An Optical Fiber Sensor for Corrosion Detection of Reinforced Concrete Structures

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Introduction

- Steel Corrosion is a Major Problem with Reinforced Concrete Structures

- Early Detection of Potential Corrosion Enables Proper Maintenance to Extend the Life of Structures
Initiation of Steel Corrosion in Concrete

- Iron oxide formed on steel surface is initially stable in the alkaline environment of concrete.
- The stable layer protects underlying material from corroding, so the corrosion rate is Negligible.
- The Protection is Lost when:
  - pH at steel surface drops below 11 (normally due to the penetration of Carbon Dioxide).
  - A Critical Chloride Concentration is reached at the Steel.
- Steel corrosion is then Greatly Accelerated.
Assessing the Penetration of Corrosive Agents

- A Core can be taken from the Concrete Structure
- To assess the penetration of CO\(_2\), pH indicator can be applied on the lateral surface to find the location of color change
- To assess Chloride penetration
  - The Core is cut into slices, which are ground into powder
  - Filtration is performed to find the chloride content in the powder
  - Chloride concentration vs depth can hence be obtained
- Disadvantages
  - Time Consuming and Costly
  - Results Do NOT Directly Reflect Corrosion Activities
  - For CO\(_2\), pH indicator changes color at pH=9 while steel starts to corrode at pH $\leq 11$
  - For Chloride Initiated Corrosion, the Critical Chloride Content decreases by an order of magnitude when pH changes from 13.5 to 12.5
In-situ Corrosion Assessment with the Corrosion ‘Ladder’

- Developed by Raupach and Schiessl at Aachen University

By measuring the corrosion current between each steel bar on the ‘ladder’ and a reference, the corrosion activity at different distances from the surface can be assessed.
The Corrosion Ladder is a very Robust ‘Instrument’ and has been used in many Real-World Projects

Limitations:
- Not Applicable to Existing Structures
- Relatively Costly

A version for Installation in Existing Structures has been developed but sealing is a problem
A Novel Corrosion Detection Concept

- The Coating can be Produced by the Sputtering Process, with many Fibers coated at the same time
  - Cost of Each Sensor can be Low
- Retrofitting of Sensor into a Structure is Possible
The Sputtering Process

Physical Principle

Coating of Optical Fibers

Coated Optical Fibers
Measurements on Sputtered Substrate and Fiber

**Film Thickness vs Sputtering Time**
- Measured from Glass Substrate with the Profilometer

**Reflectivity vs Film Thickness**
- Measured from Coated Optical Fibers in Air with OTDR
Power Measurement with OTDR

- OTDR Stands for the Optical Time Domain Reflectometer
- Measurement Principle
  - An optical pulse is sent forward and the reflected signal monitored as a function of time
  - Reflected Power at a particular point can be obtained through comparison with the signal level at the ‘floor’

A Typical OTDR Result

The measurement is hence insensitive to fluctuation of source powder and loss at connections
  - Key to reliable measurements based on Power Intensity
Tests on Bare Coated Fibers (1)

Fibers are put inside Salt Solution of different chloride Concentrations

Coated film corrodes under the presence of chlorides and the response is dependent on chloride concentration
Tests on Bare Coated Fibers (II)

Fibers are embedded inside Mortar Blocks containing salt, which are either placed in Water or left in Air

Sensor can detect corrosion and distinguish between different corrosive environments
Packaging Method of the Sensor

1. Coated fiber (sensor) and plastic tube
2. Sensor inserted into the plastic tube
3. Sensor fusion-spliced to connector
4. Protecting tube applied over bare fiber

Fiber with coated end
Protecting tube
Plastic tube
Connector to optical system

Coated Fiber
Detection of Chloride Penetration

**Test Set Up**

- Container
- Specimen
- Fiber sensor
- 3% NaCl Solution
- OTDR

**Specimen (Side View)**

- Fiber sensor
- All Lateral Sides sealed with Epoxy
- Cement Mortar W:C:S=0.6:1:2
- 15mm
- 10mm
- 5mm
Results for Chloride Penetration Test

