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Corrosion monitoring
ZAG and IGH

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The main aim of the research work within this project was:

1. To select appropriate measurement techniques and parameters for direct assessment of corrosion activity,
2. To „translate“ the output of this corrosion monitoring system into values which can be implemented in the maintenance and asset management for cost–effective operation.

Presentation:
- Principle of monitoring techniques
- Summary of laboratory and in–situ investigation
- Corrosion criteria definition
- Proposed corrosion monitoring system
## List of laboratory / in-situ investigations

Methods/techniques used during TRIMM project

<table>
<thead>
<tr>
<th>Inspection</th>
<th>Monitoring (continuous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct assessment of corrosion activity</td>
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<tr>
<td>• Half-cell potential (potential mapping)</td>
<td>• Embedded reference electrode</td>
</tr>
<tr>
<td>• Galvanostatic pulse technique</td>
<td>• EIS</td>
</tr>
<tr>
<td>• Embedded reference electrode</td>
<td>• Macrocell current</td>
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<tr>
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<td>• Electrical resistance probe (ER)</td>
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<td></td>
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<tr>
<td>Determination of influencing parameters</td>
<td></td>
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<tr>
<td>• Resistivity of concrete</td>
<td>• fiber optical sensors (pH, Cl⁻)</td>
</tr>
<tr>
<td>• Humidity</td>
<td>• resistivity sensors (concrete resistivity,</td>
</tr>
<tr>
<td>• pH, Cl⁻, T</td>
<td>humidity)</td>
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</tbody>
</table>
**Principle of monitoring techniques**

**Macro-cell current measured by multi-depth sensors (IGH):**

- Electrochemical method

**Electrical resistance probes (ZAG):**

- Physical method

**Principle:**

- Macro-cell current between cathode and anodes, $i_{corr}$
- Steel–stainless steel potential, $V_{corr}$
- Electrical resistivity of concrete between neighbour anodes by AC method, $\rho_{concrete}$

- Wheatston breadge – change of resistance because of thickness reduction is measured. Measured resistance is proportional to thickness reduction and via that proportional to corrosion rate of ER sensor made from metal.

\[
\Delta h = h_0 \cdot \frac{u}{1+u} \\
U = \frac{U_{out}}{U_{in}} \Rightarrow u = \frac{\Delta U}{U} \\
h = h_0 - \Delta h
\]
Summary of laboratory investigations

- Multi depth macro-current and electrical resistance sensors sensitive for detection of changes of corrosion processes and corrosion rate regardless to the corrosion activator

Multi depth sensors

- Corrosion and chloride content increasing near reinforcement time dependent processes

Electrical resistance sensors

- $0.06\%$ Cl, carbon steel corrosion initiation
Summary of in-situ investigation – ER sensors

Koper harbour test site
Since December 2013

Goals: long-term behaviour, compare different zones of exposure, compare different measuring techniques

Data available on WEB page:

www.corrosion-kp.zag.si
Summary of in-situ investigation – macro-cell sensors

IGH: Maslenica, Cetina and Krka bridge (Croatia)

Maslenica
No. of sensors: 21
Installed: 1996 - 1997 (during bridge construction)
Type of measurements: 29.01.2014.
(initial measurements not available).
Type of measurement: Anode Ladder (macro cell current), concrete resistivity, Half cell potentials, temperature, chloride levels and concrete properties

Cetina
No. of sensors: 6
Installed: March 2006 - 2007
Type of measurements: anode Ladder (macro cell current), concrete resistivity, Half cell potentials, temperature

Krka (over river)
No. of sensors: 6
Installed: July 2003 - March 2004
Type of measurements: Anode Ladder (macro cell current), concrete resistivity, Half cell potentials, temperature
IGH: Maslenica, Cetina and Krka bridge (Croatia)

- Maslenica: Corrosion at the top and foot of arch – 5 cm under concrete cover layer, after 18 years.
- Cetina: Initiation of arch foot after 7 years.
- Krka (over river): No corrosion in 10 years.
Summary in-situ investigation chloride content

