A comparison of strains measured by optical fibres and strain gauges with theory for a loaded bridge deck

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Abstract
Reinforced concrete (RC) structures deteriorate and as a result crack due to extreme loading and/or environmental conditions. Damage accumulation as such adversely affects the structure’s durability properties, impairing its service life. The intensity of cracking in an RC structure is usually regarded as the key criterion toward damage assessment and repair intervention. This paper presents the results of an experimental program in which the concrete strains of a small-scale RC slab, simulating an RC bridge deck, were monitored by traditional electrical strain gauges and optical fibre sensors, in an attempt to detect crack formation. A comparison of these measurements with classical bending theory is also presented. The results show that the use of optical fibre sensors for strain monitoring of RC structures is a promising technology to be used for structural health monitoring in field applications.

1 Introduction
When subjected to extreme weathering or loading, concrete deteriorates through a variety of physical and chemical processes, which often result in cracking. Cracks in concrete adversely affect its durability properties by providing easy access to water and other aggressive agents such as chloride or sulphate ions. It is the amount and intensity of concrete cracking that indicates damage accumulation in an RC structure and triggers intervention for
repair. The availability of technology to monitor deformation and cracking in concrete can therefore enable early identification of distress and prevent excessive damage accumulation.

Concrete deformation leading to cracking can be evaluated through the measurement of concrete strains. There are several ways in which strains in concrete can be quantified. Electrical strain gauges have been showed to work well in concrete provided this has not cracked. However, the effective length of the electrical strain gauge is critical for reliable results [1]. Recently, optical fibre sensors, in particular the Brillouin scattering-based distributed sensors, have emerged as a promising technology to monitor strain in structures [2, 3]. An advantage of these sensors over the traditional electrical strain gauges is that their measurements can be taken along the entire length of the fibre, rather than at discrete points, using the fibre itself as the sensing medium. However, their proper installation (good surface preparation and bonding) is essential to ensure the sensors’ reliable and accurate measurements [3]. Zhang et al. [4] have also shown that distributed Brillouin fibre sensors can be successfully used to detect and monitor crack growth in RC.

This paper presents some of the results of an experimental program in which a small-scale RC slab simulating a bridge deck is subjected to chloride exposure while sustaining in-service loads [5]. The objective of this research is to establish relationships between the rate of chloride penetration in concrete and the strain induced by mechanical loads. In order to evaluate the deformation in the slab due to the imposed loads, strains in the concrete were recorded by the use of both traditional strain gauges and Brillouin fibre sensors. The measurements thus obtained were compared with the strains calculated from classical bending theory and are reported in this paper.

2 Experimental program

2.1 Test specimen

A 4.35-m long by 2.73-m wide RC slab was chosen as the test specimen to simulate an RC bridge deck. The slab was cast with three 0.91-m width strips of different w/c: 0.35, 0.40 and 0.50. Each concrete strip, of 155-mm depth, was reinforced with eight top and eight bottom deformed steel bars of 11-mm nominal diameter. Clear concrete covers to top and bottom reinforcements were respectively 50 mm and 45 mm. The yield strength of the reinforcing steel was 400 MPa. Each RC strip was simple supported at the right end and at 1260 mm from the left end. Supports were located to create both positive and negative moment regions in the slab. The span between supports was 2.73 m. Plan and elevations views of the RC deck are illustrated in Fig.1.

The proportions of the mix ingredients used for each concrete strip are tabulated in Table 1. Both fine and coarse aggregates were well graded according to CSA A23.1-04 specifications. The concrete compressive strengths $f'_c$ at the time of loading (200 days from the casting date) were obtained as 81.0 MPa, 69.4 MPa and 64.5 MPa for w/c of 0.35, 0.40 and 0.50, respectively.

2.2 Casting and curing of test specimen

Prior to casting the slab, the formwork was lined with a plastic sheet of 0.152-mm thickness in order to prevent the formwork from absorbing mixing water. Each concrete strip was cast independently of each other, with one week apart in-between castings. The first strip to be cast was that of 0.35 w/c, followed by that of 0.50 w/c. The last strip to be cast was the middle strip of 0.40 w/c. Joints in-between strips were created by placing plastic sheets of 25-mm thickness, so that each RC strip would respond independently of each other when mechanically loaded. After one day of casting, each concrete strip was covered by wet jute
rugs, which were in turn covered by plastic sheets in order to minimize evaporation. This curing regime lasted for 28 days. The average temperature in the structural lab was 21°C and the relative humidity was 25%.