Corrosion starts at sensor closest to the surface exposed to chlorides
Performance of Sensor in a Drilled Hole

Experiment Set Up

- Sodium Chloride Solution
- Fiber Sensor
- OTDR

Specimen preparation

- Fiber sensor
- New cement mortar W:C:S=0.6:1:2
- Relative chloride concentration
- Cement Mortar W:C:S=0.6:1:2
Results for Sensors installed in the Holes of Mortar Blocks

Feasibility for Post-installation of Sensor is Demonstrated
Sensor Output vs corrosion current

Experimental Set-Up
(modified ASTM G109)

- Adhesive tape
- 3% NaCl Solution
- Ground clamp
- Fiber Sensor
- Steel bars

Corrosion Current = \( V/R \)

R = 100\( \Omega \)
Results (1)

Corrosion Initiation detected by current measurements 6 days before the optical sensor
- Corrosion Initiation detected by optical sensors 16 days before the current measurement
- Different is not significant for practical long-term monitoring
Sensor Installation in Concrete Structures

- New Structures (angled sensor)

![Diagram of sensor installation](image)

- Fiber Sensors
- Concrete Surface
- Bottom of Sensor Glued to Surface of Steel Bar
- Sensor Outlet
- Steel Reinforcement
- Sensor head
- Flat part glued to steel
- Inclined part
- Fixture end
- Fiber corrosion sensor
- Flat part glued to steel
- Sensor Encased in GFRP
**Existing Structures**

**Box Section**
- Optical Fiber Sensor
- Hole Drilled from inside of Box Section
- Steel Reinforcements
- Hole Fully Sealed on the side

**Solid Section**
- Optical Fiber Sensor in the Drilled Hole
- Steel Reinforcements
- Chloride Penetration from the Lower Surface to be Monitored
Field Trial in an Existing Structure

- 10 sensors installed on two piers of a footbridge right next to the sea

Sensors are installed in holes drilled on these surfaces
Locations of the Sensors

- 5 sensors installed in each pier

Sensor #1
60mm from surface
40mm depth

Sensor #2
80mm from surface
40mm depth

Sensor #3
100mm from surface
40mm depth

Sensor #4
60mm from back surface
40mm depth

Sensor #5
300mm from surface
100mm depth
Installation Procedure (1)

- Locating of Steel Reinforcements
- Drilling of Hole for the Sensor
- Cleaning of Hole with Compressed Air
Installation Procedure (2)

Sensors Placed inside the Holes

Sealing of Hole Surface with Epoxy Coating

Filling of hole with Cement Grout

The sensors have survived THREE big typhoons since their installation
The loss for each sensor is measured at different times.
The reference is a fiber embedded inside an epoxy block.
Results appear to correlate well with location of sensors
Correlation with Chloride Content in Pier

- Powder taken around the 3 sensors on the seaward side (at 25-40mm depth) and also around the sensor in the middle of the pier (at 85-100mm depth)
- Chloride content obtained through titration with silver nitrate solution

<table>
<thead>
<tr>
<th>Location</th>
<th>Chloride Content (%wt of cement)</th>
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<tbody>
<tr>
<td>Near the Sea</td>
<td>0.314</td>
</tr>
<tr>
<td>Center of Pier</td>
<td>0.214</td>
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- Results seem to be reasonable as chloride threshold is normally between 0.2 to 0.4% cement weight
Conclusion

- A New Corrosion Sensor based on OTDR Measurement of Reflected Light Intensity is developed together with a simple packaging technique.
- The Sensor can be mass produced at low cost and is suitable for both new and existing concrete structures.
- Laboratory Results show that:
  - The sensor can monitor corrosion penetration.
  - The sensor can be post-installed into an existing structure.
  - There is reasonable agreement between sensor measurement and macro-cell current.
- Site Trial indicates robustness of sensor and reasonable correlation between measured corrosion and sensor location.
- Through this investigation, the potential of a novel corrosion sensor is demonstrated.