Impact of Spectral Shift Quality (SSQ) on Fibre Optic Sensor Readings in Reinforced Concrete Beams

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ABSTRACT

Efficient maintenance and health monitoring programs prevent irreversible damage to critical civil infrastructures and save millions of dollars of taxpayer's money. The precision of the sensors and the volume of the experimental data collected are extremely important factors in the actual testing of structural health monitoring systems. Distributed fibre optic sensors (DOFS), currently being used extensively in civil structures for structural response measurements. However, DOFS suffers from exceeding its measurable range of strain when applied to concrete structures after initiation of cracks which cause erroneous data in the data stream. This phenomenon can be identified by using spectral shift quality (SSQ) levels of the measurements. Therefore, an experimental plan was proposed with representative size reinforced concrete (RC) beam to study the effect of SSQ on DOFS (SMF 28) readings. A RC beam with a dimension of 4000 mm × 200 mm × 400 mm was cast with embedded DOFS rebar sensor for the tension side. After the curing period, DOFS surface sensor was attached to concrete bottom surface. The beam was tested under flexural loading up to a maximum load of 160 kN until the beam failure. Four-point bending arrangement was used to test the beam and the measurements were taken in 10 kN intervals by using an optical backscattered reflectometer (OBR 4600). The SSQ should

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theoretically have a value between zero and one. The manufacturer of OBR 4600 recommended to remove any data with an SSQ of equal or less than 0.15, and the same threshold was applied in the study. Due to the crack initiation on bottom surface, SSQ reached 0.15 threshold after 40 kN load and for subsequent loadings for bottom surface sensor. This means that the sensor can be utilized until a load of 40 kN, which is 25% of the maximum load. However, experimental findings reveal that rebar attached DOFS SSQ values are within an acceptable range until 80% elastic limit strain. The rebar sensors functioned until 120 kN of loading, or 75 % of the maximum loading. Consequently, it can be noted that DOFS operate well with rebars and that SSQ had no effect on the results until 80% of elastic limit. However, the influence of SSQ on the concrete surface sensor was notably substantial. Therefore, it is warranted to pay a closer attention to the DOFs sensor readings after formation of hairline cracks on the attached concrete surfaces.

INTRODUCTION

The Structural health monitoring (SHM) has become a crucial tool for assessing the integrity of civil structures. With the growth in size and complexity of civil structures, it has become necessary to monitor their health to ensure their long-term durability and safety. SHM involves the use of various sensors and techniques to detect, analyses, and evaluate the performance of civil structures [1]. The information gathered from SHM is used to determine the condition of the structure, identify any potential defects, or damage, and make informed decisions about maintenance and repair [2].

SHM systems responses heavily depends on the experimental data collected by sensors. SHM sensors can be classified into various types, including strain gauges [3], accelerometers [4], piezoelectric sensors [5], and optical fibre sensors (OFS) [6]. Among these sensors, OFS have gained significant attention due to their numerous advantages over other sensors. OFS offer high accuracy, high sensitivity, immunity to electromagnetic interference, and durability in harsh environments [6]. OFS also provide a wide range of sensing capabilities, including temperature [7], strain [8], and pressure sensing [9]. Although discrete OFS have been widely used in SHM applications, DOFS have gained increasing attention due to this specific feature enabling the detection of local and global changes in the structure. DOFS can also be easily installed in existing structures and provide real-time monitoring of the structure's health. In addition, DOFS shares all the advantages with OFS and these advantages make DOFS an ideal choice for SHM applications, particularly for large structures such as bridges [10], pipelines [11], tunnels [12], and Buildings [10].

In DOFS, the measurement of strain or temperature is based on light scattering which allows for the monitoring of virtually every cross-section of the structural element. As light propagates through the fibre, it undergoes scattering due to imperfections in the fiber's material, resulting in a change in the intensity of the light. Three different types of scattering processes may occur in a DOFS, namely the Raman, Brillouin, and Rayleigh scattering. Rayleigh scattering is particularly useful for monitoring concrete structures due to its sensitivity to crack formation enabling early detection of structural defects before they become critical. DOFS can be used to analyse strain and cracks in concrete members. Sieńko et al (2019) verified the suitability of standard optical fibres for strain analysis within concrete members. The results of the studies showed very good accuracy of optical fibre sensor technology as a reference technique during the analysis of microcracks and narrow cracks, and moderate accuracy in the case of wider cracks [13]. Corrosion of steel bars compromises the safety and service life of reinforced concrete structures. Fan et al (2020) developed a an in-situ corrosion monitoring method for reinforced concrete with a DOFS through experimentation. The DOFS was deployed in a helix pattern on the steel bar to measure expansive strains generated by corrosion of the steel bar. The strain measured from the sensor was utilized to evaluate the volume of the corrosion products surrounding the steel bars and predict the cracking of the concrete cover [14]. Fatigue performance is a serious concern for mechanical components subject to cyclical stresses, particularly where safety is paramount. Barrias et al (2019) studied the Fatigue performance of distributed optical fibre sensors in reinforced concrete beams. It was discovered that The DOFS showed a good performance under fatigue loading, without malfunctions for cycles up to 2 million. The strains measured along the tests were accurate when compared to the results obtained with strain gauges, with good stability and both for the un-cracked and cracked conditions [15].

