signal

Figure 6 shows the output obtained from specimen 4. In specimen 4, the spike of the strain profile is expected to be at 3.7m & 4.2m (Segment 1), 6.65m & 7.15m (Segment 2), 10.5m & 11m (Segment 3) and 14.1m & 14.6m (Segment 4) along the fibre optic cable. Signals are obtained in Segment 1 and Segment 2. For Segment 3 and Segment 4, very weak signals are obtained and no spike was detected at 10.5m and 14.1m. There are also fluctuations in the signal which is not consistent throughout the specimen. There are a few possible factors affecting the results which are discussed at the end of this section. Table 6 provides a summary of the results.

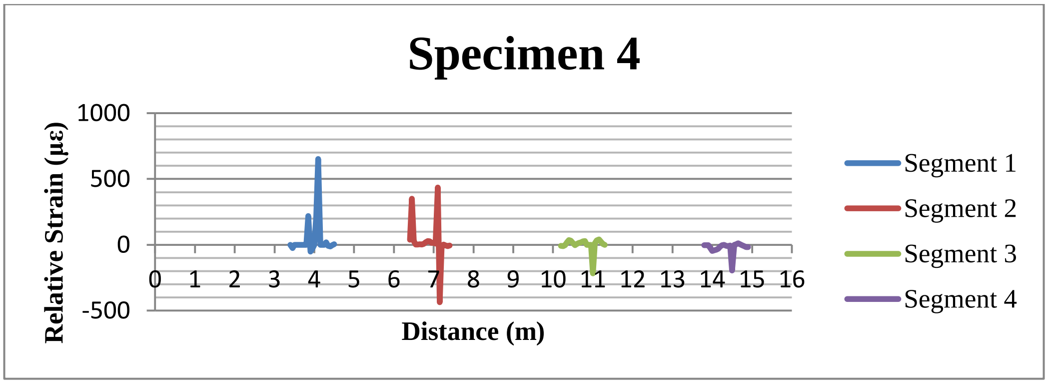

Figure 6: Strain Profile for Specimen 4

Table 6: Summary of Results for Specimen 4

Location	**Spike Detected?**	**Remarks**
3.7m (Segment 1)	Yes	Unstable signal
4.2m (Segment 1)	Yes	Unstable signal
6.65m (Segment 2)	Yes	Unstable signal
7.15m (Segment 2)	Yes	Unstable signal
10.5m (Segment 3)	No	Unstable weak signal
11m (Segment 3)	Yes	Unstable weak signal
14.1m (Segment 4)	No	Unstable weak signal
14.6m (Segment 4)	Yes	Unstable weak signal

The following are the possible factors affecting the results. Further research could be conducted to look into the factors.

a) Configuration of fibre optic cable in specimen
b) Strength of pulse width of 1ns
c) Scale of the experiment / specimen
d) Uncertainties during specimen casting process which include compaction and vibration

6.2 Comparison between Different Spatial Resolutions

Another objective of this research is to compare the effects of difference spatial resolution in the detection of corrosion in this experiment. Results from different spatial resolution were obtained for comparison and are shown as follow. Figure 7 shows the comparison of detection from experiments with different spatial resolution for Specimen 1. It was observed that pulse width ns5 and ns10 produces more stable strain profile as compared to pulse width ns1. In terms of relative strain values, the values obtained by using ns5 and ns10 are observed to be smaller than the measured relative strain values obtained by using ns1. The reason affecting the results is unjustified. Factors could be due to the effect of averaging of strain values from a longer distance as a result of using pulse width of larger spatial resolution or some other factors.

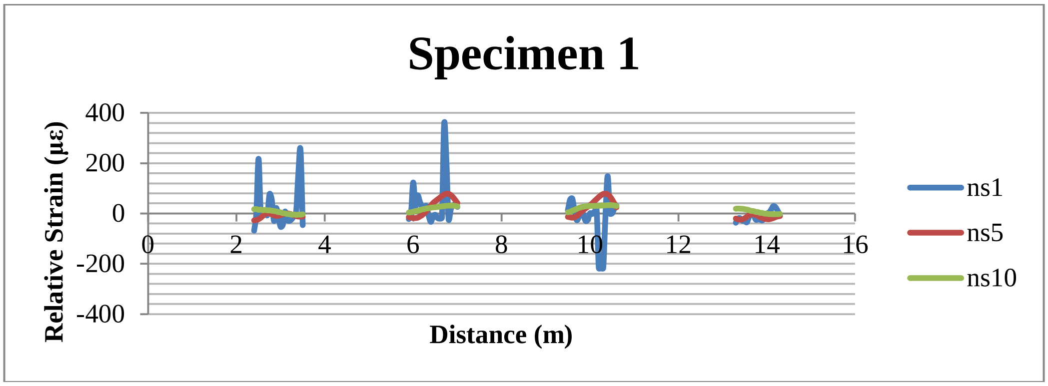

Figure 7: Comparison of Strain Profile from Different Spatial Resolution for Specimen 1

Figure 8 shows the comparison of different spatial resolution for Specimen 2. Similar to Specimen 1, it was observed that pulse width ns5 and ns10 produces more stable strain profile as compared to pulse width ns1. In terms of relative strain values, the values obtained by using ns5 and ns10 are observed to be smaller than the measured relative strain values obtained by using ns1.

