

Use of Distributed Optical Fibre Sensing for Structural Health Assessment of Reinforced Concrete Beams

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ABSTRACT

Structural health monitoring (SHM) plays a vital role in ensuring the safety and longevity of civil infrastructure, where distributed fibre optic sensors (DOFS) offer high-resolution, full-field strain measurement capabilities. However, DOFS performance can be affected by the formation of micro-cracks in concrete, often resulting in erroneous strain data due to spectral anomalies. This study investigates the reliability of DOFS measurements under progressive loading conditions in a full-scale reinforced concrete (RC) beam. A $4000 \times 200 \times 400 \text{ mm}^3$ RC beam was cast using Grade 25 concrete and reinforced with embedded DOFS along the tension rebar. Additionally, another DOFS was added to the bottom of the concrete after curing to measure strain. The beam was subjected to a four-point bending, with loading applied incrementally up to 40 kN. Strain data were acquired using an OBR 4600 system at 5 kN loading intervals. While consistent strain profiles were observed across mid-span, strain spikes and residual strains were identified on both the rebar and the bottom surface, indicating the formation of micro-cracks. Controlled rebar loading tests confirmed that adhesive bonding had negligible impact on residual strain, supporting the effectiveness of DOFS in detecting internal cracking. The findings highlight the potential of DOFS for early-stage damage detection in concrete structures.

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INTRODUCTION

Reinforced concrete (RC) beams serve as a fundamental component in the construction of a broad range of civil structures, including buildings and bridges [1, 2]. They play a crucial role in the modern infrastructure. The inherent properties of RC, a composite material formed by embedding steel reinforcement bars within a concrete matrix, enable it to withstand both compressive and tensile loads effectively. This unique combination enables RC beams to distribute structural loads efficiently and provide robust support for the diverse load-carrying needs of infrastructure assets.

Currently a few methods of structural health monitoring (SHM) for civil structures play a crucial role in preserving the integrity and safety of vital infrastructure components. Non-destructive testing (NDT) techniques are extensively employed in SHM because they permit structural health evaluation without damaging the structures [3]. Despite the subjectivity of human judgement and accessibility restrictions, visual inspection [4, 5] continues to be a popular and cost-effective technique. These include ground-penetrating radar (GPR) [6], which uses electromagnetic waves to detect internal defects; acoustic emission (AE) monitoring [7], which captures the release of elastic energy due to micro-cracking within the concrete; and vibration-based monitoring [8], which assesses structural damage by tracking changes in vibrational characteristics such as natural frequency, mode shapes, and damping ratio.

The potential use of distributed fibre optic sensor (DFOS) networks, and robust deep learning (DL) algorithms in SHM are enormous, as these cutting-edge technologies can revolutionize how infrastructure is evaluated and maintained [9]. DOFS allow for the continuous, real-time monitoring of structures, capturing vital data regarding their response to various loads and environmental conditions. These sensor networks can be configured to monitor specific parameters, such as strain [10], temperature [11], or vibration [12], providing valuable insights into the behaviour and performance of the structure. These sensor networks can be deployed to monitor a parameter in a distributed fashion [13], allowing comprehensive SHM.

This research presents significant findings on the health monitoring of a 4 m RC beam equipped with a DFOS network attached to the reinforcement bars and the bottom surface, under lateral loading conditions.

MATERIALS AND METHODS

Reinforced concrete beams with dimensions of $4000 \times 200 \times 400 \text{ mm}^3$ were cast using Grade 25 concrete, commonly employed in standard structural applications. Precise control over the casting process was maintained to ensure compliance with design specifications and structural integrity. The beam was reinforced with 12 mm compression rebars and 16 mm tension rebars. A 30 mm concrete cover was maintained at the bottom to ensure adequate protection and load-bearing capacity. The beam was designated as R16C30. 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.

DOFS can be used to monitor the behaviour of concrete structures by attaching them to surfaces of the concrete beam and the reinforcements. Before preparing the

reinforcement cage, a slot was ground into the tension rebar using an angle grinder to accommodate the sensors. 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. Figure 1 illustrates the placement of the DOFS, including its attachment along the rebar and installation on the concrete surface, as well as the loading arrangements used for strain data generation during structural testing.