Chloride depth (cm)

0,06% Cl, carbon steel corrosion initiation

Chloride content (% on concrete weight) measured on Maslenica bridge
Critical corrosion sites – pavements, carriageway construction, water drainage

Moderate corrosion risk, mostly due to carbonatization

Water droplets, high corrosion risk

Spray zone, moderate corrosion risk

Splash, tidal zone, high corrosion risk

SEA
Corrosion criteria definition

- Macro-cell currents transformation to corrosion rates (CR):
  - $I_{corr} = 0.1 \, \mu A/cm^2 \rightarrow CR = 1.1 \, \mu m/Y$ - corrosion initiation (Condition category=1)
  - $I_{corr} = 3 \, \mu A/cm^2 \rightarrow CR = 34 \, \mu m/Y$ - first cracks appearance (Condition category=5)

  \[ CR = i_{corr} \times 11.46 \]

<table>
<thead>
<tr>
<th>Corr. rate (\mu m/Y)</th>
<th>Condition category</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>1</td>
<td>Very good</td>
</tr>
<tr>
<td>1–5</td>
<td>2</td>
<td>Good</td>
</tr>
<tr>
<td>5–15</td>
<td>3</td>
<td>Acceptable</td>
</tr>
<tr>
<td>15–30</td>
<td>4</td>
<td>Poor</td>
</tr>
<tr>
<td>&gt;30</td>
<td>5</td>
<td>Very poor</td>
</tr>
</tbody>
</table>
Protective actions to restrain corrosion

1. Barrier coating application (short-term efficiency)
2. Application of active coatings
3. Removal of contaminated concrete
4. Cleaning of corrosion products from reinforcement
5. Application of coating for reinforcement protection
6. Reprofilation of concrete
7. Replacement of first layer of reinforcement (suggested use of stainless steel reinforcement)

**Failure Stages of Construction**

- **1 - Depassivation of steel**
- **2 - First micro cracks of concrete**
- **3 - Cracking of concrete**
- **4 - Delamination of concrete**
- **5 - Loss of bond**

**Corrosion Rate [µm/year]**

- **A - Concrete cracks repair**
- **B - Cathodic protection**

**Without corrective actions**

- **1 + 2**

**With corrective actions**

- **3 + 4 + 5 + 6**
- **A + B + 1**
- **(3 + 4 + 5 + 6) + 7**
## Advantages/disadvantages of proposed monitoring techniques

<table>
<thead>
<tr>
<th></th>
<th>ER PROBE</th>
<th>MACRO–CELL CURRENT SENSOR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PROS</td>
<td>CONS</td>
</tr>
<tr>
<td>Measuring depths</td>
<td>1 sensor per chosen depth</td>
<td>Nothing noted</td>
</tr>
<tr>
<td>Measuring range</td>
<td>Good for early stages 1–3</td>
<td>Not appropriate for long term monitoring during stages 4–5</td>
</tr>
<tr>
<td>Cost</td>
<td>Not costly sensors and automatic data acquisition system</td>
<td>Nothing noted</td>
</tr>
<tr>
<td>Results interpretation</td>
<td>User–friendly simple data analysis</td>
<td>Nothing noted</td>
</tr>
</tbody>
</table>
System installation on RC bridge

- **December 2013**  
  Koper harbor

- **Spring 2014**  
  Krk bridge

Sections repaired 2013
- Multi depth sensors (December 2013),
- ER probes (July 2014)

Combined with other conventional inspection methods
Conclusion

- Good correlation between both methods during the investigation (verified in lab)

- Both techniques can be used for chloride as well as carbonation induced corrosion

- Macro-cell sensor is sensitive for detection of anodic/cathodic changes at different depth of „corroded concrete“, however, results need interpretation

- Electrical resistance (ER) sensors are sensitive method to detect initiation and monitor changes in damaged concrete in earlier stages

- Installation of sensors on critical corrosion sites of construction – necessary inter-collaboration between designer-projectant and corrosion specialist