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Distributed strain sensing to determine the impact of corrosion on bond performance in reinforced concrete

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HIGHLIGHTS

- Distributed fibre optic strain measurements were made on tension tests.
- A method of protecting the steel-fibre optic bond from corrosion was developed.
- Strain profiles illustrated the breakdown in steel-concrete bond with corrosion.
- Pitting corrosion resulted in strain peaks but were difficult to identify.

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ABSTRACT

Corrosion of reinforcing steel is the primary deterioration mechanism for reinforced concrete structures, however its impact on structural behaviour can be difficult to assess using visual inspections. This paper investigates the potential for using distributed fibre optic sensors to monitor the impact of corrosion to supplement visual inspections. Tension tests were conducted on bare reinforcement and reinforced concrete specimens subjected to accelerated corrosion. The distributed fibre optic strain data provided insights into the concrete-reinforcement bond performance of corroded specimens and the detection of pitting corrosion appeared to be possible although challenging.

1. Introduction

Reinforced concrete infrastructure around the World is reaching a critical point whereby structures built in the construction booms following the Second World War are reaching the end of their service lives. For example, Canada's infrastructure is currently at a critical stage with over 40% of bridges in Canada being more than 50 years old, and requiring strengthening, rehabilitation or replacement [5]. To illustrate the monetary impact of deterioration on infrastructure, the American Society of Civil Engineers has estimated a cost of $76 billion for the rehabilitation of bridges and another $21 billion for dams in the United States alone [3]. For reinforced concrete structures, corrosion of reinforcing steel is recognised as the predominant deterioration mechanism [4].

Traditionally, monitoring the safety of structures has relied heavily on visual inspections and few, if any, sensors to provide quantitative data. The assessment of infrastructure based on visual inspections is limited and has varying degrees of effectiveness [27]. Additionally, visual inspections cannot identify deficiencies hidden within a structure. Thus, major deterioration issues may only become apparent once the structure is already in need of rehabilitation. A better management system to optimise maintenance strategies is required to prolong the service life of structures, ensure safety, and reduce costs. One potential strategy to improve bridge management is to use sensor technologies, such as strain gauges, for regular measurement and analysis of important structural and environmental parameters under operating conditions to identify problems at an early stage. These monitoring systems would be used to supplement visual inspections with quantitative data to ensure safety and structural integrity rather than to replace visual inspection.

Fibre optic sensors (FOS) are an attractive option for monitoring in new and existing structures. Systems based on the measurement

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of Rayleigh backscatter can provide strain and temperature resolutions better than 1 με and 0.1 °C, respectively [18]. Unlike other fibre optic systems, Rayleigh backscatter systems can provide distributed strain and temperature sensing along the length of the fibre. The gauge length and sensor spacing can be changed as required for the structure being assessed with values of less than 1 mm being possible. Regier and Hoult [23] illustrated the impact of varying the spatial resolution between 5 mm and 50 mm for reinforcement bars with a 6.25 mm notch in them tested in tension. They showed that if the spatial resolution is too large relative to the size of the defect, in this case a 50 mm gauge length relative to a 6.25 mm defect, the effects of the localised change in area cannot be determined accurately using distributed sensing. Additionally, the flexibility in data analysis allows the gauge length and sensor spacing to be changed after the data has been gathered to analyse the data in a variety of ways. Furthermore, the optical fibres are small in size, light weight, flexible, have immunity to electromagnetic interference, do not corrode, and can be embedded in concrete structures [9].

Although the optical fibres themselves do not corrode, corrosion can still cause inaccurate measurements if it progresses beneath the adhesive that bonds the fibres to the reinforcement. In order to develop a successful monitoring system, it is necessary to develop an installation technique that would protect the sensors from being affected by the corrosion. Ideally, the FOS could measure approximate levels of corrosion, areas of pitting corrosion, crack locations and evidence of bond deterioration. If fibre optic sensors could be used to identify corrosion deterioration within reinforced concrete structures, it would greatly benefit current monitoring and inspection methods.

However, before FOS can be used as a reliable tool for infrastructure assessment, several issues must be investigated. The specific objectives of the current research are to:

1. Develop a fibre installation method to withstand harsh conditions present in corroding reinforced concrete,
2. Investigate the ability of the fibre optic sensors to detect and quantify corrosion levels of the reinforcing steel, and
3. Determine how bond performance is affected by corrosion in reinforced concrete using distributed strain measurements.

