IN-SITU USEFUL LIFE OF AN ACCORDION JOINT SALT BRIDGE IN AN ELECTROCHEMICAL ALERT SENSOR (ECAS) FOR SHM OF CIVIL INFRASTRUCTURE

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Abstract: Structural Health Monitoring (SHM) technology has become increasingly important as an approach to reduce the maintenance costs and increase the availability of civil engineering structures like suspension bridges, railway bridges and high rise buildings. One of the critical failures in such concrete structures is crack formation due to dynamic loading that the structure undergoes during the period of operation. Damages to the structure are reflected in the modal response and affect the natural frequencies of the healthy structure only to a limited extent. Also, accurate measurement of deflection at critical points in the structure can give useful timely information to the concerned authority to take corrective maintenance procedure. Displacement sensors like the Linear Variable Displacement Transducer (LVDT) sensor have allowed this technology to become an integral part of structures to detect deflections in real-time. However, these sensors are costly and not ruggedised to work on the field. This paper proposes a electrochemical based deflection threshold/alert sensor (ECAS) which can be prepared in-situ and installed during construction of the civil structure. The sensor acts like a ON-OFF switch with very high sensitivity and can alert authorities well in advance of the structural deterioration due to dynamic loading leading to preventive maintenance.

Key Words: structural health monitoring, electrochemical sensor, salt bridge

INTRODUCTION

The emerging field of structural health monitoring (SHM) [13] addresses the in situ behavior of structures by assessing their performance and recognizing damage or deterioration. The SHM field involves the probing of a structure using sensor measurements and data processing procedures to assess its integrity. A considerable sub-field of SHM involves measuring the structural response from a dynamic forcing [2]. Time series analysis techniques are then utilized to extract a feature that provides information about the structures condition. Research has led to features incorporating resonant frequencies and mode shapes [11], Ritz vectors [12], model updating [9], and wavelets [5] among many others. Recent research has attempted to make use of the manifestation of damage as a nonlinearity (e.g. opening and closing of a crack), employing prescribed nonlinear time series analysis techniques for feature extraction [1] [8] [7] [10]. A need for SHM arises with the fact that properties of both concrete and steel depend on large number of factors which are often hard to predict in practice.

The representative parameters selected for health monitoring of a structure in general can be of mechanical, physical and chemical in nature. Deflection of the girder in a bridge structure can be a very good indication of the health of the bridge and online monitoring of the same is crucial to make predictive decisions regarding the failure of the structure. The oldest and reliable method for deflection measurement is described below:

WATER LEVEL MEASUREMENT FOR DEFLECTION [3]

Sometimes the readings by linear potentiometer are not reliable as it requires a stable support with respect to the ground frame which is not possible at higher floors. Due to this limitations water level in a tube which directly uses gravity can be used. One end of tube is kept in the middle of girder and the other end is fixed to
the main column which is fixed. When the girder deflects in middle it changes the water level in the tube by the amount beam has deflected and hence gives us the proper deflection. This is one of the oldest and reliable method of finding difference in level between two points.

This paper deals with the development of a sensor based on the electrochemical principle which can be prepared in-situ during the fabrication of the structure itself. The ratio of dynamic to static mid-span deflection for a simply supported beam can be taken to be equal to 10 from a designers perspective. In reality, the ratio is upto 1.6 by mathematical formulation as shown by [4]. The static deflection curve based on LVDT readings at mid-span is shown in Figure 7 in [6], which clearly indicate that the yield point load creates a deflection of 8 mm in the concrete beam. Considering a safety factor of 5 for the static loading and a additional factor of 10 for the dynamic loading, we can arrive at the following threshold for the allowable deflection for the civil structure.

| Allowable deflection (mm) for static loading from nominal condition | = 8/5 = 1.6 mm.......(1) |
| Allowable deflection (mm) for dynamic loading from nominal condition | = 8/(5 x 10) = 0.16 = 160 µm.......(2) |

**BASIC PRINCIPLE OF OPERATION: ELECTROCHEMISTRY**

Electrochemistry is the study of chemical processes that cause electrons to move. This movement of electrons is called electricity, which can be generated by movements of electrons from one element to another in a reaction known as an oxidation-reduction ("redox") reaction. The history of the development of various types of cells is as shown in Figure 1 below. The sensor proposed in this paper is a simple Daniel cell with suitable modifications.
Chemical reactions involving the transfer of electrons from one reactant to another are called oxidation-reduction reactions or redox reactions. In a redox reaction, two half-reactions occur; one reactant gives up electrons (undergoes oxidation) and another reactant gains electrons (undergoes reduction). A piece of zinc going into a solution as zinc ions, with each Zn atom giving up 2 electrons.