The applications of DOFS can be seen in reinforced concrete beams such as strain monitoring and crack width assessments, monitoring corrosion of steel bars and fatigue performance. However, to the best of authors knowledge the studies conducted to investigate the impact of Spectral Shift Quality (SSQ) on DOFS readings in reinforced concrete beams under flexural loading is limited. Therefore, in this study, the impact of SSQ on fibre optic sensor readings in reinforced concrete beams were investigated under flexural loading to assess the accuracy and reliability of DOFS. SSQ is a measure of the strength of the correlation between the measurement and reference reflected spectra in an OFS caused by changes in the surrounding environment, such as temperature or strain. SSQ is an important factor to consider in fibre optic based SHM systems as it can have a significant impact on the accuracy and reliability of the measurement. In practical use, the SSQ should have a value between 0 and 1, with 1 indicating perfect correlation and 0 indicating no correlation. A Low SSQ can lead to errors in the measurement, making it difficult to detect changes in the structure's condition. Therefore, understanding SSQ is crucial for the effective use of DOFS in SHM systems for civil structures

MATERIALS AND METHODS

Concrete beam casting is a critical process in the construction of any structure, and it requires careful attention to detail to ensure that the resulting beam meets the required specifications. In this case, the beam dimensions are 4000 mm x 200 mm x 400 mm, and it is made using grade 25 concrete, which is suitable for most standard structural applications. The beam is reinforced with compression rebar size 12 mm and tension rebar size 20 mm, which ensures that it can withstand the expected loads. The curing period for the beam is 28 days, which is essential to achieve the required strength and durability. The characteristic cylinder compressive strength of the beam is 29.9 MPa. The beam was designed according to the European Community code EN 1992-1-1: Eurocode 2: Design of concrete structures. The beam definitions are shown in Figure 1

DOFS can be used to monitor the behavior of concrete structures by attaching them to both the bottom surface of the concrete beam and the tension rebar. To attach the

DOFS to the bottom surface of the concrete beam, a two-component epoxy glue mixture of TECHNIGLUE R60 and H60S mixed in a 2:1 ratio is used. This adhesive is suitable for bonding the fibre to the concrete surface, and the sensor's length runs along 3000 mm of the bottom surface, providing admissible coverage to monitor the beam's behavior. The bottom sensor length was limited due to the ease of handling the beam. For the attachment of DOFS to the rebar surface, a slot is ground in the tension rebar using an angle grinder to accommodate the sensors. In this case, the attachment method involves using a two-component epoxy glue mixture of TECHNIGLUE R15 and H15S mixed in a 1:1 ratio. The sensor length runs along the full length of the rebar, providing comprehensive coverage to monitor the rebar's behavior and detect any changes in the strain. The use of appropriate materials and techniques, such as the specific epoxy glue mixtures and slot grinding method, is crucial to ensure accurate and reliable measurement of the behavior of the concrete structure beam. Figure 2 displays the surface sensor layout AND Figure 3 displays the DOFS attached rebar and concrete surface sensor and loading arrangement.