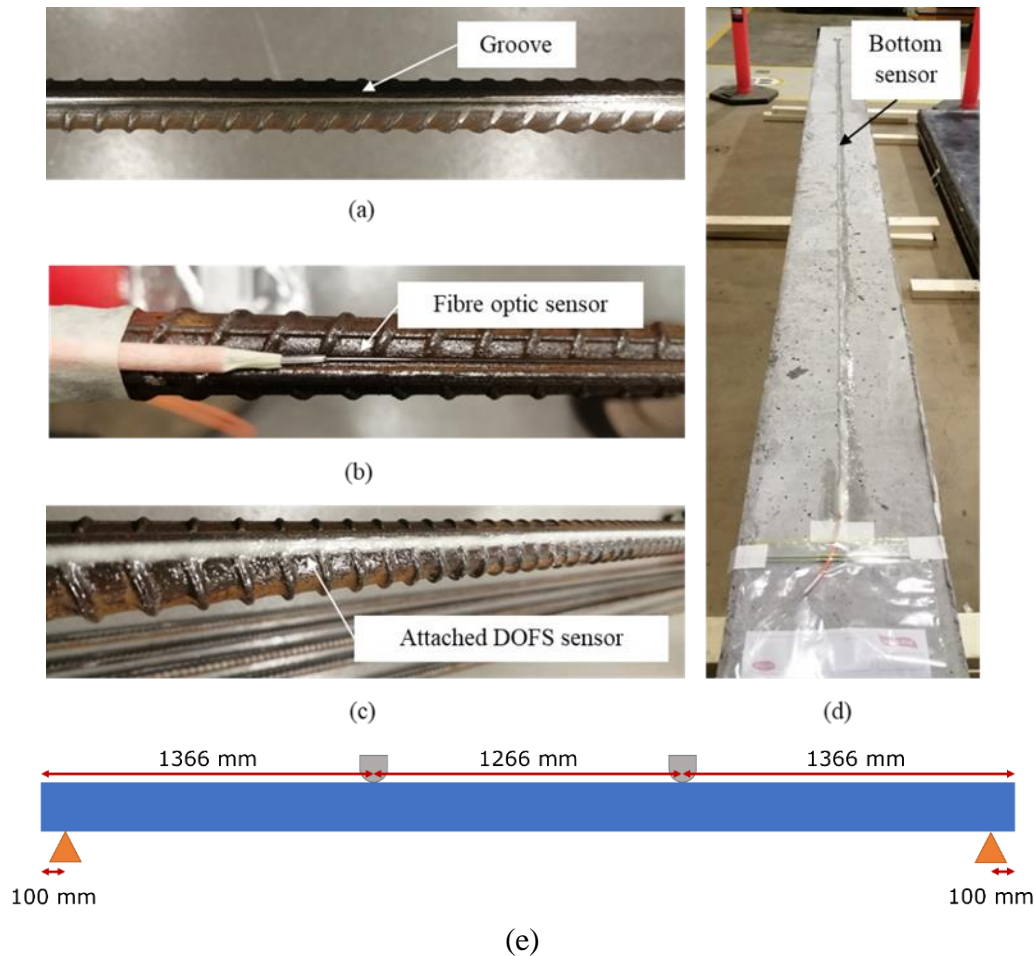


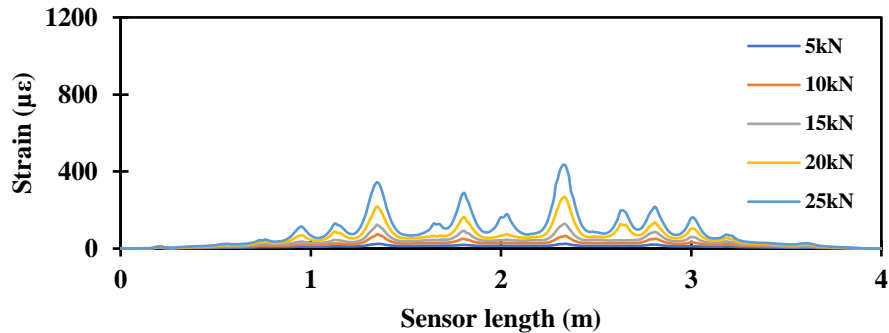
Figure 1: (a) The groove cut on the rebar; (b) DOFS before attachment; (c) Attached DOFS to the rebar; (d) DOFS attached rebar and concrete surface sensor; (e) Loading arrangements for strain data generation