This paper provides a background on the effects of corrosion on reinforced concrete behaviour, an accelerated corrosion technique, and the fibre optic strain measurement technology. Following that, a detailed explanation of the experimental program is given, including the development of a fibre installation technique for both bare reinforcement and reinforced concrete specimens, the accelerated corrosion technique and setup used, and the testing program. The results section presents the test results accompanied by a discussion of the findings followed by key conclusions.

2. Background

2.1. Corrosion deterioration in reinforced concrete

Corrosion is a natural electrochemical process by which metals deteriorate. Corrosion of steel in concrete is usually due to either the ingress of chloride ions from marine exposure and de-icing salts or carbonation of the concrete. Chloride induced corrosion typically results in pitting of the reinforcing steel while carbonation results in a breakdown of the passive layer that results in more uniform corrosion. Corrosion of the reinforcing steel will cause two main deterioration issues in reinforced concrete. The first is a reduction in cross sectional area of the reinforcement which will decrease the overall strength of the structural element. This will decrease the size of the transverse ribs on deformed rebar, weakening the mechanical interlock with the surrounding concrete [16]. This reduces the primary bond mechanism that restrains slip between deformed bars and surrounding concrete. Additionally, bond deterioration issues occur long before the reduction in cross-sectional area of the bars becomes a problem [1]. Both deterioration of bond and section loss of the reinforcement are critical issues affecting reinforced concrete performance [1].

The second deterioration issue is that the corrosion of the reinforcement creates expansive products. Research by Almusallam et al. [2] showed that initially at low levels of corrosion before cracking (0–4%), the expansive force on the confining concrete will increase the concrete-reinforcement bond performance. This is due to the reactionary confinement of the corrosion products from the reinforcement, increasing the mechanical pressure and interlock on the surrounding concrete. Additionally, this initial amount of corrosion increased bar roughness and therefore the friction with the surrounding concrete [2]. The expansive products formed during corrosion can also cause concrete between the transverse ribs on the reinforcement to crush thereby increasing the rate of slip of a bar under repeated loading [1]. The expansive nature of corrosion will eventually induce stresses that exceed the tensile capacity of the surrounding concrete and cause cracking [16]. Once cracked, the bond performance decreases significantly as the confinement diminishes. Almusallam et al. [2] observed a significant decrease in bond strength once cracks began to develop where after the cracks reached a width of 1 mm the bond strength was approximately 15% of the ultimate bond strength for an uncorroded specimen. Mancini and Tondolo [21] noted that a reduction in the tension stiffening occurs when splitting of the concrete occurs. Following cracking, the rate of corrosion increases significantly as there is a direct path for water and chlorides to corrode the steel [10]. Cracks will propagate further, causing delamination and spalling if not dealt with.

2.2. Accelerated corrosion technique

Preferably, natural corrosion of reinforced concrete members would be used to evaluate bond performance [26]. However, corrosion damage in reinforced concrete structures takes many years to occur. While this is beneficial to reinforced concrete structures, it makes studying the effects of corrosion deterioration more difficult. Fortunately, options exist to accelerate the rate of corrosion so that deterioration that would normally take years to occur can be reduced to several days or weeks depending on the size of the specimen. The current research program uses an electrochemical accelerated corrosion technique which involves submerging the specimen in a salt water bath and impressing a current through the reinforcement. Previous research has experimented with impressed current densities ranging from 45 $\mu A/cm^2$ [6] to 10,400 $\mu A/cm^2$ [2]. The corrosion rate of steel using this technique can be predicted using Faraday's Law shown in Eq. (1) which indicates the mass loss is proportional to the number of electrons exchanged and the molar mass of the element.

$$m = \frac{t \times I \times M}{z \times F} = \frac{t \times I \times 55.847}{2 \times 96487} \tag{1}$$

where m = mass loss (g), I = current (Amps), M = molar mass of the element, z = valency of the element, t = time (s) and F = Faraday's Constant = 96487 A/s.

The rate of corrosion can be significantly increased using this technique, however, the corrosion process and products can vary from natural corrosion. The amount of volumetric expansion depends on the type of oxide that is produced as noted by Kivell et al. [17]. Typically, natural corrosion products are composed of iron (III) oxide (Fe_2O_3) which is a red-orange colour. However, the electrochemical accelerated corrosion technique often pro-