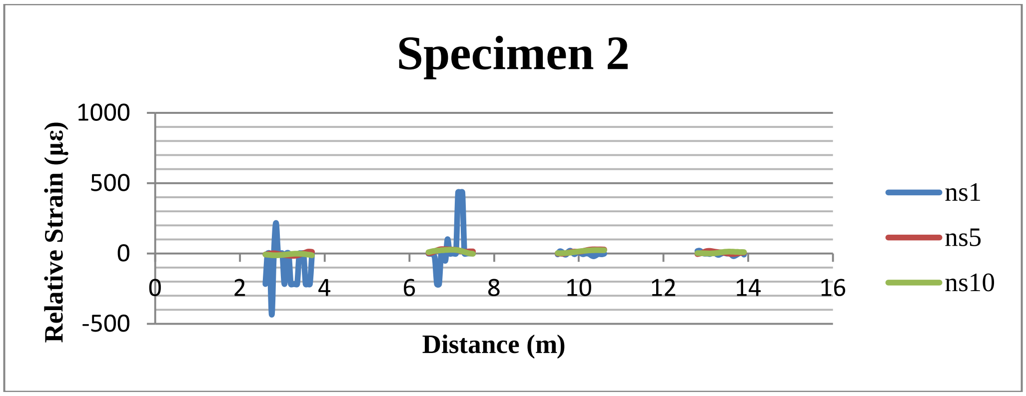

Figure 8: Comparison of Strain Profile from Different Spatial Resolution for Specimen 2

Figure 9 shows the comparison of different spatial resolution for Specimen 3. Similar to Specimen 1 and 2, it was observed that pulse width ns5 and ns10 produces more stable strain profile as compared to pulse width ns1. In terms of relative strain values, the values obtained by using ns5 and ns10 are observed to be smaller than the measured relative strain values obtained by using ns1.

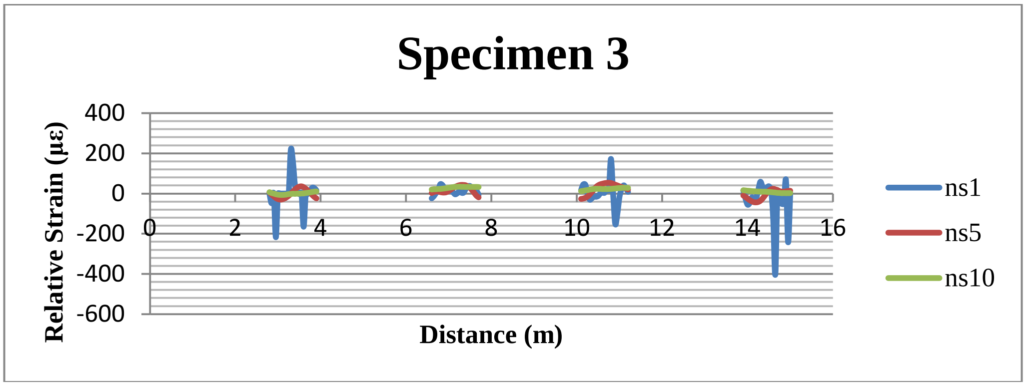

Figure 9: Comparison of Strain Profile from Different Spatial Resolution for Specimen 3

Figure 10 shows the comparison of different spatial resolution for Specimen 4. Similar to Specimen 1, 2 and 3, it was observed that pulse width ns5 and ns10 produces more stable strain profile as compared to pulse width ns1. In terms of relative strain values, the values obtained by using ns5 and ns10 are observed to be smaller than the measured relative strain values obtained by using ns1.