\[ \text{Zn}(s) \rightarrow \text{Zn}^{2+}(aq) + 2e^- \]

In a reduction there is a decrease (or reduction) in oxidation number. Chemical equation representing half-reactions must be both mass and charge balanced. In the half-reactions above, there is one zinc on both sides of the equation. The charge is balanced because the 2+ charge on the zinc ion is balanced by two electrons, 2e-, giving zero net charge on both sides.

\[ \text{Cu}^{2+}(aq) + 2e^- \rightarrow \text{Cu}(s) \]
DESIGN OF IN-SITU ELECTROCHEMICAL ALERT SENSOR (ECAS)

The in-situ electrochemical sensor as seen in Figure 1 (b) below is made using the conventional technique. Two electrodes of Cu and Zn are placed in their respective electrolytes. In-order to complete the circuit, a salt bridge is made using the following procedure.

PROCEDURE FOR MAKING ACCORDION JOINT SALT BRIDGE

The salt bridge acts as a connector between the electrolytic solutions and thereby completes the circuit. Basically the salt bridge is in the galvanic cell to regulate the charges in solution and keep them neutral. Without this, there is no flow of electrons, and therefore no electrical output. It avoids voltage drop.

The standard procedure of making a salt bridge is enlisted below:

1. Prepare about 150 ml of distilled water in 400 ml beaker and bring to boil.
2. Take 3 g agar-agar powder and stir the mixture as the suspension boils
3. Remove the beaker from the heat and stir in 15 g KCL until the salt dissolves.
4. Pour the warm mixture in the bent straw salt bridge until it is completely filled. Once agar is set, store in plastic bag for preventing drying out.
5. Seal one end with cotton plug and ensure that no air bubbles are present in the salt bridge prepared.

WORKING OF ELECTROCHEMICAL ALERT SENSOR (ECAS)

The electrochemical alert sensor is modeled as a mass-spring-damper system as shown in Figure 1 above. The parameters used in the design of the electrochemical sensor are given in Table 1 below. The static deflection due to the container, salt bridge and spring is 51.4 μm. In order to test the sensitivity of the sensor, raindrops were considered as a forcing input.[14]

Diameter of raindrop – 3 mm, Terminal velocity – 10 m/s, Time taken to come to rest – 100 ms
Force generated due to impulse = \( \text{mv/t} = (1000 \times \pi \times (0.003)^3 \times 10)/(6 \times 0.1) = 1.41 \text{ mN} \)

Every raindrop generates an impulse force of 1.41 mN resulting in a deflection of 3.2 μm of the assembly (container + salt bridge + spring) which slowly reached to static deflection in about 1.2 s. This was in consideration with the value of damping of air, \( \zeta_{air} = 0.01 \) while in practice air has almost negligible damping and will continuously produce a sinusoidal oscillation of amplitude 3.2 μm. This implies that the sensor is very sensitive to small deflections and can very well meet the safety criteria for civil structures under dynamic loading as mentioned in Equation (1) and (2).
### Table

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
<th>UNIT</th>
<th>AVAILABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of container (m&lt;sub&gt;c&lt;/sub&gt;)</td>
<td>1.47</td>
<td>gm</td>
<td>General purpose container to give medicine to children and adults (10 ml)</td>
</tr>
<tr>
<td>Mass of salt bridge (m&lt;sub&gt;s&lt;/sub&gt;)</td>
<td>3.5</td>
<td>gm</td>
<td>Normal straw with center bend</td>
</tr>
<tr>
<td>Mass of spring (m&lt;sub&gt;k&lt;/sub&gt;)</td>
<td>0.17</td>
<td>gm</td>
<td>Used in normal ball-point pen</td>
</tr>
<tr>
<td>Stiffness of spring (k)</td>
<td>950</td>
<td>N/m</td>
<td>NA</td>
</tr>
</tbody>
</table>

The steady state response to raindrop force can be seen in Figure 2 below. The ECAS when attached to a rigid surface like a girder of a bridge will dynamically move with the structure and reproduce the time history whenever the structure deflection exceeds the desired threshold. Also, by adjusting the gap 'y' in Figure 1 (b) above the designer or contractor can ensure the safe operation of the structure throughout its lifetime.