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 as shown in Figure 1 (e). The span of the beam being tested was set to 3800 mm. During testing, the beam R16C30 was loaded in three different loading stages: the first and the second stages involve loading up to 25 kN, and the third stage involves loading up to

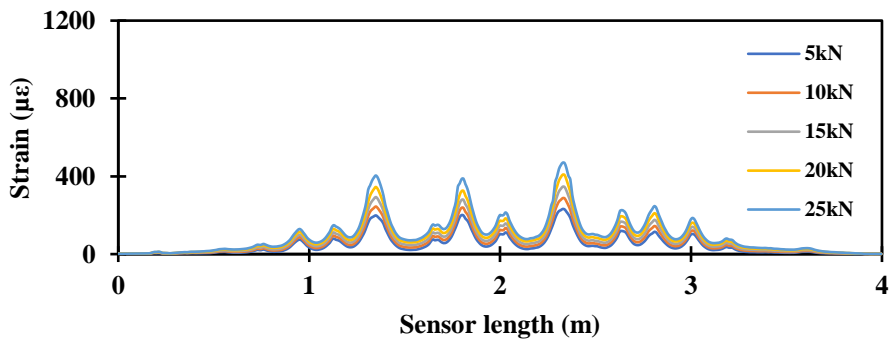
40 kN. To accurately apply the load at each stage of the testing process, a measurement interval of 5 kN was used.

RESULTS AND DISCUSSION

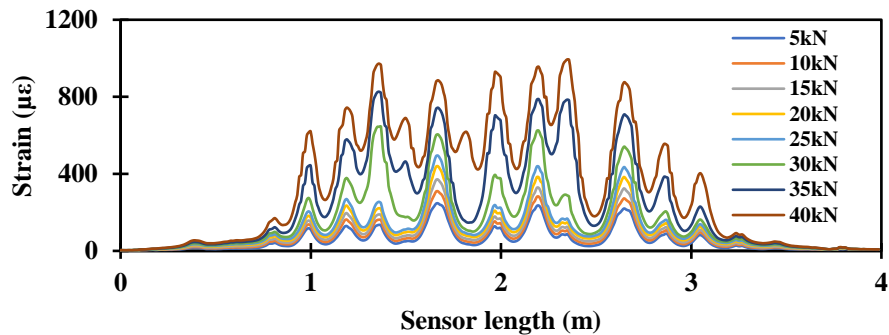
Notably, the data presented in these figures are based on a threshold of 0.15 spectral shift quality (SSQ). Figure 2 provides data for variation in the rebar strain during different loading stages.



(a)



(b)



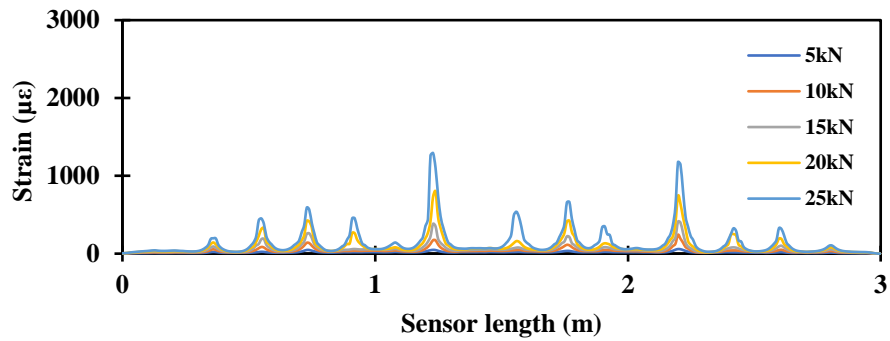
(c)

Figure 2: The experimental rebar strain variation for R16C30. (a) 0-25kN; (b) 0-25kN; (c) 0-40kN