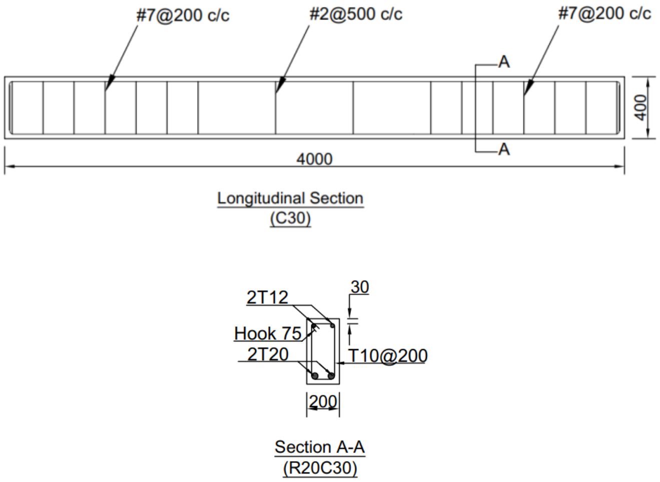

Figure 1. Beam definition

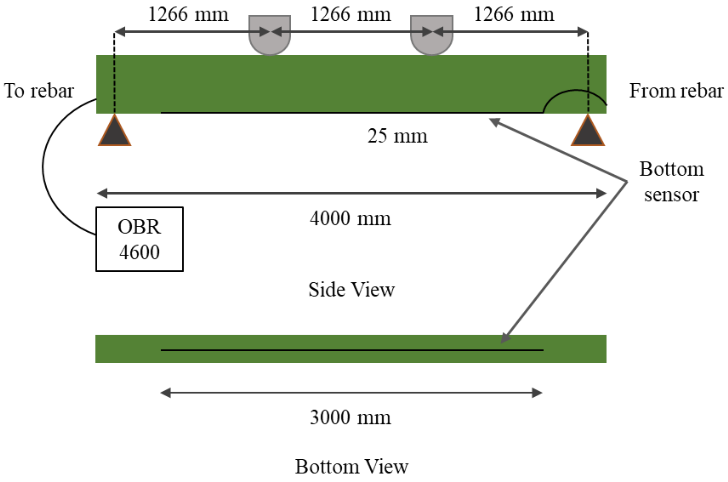

Figure 2. The surface sensor layout and loading arrangement

The DOFS was connected to the OBR4600 equipment to enable real-time and high-resolution measurements of the strain along the entire length of the fibre. To ensure accurate and reliable measurement, a gauge length of 2.5 cm was used and additionally, the sensor spacing set to 1 cm. To test the behavior of a concrete beam, a hydraulically operated load frame was used. This load frame can apply loads up to 50 tons, and the testing arrangement involved was four-point bending, where two load points are applied to the top of the beam, while two support points are placed on the bottom surface. The span of the beam being tested was set to 3800 mm. During testing, the load is gradually applied to the beam until it reaches its maximum load capacity until it fails. In this case, the maximum load until failure is 160 kN. To accurately apply the load at each stage of the testing process, a measurement interval of 10 kN was used.