![Response of Electrochemical (ECS) Sensor to Impulse force exerted by raindrop](image)

The typical deflection curve for a roadway bridge[7] is as shown in Figure 3 below. The deflection as found in FEM is very much comparable to the CASI methodology. As per the safety criteria for civil infrastructures, the following table exhibits the allowable deflections for various structure...
The placement of the Electrochemical Alert Sensor (ECAS) at various locations on the roadway bridge can be seen in Figure 2 below. The nominal deflection as predicted by FEM under the normal loading condition is around 3.5 mm at mid-span. When due to abnormal conditions or due to deterioration the deflection increases to 4 mm, an alert is sounded by the ECAS to the concerned authorities to take corrective actions. The safety threshold as per Table 2 above is 3000/600 = 5mm.

The voltage from the ECAS can be relayed to a centralized server via ESP8266 and Arduino UNO so that the concerned authorities are aware of the deflection at the various critical points of the civil infrastructure.

**TABLE 2:**

<table>
<thead>
<tr>
<th>Category</th>
<th>Max allowable deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Railway bridges</td>
<td>L/800</td>
</tr>
<tr>
<td>Roadway bridges</td>
<td>L/600</td>
</tr>
<tr>
<td>Structural buildings</td>
<td>L/300</td>
</tr>
<tr>
<td>Crane track girders</td>
<td>L/800</td>
</tr>
</tbody>
</table>
USEFUL LIFE OF THE ELECTROCHEMICAL ALERT SENSOR (ECAS)

The sensor produced in the manner as described above is very light in weight and sensitive to small disturbances. Also, due to the field environment, the sensor may lose its capability of sensing. Due to changes in ambient temperature, the salt bridge characteristics may change and thereby make the sensor malfunction. Hence, in-order to understand the exact behavior of the sensor, we conducted a test for determining the average lifespan of the sensor when it is continuously in the conducting state.

The experiment was conducted with an accordion salt bridge over a period of 18 days using 0.1 M solution of each of the electrolytes CuSO\textsubscript{4} and ZnSO\textsubscript{4}. The voltages and current were measured at different time intervals. The measured voltages and current were used to compute the actual power of the sensor(cell). The theoretical time for the cell life was computed as given below:

\[
\text{Cell life in days} = \frac{\text{(No of cells} \times \text{Molarity} \times \text{Volume (liters)} \times \text{No of electrons/mole} \times 96485)}{(60 \times 60 \times 24 \times (\text{Final current} + \text{Initial current})/2)}
\]

The theoretical current is taken to be average of initial and final current value. The theoretical cell (sensor) life turned out to be 22.9 days. The actual experiment worked for 18 days (432 hours). The performance of the ECAS is as seen in Figure 4 below. The actual curve of the current indicates that the ECAS will discharge as a battery in an exponential manner. The voltage provided by the ECAS is almost constant at 1.04 V which is less than the expected value of 1.1 V due to polarization effects.

Figure 4 – Performance of ECAS (Cu-Zn Voltaic cell with accordion salt bridge in 0.1 M 100 ml solutions)§

The current of ECAS gradually drops following an exponential curve like the discharging of a voltaic cell. As seen in Figure 4 above, we can confidently say that the Sensor will work for a period of 15 days where the current drops to 0.1 mA. The ECAS can be very well used as an alert system for abnormal deflections that the civil structure might witness during the period of operation.

§ The data for the Cu-Zn cell can be shared upon request and proper authorization from Rizvi College of Engineering
CONCLUSIONS AND FUTURE WORK
The paper proposes the usage of an electrochemical alert sensor (ECAS) made from the modification of a normal voltaic cell with the use of an accordion salt bridge. The sensitivity of the sensor is around 3.2 μm for the impulse force generated by a raindrop. The life of the sensor is around 15 days with continuous contact with electrolytes. Also, the sensor can be easily attached to suitable locations of the civil structure like railway bridges, high rise buildings and suspension bridges for safety consideration. Future work will involve making of an experimental setup to actually embed the sensor in-situ with the structure and test its robustness and useful life.

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