**Table 1. Mix proportions (per m$^3$).**

<table>
<thead>
<tr>
<th>Material</th>
<th>w/c = 0.35</th>
<th>w/c = 0.40</th>
<th>w/c = 0.50</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>Type 10 Bath</td>
</tr>
<tr>
<td>Coarse agg. – 20 mm (kg)</td>
<td>1055</td>
<td>1048</td>
<td>1020</td>
<td>Tomlinson Moodie</td>
</tr>
<tr>
<td>Fine agg. (kg)</td>
<td>852</td>
<td>815</td>
<td>760</td>
<td>Burnside Moodie</td>
</tr>
<tr>
<td>Water (kg)</td>
<td>140</td>
<td>160</td>
<td>200</td>
<td>Well</td>
</tr>
<tr>
<td>Water reducer (ml)</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>Pozzolith210</td>
</tr>
<tr>
<td>Plasticizer (ml)</td>
<td>3000</td>
<td>1000</td>
<td>-</td>
<td>1466</td>
</tr>
<tr>
<td>Retarder (ml)</td>
<td>300</td>
<td>300</td>
<td>-</td>
<td>Pozzolith 100XR</td>
</tr>
</tbody>
</table>

![Diagram of concrete strain gauges and loading system with numbers indicating locations.]

**Figure 1.** Plan and elevation views of the RC deck (numbers correspond to location of concrete and steel strain gauges).

### 2.3. Loading system and strain gauges
Each RC strip was loaded by means of three threaded steel bars located at the end of the left overhang, 910 mm from the left support, and 910 mm from the right support, respectively, as illustrated in Fig.1. Springs were used in order to counteract long-term relaxation effects. The applied loads corresponded to 60% of the ultimate moment capacity of the slab (P = 27.5 kN).

In order to monitor deformation during testing, both concrete and steel strain gauges were used. The location of strain gauges is shown in Fig.1. The steel strain gauges, located along the top and bottom reinforcements, are of 10 mm and numbered from 1 to 14. The concrete strain gauges, located at the top and bottom surfaces of the deck, are of 60 mm and numbered from 15 to 26. Two strain gauges were fixed on each threaded bar used to apply the load (numbered from 27 to 32 in Fig.1).

In addition, three distributed Brillouin fibre sensors, one on each RC strip, were continuously glued to the top surface of the RC deck to measure the compressive and tensile strain distributions resulting from the applied load (see Fig.1). The type of sensing fibre used was the carbon-coated fibre. The completed RC deck and the optical fibre data acquisition system are respectively shown in Figs.2 and 3.

Figure 2. Completed RC deck.  
Figure 3. Optical fibre data acquisition system.

3 Test results and discussion

After loading the deck, the strain readings on the top surface along each RC strip were recorded through concrete strain gauges 23, 23’, 22, 19, 17, 17’, and 15. Likewise, the strain distribution along each RC strip was also obtained from the optical fibres by using the multiple-peak fitting method, in which the strains along the sensing fibres are extracted from the recorded Brillouin spectrum for the applied load. A spatial resolution of 0.1 m was used. The strains measured by both methods are plotted in Fig.4 for the RC strips of w/c of 0.35, 0.40, and 0.5. Also shown in Fig.4 are the strains calculated from bending theory. For sections where the moment applied is below the cracking moment (0.45 m and 3.18 m in Fig.4), the slab is assumed to act elastically, and the moment of inertia corresponding to the uncracked transformed section is used in the calculations. In the sections where the moment applied is above the cracking moment, the service load compressive stresses are assumed to be linear elastic, and the moment of inertia corresponding to the cracked transformed section is used in the calculations. The location of the neutral axis for the cracked section was found to be 30.9 mm from the concrete fibre subjected to maximum compressive stress.
From the obtained results, both concrete strain gauges and optical fibres readings were consistent with expected results, with the exception of the optical fibre readings between 1.36 m and 1.82 m for the strip with w/c of 0.35 and between 0.91 m and 1.36 m for the strip with w/c of 0.40. Whereas in the former the measured strains should have been in compression
while the values displayed are tensile, the latter results should have been tensile strains instead of compressive strains. In order to obtain reliable data from the optical fibres, these need to be fixed properly on the concrete surface. It is believed that the lack of bonding between the fibres and the concrete is the reason for the above discrepancies. The strain distribution provided by the Brillouin fibre sensor in the strip with w/c of 0.5 is in good agreement with the strain data provided by the other two methods. In general, the compressive strains measured with the concrete strain gauges are closer in value to those calculated through bending theory than the ones measured by the optical fibres. The high value recorded by the concrete strain gauge at 0.91 m for the strip with w/c of 0.35 was due to a crack going through the gauge. It was observed that the other RC strips had several visible cracks at this section as well; however, the cracks did not cross the strain gauges.

4 Conclusions

This paper has presented the results of an experimental testing of two strain measurement techniques (electrical strain gauges and Brillouin distributed fibre sensors) on an RC slab subjected to service loads. Strain due to the applied load was monitored through both techniques and compared to theoretical values obtained from classical bending theory. While traditional concrete strain gauges were accurate provided concrete had not cracked, the optical fibre sensors showed good agreement with theoretical results provided that the fibres were properly fixed on the areas where strains exist. An advantage of the optical fibre sensors over the traditional strain gauges was the ability to provide both tensile and compressive strain data simultaneously at various locations. The Brillouin distributed fibre sensors are promising devices to be used in the field for on-going monitoring of damage detection and accumulation of RC structures.

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References