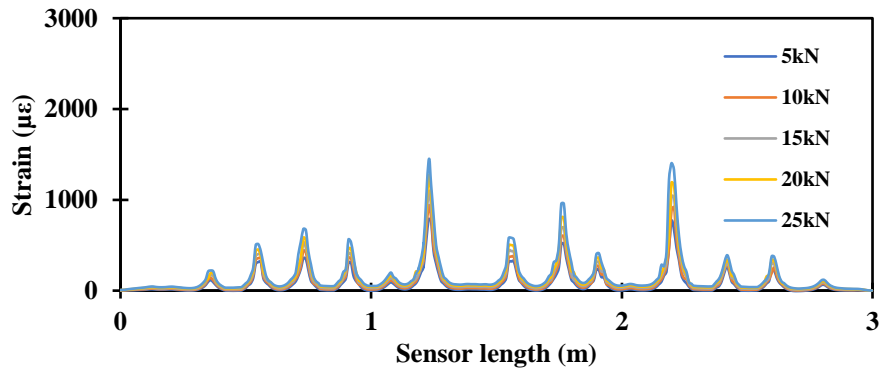
The key finding of examining Figure 2 is that presence of the residual strain in the rebar, as shown in Figure 2 (b) and (c), even after the beam was allowed to relax for 10

minutes. Furthermore, a slight rise in rebar strain was observed during the second loading phase. In contrast, Figure 2 (a) exhibits no residual rebar strain. According to Figure 2(b) and (c), the surface cracking of the concrete continued even though the loading was limited to 15 kN. However, due to loading and reloading, the crack may not close due to aggregate interlocking and remain open to some extent, making it report some strain (residual) after unloading.

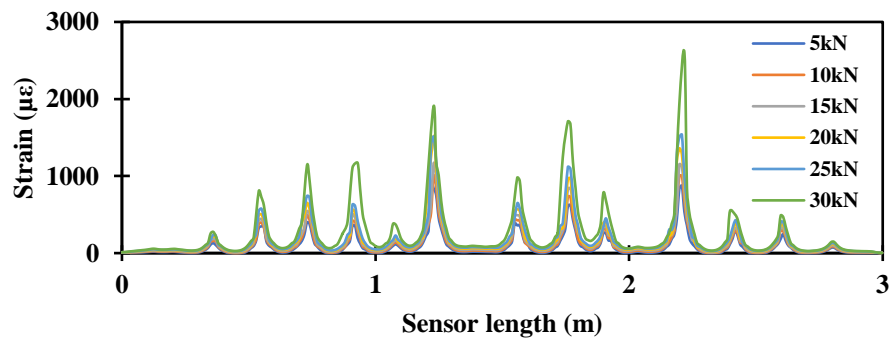
Figures 3 present data for variation in the bottom surface strain during different stages of loading, respectively. Insights can be gained into the behaviour of the bottom surface of the beam under different loading conditions by analysing the data presented in Figures 3.



(a)



(b)



(c)

Figure 3: The experimental bottom surface strain variation for R16C30 (a) 0-25kN; (b) 0-25kN; (c) 0-30kN

Behaviour of Residual Strain

This section describes the assessment of the residual strain in R16C30 beams after the initial and subsequent loading stages. Figure 4 demonstrates a slight increase in residual strain during the second loading stage compared to the first stage. When an RC beam is subjected to a load, both the concrete and rebar undergo deformation, increasing their strain. However, after unloading, the concrete and rebar may not return to their original positions, which results in residual strain. One of the main reasons for residual strain is the presence of cracks in the concrete, which can cause the rebar to experience additional strain. This additional strain can contribute to the residual strain after unloading.

In this case, the residual strain was slightly increased during the second pass of loading when compared to the first pass. This increase in residual strain can be attributed to cracks in the concrete during the first stage, which may have weakened the structure (stiffness reduction after cracking) and made it more vulnerable to further damage during the second stage of loading.

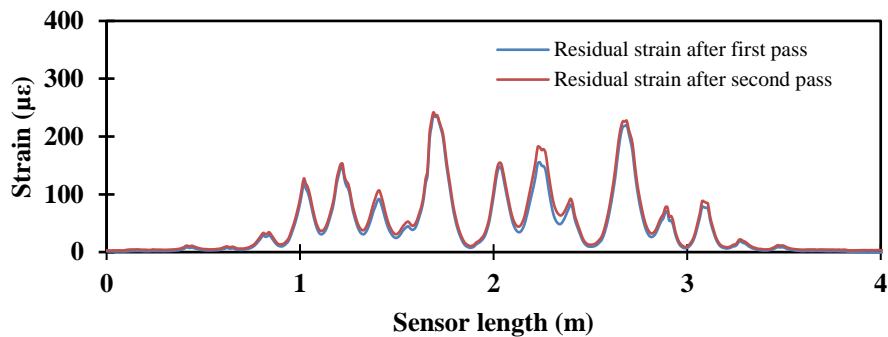


Figure 4: Comparison of residual strain on 16 mm rebar after the first stage of loading and second stage of loading for beam R16C30

A study investigated the effect of the adhesive used on the residual strain on the rebar. The experiment aimed to assess the residual strain of 16 mm diameter rebar with a procedure involving loading and unloading using a universal tensile machine. Figure 5 (a) illustrates the schematic diagram of the rebar with the attached DOFS, and Figure 5 (b) presents the experimental setup.