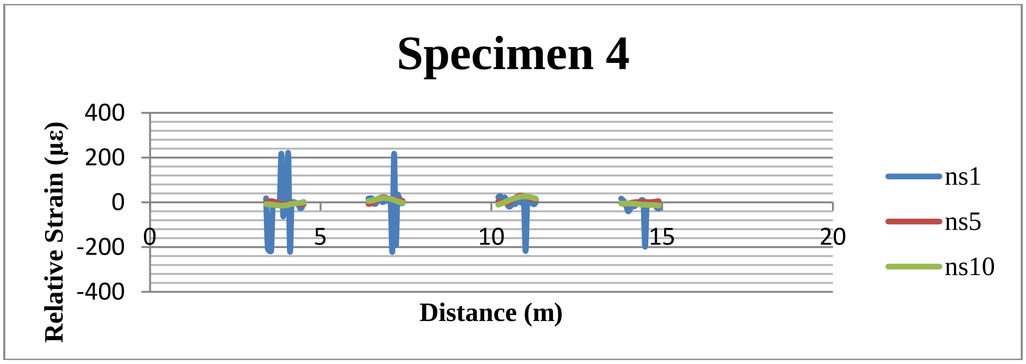

Figure 10: Comparison of Strain Profile from Different Spatial Resolution for Specimen 4

It was unable to justify the effectiveness of the three types of spatial resolution through this research because it was found that many factors affect the results of this experiment and the results is unable to be properly compared. The factors affecting the results can be summarized into two main categories. The first are the technical factors of the BOTDA such as data acquisition time and number of scans. The second are the experimental factors which include the configuration of fibre optic cables, the scale of the experiment and specimens, the size of the defect relative to the spatial resolution used, the configuration of direct loading used and the magnitude of direct loading used.

7.0 Conclusion and Recommendations

Based on the results obtained, the hypotheses of this research were unable to be proven. In this research, it was expected that pulse width of ns1 is suitable to be used for detecting the defect in this experiment due to its spatial resolution. However, from the experiments conducted, the hypothesis was unable to be justified due to the unverified factors affecting the output of this research. The results of utilizing pulse width of 5 ns and 10 ns have shown stable strain profile as compared to pulse width of 1 ns but their spatial resolution does not support they suitability as the strain profiles. It is suggested that the factors affecting the results to be considered to make better sense of the results. Separate experiments can be conducted to address these issues. Increased number of scans is an aspect that can be looked into, as it can contribute better results in terms of improved signal to noise ratio. However, it is important to note that data acquisition time may be jeopardized.

It is important to note that the results of this work are limited to the following conditions:

a) Corrosion is simulated for the case of pitting corrosion only and does not take into account of other forms of corrosion
b) The results obtained is due to instantaneous loading and hence is not time dependant
c) Results obtained from this work is limited to the type of the specimen, materials, fibre optic cable, parameters as specified

8.0 Acknowledgements

The authors are indebted to Research Management Centre, Universiti Teknologi Malaysia for the GUP grant no. 16H94 and the Ministry of Higher Education for the FRGS grant no. 4F528 that help to scale through this research. Also acknowledge support from technical staff of Faculty of Civil Engineering, UTM.

References

Abdul Rahman, S., Ismail, M., Md Noor, N., & Bakhtiar, H. (2012). Embedded Capacitor Sensor for Monitoring Corrosion of Reinforcement In Concrete. Journal of Engineering Science and Technology , 209 - 218.

Afzal, M., Kabir, S., & Sidek, O. (2012). An In-depth Review: Structural Health Monitoring using Fibre Optic Sensor. IETE Technical Review , 9, 105-113.

Annamdas, V. G. (2011). Review on Developments in Fibre Optical Sensors and Applications. International Journal of Materials Engineering .

Fernandez-Vallejo, M., & Lopez-Amo, M. (2012). Optical Fibre Networks for Remote Fiber Optic Sensors. Sensors , 3929 - 3951.

Leung, C., Wan, K., & Chen, L. (2008). A Novel Optical Fiber Sensor for Steel Corrosion in Concrete Structures. Sensors .

Mao, J., Chen, J., Cui, L., Jin, W., Xu, C., & He, Y. (2015). Monitoring the Corrosion Process of Reinforced Concrete Using BOTDA and FBG Sensors. Sensors , 8866 - 8883.

Sidek, O., Kabir, S., & Afzal, M. (2011). Fiber Optic-based Sensing Approach for Corrosion Detection. PIERS Proceedings , 642 - 646.

Sigurdardottir, D., & Glisic, B. (2015). On-Site Validation of Fibre-Optic Methods for Structural Health Monitoring: Streicker Bridge. Journal of Civil Structural Health Monitoring .

Sinchenko, E. (2013). Fibre Optic Distributed Corrosion Sensor. Melbourne: Faculty of Engineering and Industrial Science.

Song, H.-W., & Saraswathy, V. (2007). Corrosion Monitoring of Reinforced Concrete Structures. International Journal of Electrochemical Science , 1 -28.

Verma, S. K., Bhadauria, S. S., & Akhtar, S. (2014). Monitoring Corrosion of Steel Bars in Reinforced Concrete Structures. The Scientific World Journal .

Ye, X., Su, Y., & Han, J. (2014). Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review. The Scientific World Journal .