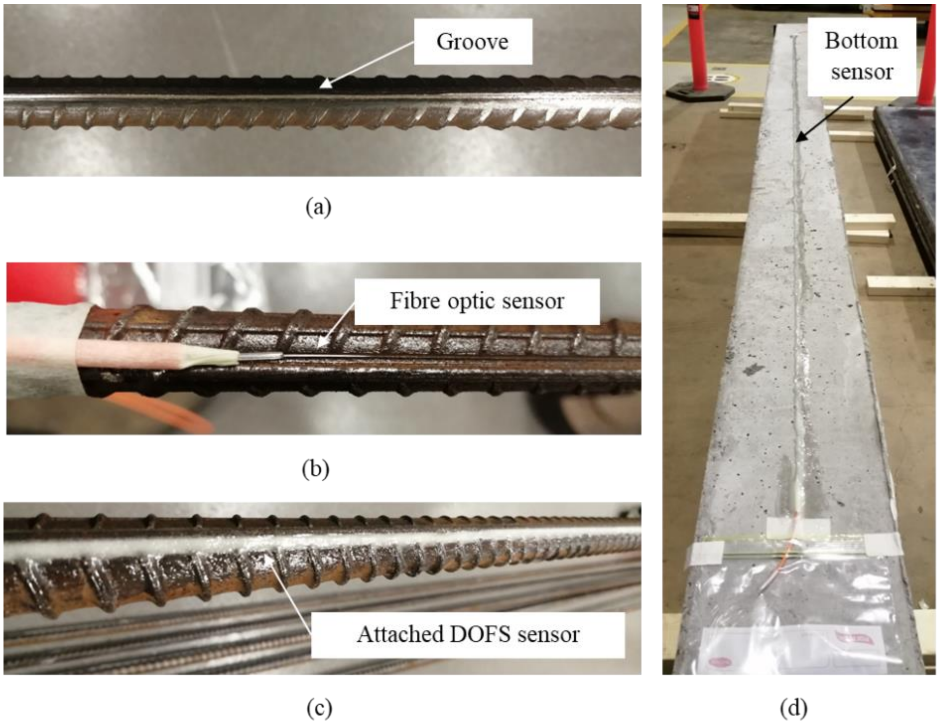

Figure 3. DOFS attached rebar and concrete surface sensor

RESULTS AND DISCUSSION

In this section, the results were presented, analyzed, and discussed on the impact of spectral shift quality (SSQ) on fibre optic sensor readings in reinforced concrete beams. The objective of this study was to investigate the effect of SSQ level on the accuracy and reliability of fibre optic sensors in measuring strain in reinforced concrete beams. The manufacturer of the data acquisition system (OBR 4600) states that the SSQ quantifies the correlation between the measured and reference reflected spectra. The manufacturer recommends disregarding the data below 0.15 threshold value. Therefore, for this study 0.15 threshold level was selected. SSQ values can be calculated using the following expression,

$$Spectral\ Shift\ Quality\ (SSQ) = \frac{MAXIMUM(U_j(v) \star U_j(v - v_j))}{\sum U_j(v)^2} \quad (1)$$

$U_j(v)$ - baseline spectrum for a given data segment
$U_j(v - v_j)$ - the spectrum measured during a strain or temperature change
$\star$ - The symbol stands for the cross-correlation operator.

The experiments conducted involved measuring the strain on rebar with DOFS attached to an RC beam as the load levels increased. The results indicated that the accuracy and reliability of the DOFS were significantly impacted by SSQ at higher loads. For clarity, the results were presented in 20 kN intervals. Figure 6 displays the raw strain data, raw strain data after removing data less than or equal to 0.15 SSQ threshold, SSQ variation, and 0.15 SSQ threshold for rebar DOFS at 120 kN, 140kN, and 160kN. The strain data presented at 120 kN demonstrated that the data was not affected, and the SSQ variation along the rebar was not less than or equal to the 0.15 SSQ threshold. However, for the 140 kN and 160 kN graphs, the SSQ variation graph was below the threshold level at several locations, and the strain variation showed how affected the data was. Increasing loads led to decreasing SSQ levels and an increase in the number of data affected due to exceeding the measurable range of DOFS. The rebar attached DOFS sensor can only withstand up to 120 kN load and 75% of the failure load in this application. However, the maximum experimental strain measured was well past the 80% limit of the yield strain of the rebar. Therefore, it is recommended to use rebar attached DOFS sensors in reinforced concrete structures.

In Figure 7, the strain data, after removing data less than or equal to 0.15 SSQ threshold, the SSQ variation, and the 0.15 SSQ threshold for bottom surface DOFS at various loadings starting from 40 kN, are presented. The strain data at 40 kN showed that the data was not affected, and the SSQ variation along the rebar was not below the 0.15 SSQ threshold. However, for the 60 kN and 80 kN graphs, the SSQ variation graph was below the threshold level at multiple locations, leading to the removal of affected data based on the manufacturer's suggestion. The strain variation of the 60 kN and 80 kN graphs demonstrated how the data was affected. Increasing loads resulted in decreasing SSQ levels and an increasing number of affected data. The surface attached DOFS sensor can only withstand up to 40 kN load and 25% of the failure load. Compared to rebar attached DOFS, the concrete surface attached DOFS was significantly affected by low SSQ values due to crack initiation and increasing crack widths on the concrete surface as the load increased, leading to exceeding the measurable range of the DOFS attached surface sensor.

According to the results, using DOFS with higher SSQ values (above 0.15) can enhance the accuracy and reliability of sensor readings in reinforced concrete structures. The position of the sensors within the concrete beam is also a critical factor that needs to be considered to ensure consistent and reliable readings. These findings have considerable implications for using DOFS in the structural health monitoring of concrete structures. It is crucial to have reliable sensor readings to detect and monitor any potential structural defects and failures. The outcomes of this study provide essential insights into the design and implementation of DOFS systems for the structural health monitoring of concrete structures.