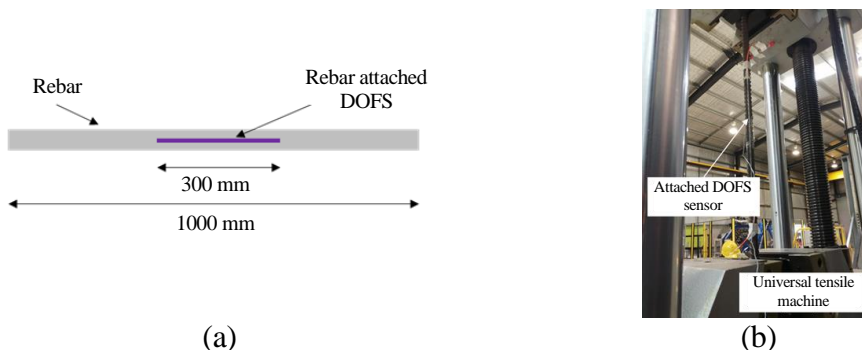


Figure 5: (a) Schematic diagram of rebar with attached DOFS, (b) Experimental setup of rebar testing

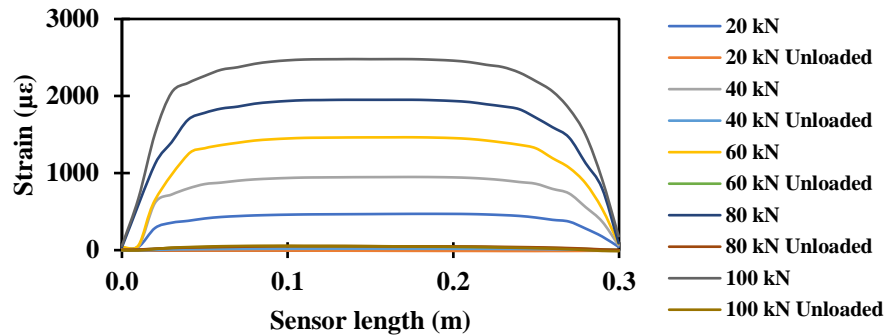


Figure 6: Rebar strain variation at loading and unloading

Figure 6 shows the strain variations of rebar size 16 mm during loading and unloading. The rebars were strained up to a maximum of 2500 $\mu\epsilon$, but the results indicate that the residual strain on the rebars is insignificant. This concludes that the impact of adhesive on residual strain is negligible.

CONCLUSION

A DOFS network was successfully implemented both inside and on the surface of a 4 m long reinforced concrete beam. The beam was subjected to four-point bending, and the DOFS data revealed a consistent strain distribution across the mid-span where the bending moment is constant as well as between the loading and support spans. The strain spikes were observed on both the rebar and the bottom surface of the beam, indicating the possible formation of micro-cracks along the tensile face of the structure.

The strain peaks observed in the rebar exhibit a wave-like behaviour in all measurements, which becomes more pronounced with increasing load. The cause is the propagation of cracks along the concrete. Typically, the appearance of strain peaks indicates the occurrence of tension-induced cracks in that area, while strain valleys imply less strain on the concrete. Since surface strain spikes result from crack formation, so do the spikes in rebar strain. Therefore, it can be concluded that the rebar strain peaks result from concrete cracks extending beyond the rebars.

Moreover, as the load levels increased, residual strains were detected in the rebar, which may suggest the development of internal micro-cracks in the vicinity of the reinforcement. To further investigate this phenomenon, individual rebar segments with attached optical fibre sensors were tested under a controlled loading and unloading sequence. The negligible residual strain observed in this test supports the conclusion that the residual strains in the beam are likely to be due to micro-crack formation within the concrete rather than the effects of the adhesive. These findings highlight the effectiveness of DOFS in capturing early-stage damage in concrete structures.

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