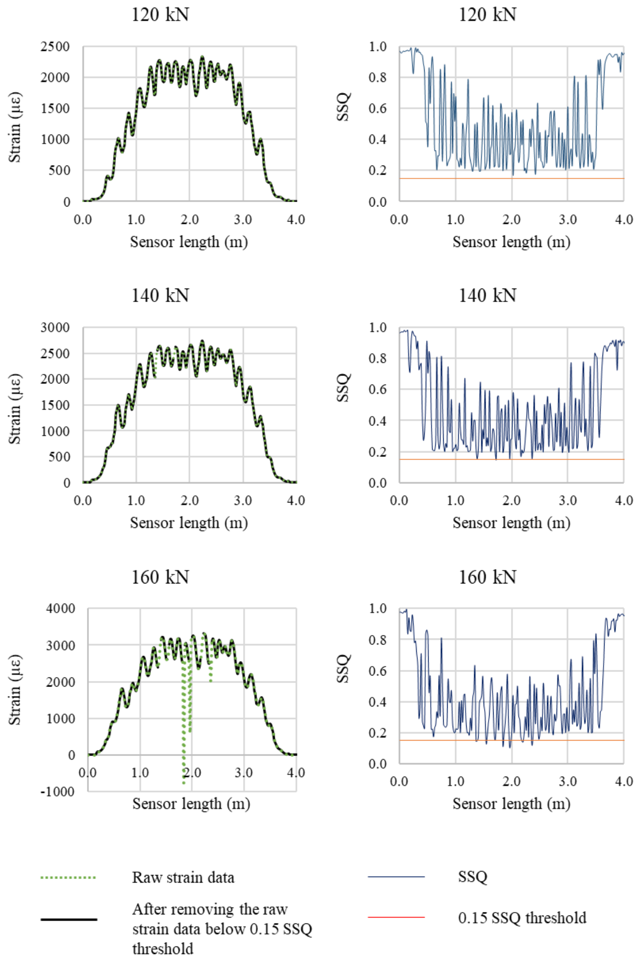

Figure 6. Raw strain data, after removing the raw strain data below 0.15 SSQ threshold, SSQ and, 0.15 SSQ threshold for rebar DOFS at different loadings

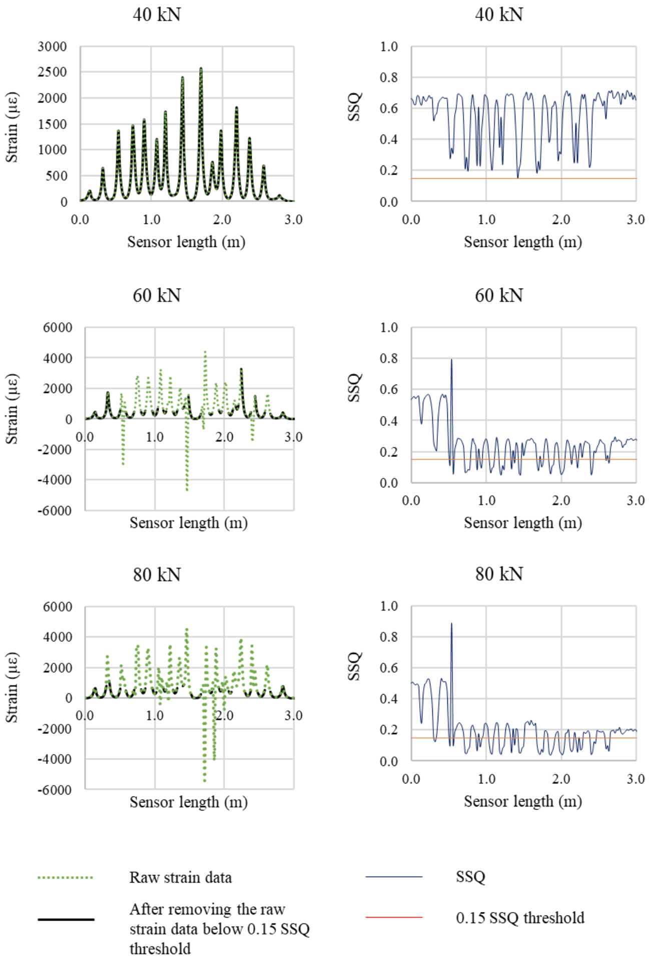

Figure 7. Raw strain data, after removing the raw strain data below 0.15 SSQ threshold, SSQ and, 0.15 SSQ threshold for bottom surface DOFS at different loadings

CONCLUSION

In conclusion, this study has demonstrated that SSQ has a significant impact on the accuracy and reliability of fibre optic sensors in measuring strain in reinforced concrete beams. These findings provide valuable insights into the design and application of DOFS systems for structural health monitoring of concrete structures. It is important to note that DOFS function well with rebars, and SSQ did not affect the results until the elastic limit was reached (up to 80% of the yield strain). However, the influence of SSQ on the concrete surface sensor was notably substantial. Therefore, it is necessary to closely monitor DOFS sensor readings after cracks form on the attached concrete surfaces. Further investigation is required to explore the impact of other factors, such as temperature and sensor packaging, on SSQ and the performance of DOFS in concrete

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