Changing Model Properties with Time due to Corrosion of a Dynamically Loaded Reinforced Concrete Beam

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Abstract: Structural Health Monitoring (SHM) systems are frequently used in civil infrastructures. One important durability property in reinforced concrete (RC) structures is the level of steel bar corrosion. In a dynamic four-point-bending test, two beams are loaded simultaneously, in which corrosion is accelerated in one of them. Since geophones are commonly used in SHM systems to monitor vertical deformations and to calculate modal properties, the first natural frequency of both beams are analysed in this paper. It is discovered that many properties, like temperature and moisture, may influence natural frequencies. Besides this, calculated natural frequencies may fluctuate. Experiments showed that the first natural frequency in the corroded beam decreases while it remains almost constant in the uncorroded situation.

Keywords: Chemical degradation, concrete beam, dynamic load, natural frequencies, time dependency.

1 Introduction

Over the past few years, Structural Health Monitoring (SHM) has become a commonly used system to measure the structural health of civil infrastructures. Geophones, which measure the vertical movement of a bridge deck, are one of the most frequently used sensors in SHM systems. Geophones provide information for calculating modal properties of a bridge, i.e. natural frequencies, damping ratios, and mode shapes. Due to the prevailing degradation mechanisms, modal properties may change with time. However, it is very complicated to observe degradation from SHM data in real time situations [1].

One of the key-degradation mechanisms in reinforced concrete (RC) structures is corrosion of steel reinforcement. A four-point-bending test is developed to provide information about the structural behaviour under corroded conditions [2]. During this experiment, two comparable beams are loaded simultaneously. One of these beams is exposed to a chloride-water solution and the other with tap water only, which results in different corrosion conditions with time. Deflection and crack width measurements give information about the behaviour and the stiffness of the structure. Since the exposure conditions are different, the development of corrosion with time is unequal for both beams. In the chloride-affected beam a reduction of the stiffness is visible, which cannot be observed in the water-affected beam. This knowledge can be considered as useful information when designing an SHM. The current paper will report the test details and an analysis of the results.

2 Experimental plan

Two beams are casted in one go, from one batch and one concrete composition. After casting, there was only 1\% mass difference between both beams (Table 1). The 28-day compression strength is measured from three cubic specimens with dimensions 150x150x150 mm\(^3\) (Table 1). The two beams are installed in a specially designed testing frame and are loaded by the same load cylinder with one pressure cell. The beams are installed and loaded up-side-down to initiate

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bending moments at the top, and to mimic midspan supports of multiple span bridges, i.e. upper reinforcement is more sensitive to corrosion due to de-icing salts than the reinforcement situated in the lower parts of bridge elements. The dimensions and frame setup can be found in Figure 1. An extended description about the experimental programme is discussed in an earlier publication [2].

To activate corrosion, a bath with a 10% chloride-water solution is mounted on top of one of the beams. Similar was done for the other beam but then tap water is used as reference. Because wetting-drying cycles are generally identified as most unfavourable environmental conditions for concrete elements [3], a two days wet and five days drying cycle is initially scheduled during dynamic loading of the experiment. Unfortunately, some leakage was observed which shortened the wetting time undesirable and uncontrollable. Since leakage was very hard to prevent in the running experiment, and while the beam was still corroding under these conditions, the shortened time the beams were exposed to Cl and/or a pure water solution was acceptable. Due to irregular leakages, the water level on top of the beams was not equal, which initiated a different water-induced fluctuation of the structural response. In previous publications it was already discussed that the wetting-drying cycle was chosen appropriately [4].

<table>
<thead>
<tr>
<th>Concrete compressive strength</th>
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<tbody>
<tr>
<td>Concrete mass</td>
</tr>
<tr>
<td>Beam 1: 54.68 kg</td>
</tr>
</tbody>
</table>

**Figure 1** Schematic impression of the experimental setup

### 2.1 Loading and measurements

Before commencing the dynamic test, the capacity of the beam was determined by loading a third beam to failure under static conditions. The measured failure load was approximately 24 kN. To simulate real traffic conditions, the beams are loaded dynamically. The maximum impact of the dynamic load was 12 kN, which is corresponds to 50% of the failure load. To avoid compressive bending stresses from turning into tension, a minimum load of 2 kN was applied on the beams. The loading frequency was 0.5 Hz.

During the experiment, the deflection between the acting point of the load and midspan is measured with Linear Variable Differential Transformers (LVDTs) for both beams. Due to
imperfections in the beam geometry, experimental setup, and heterogeneity of the material, deformations are not equally distributed over the width of the beam. Because of this, the deflection is measured on both sides of the beam and the average value is considered as the maximum deflection, which is used in the calculation of the first natural frequency, as discussed later in this paper.

A dynamic load, as applied in the experimental setup, can be described by a sine and has the following shape:

$$ F(t) = A \cdot \sin(\omega (t+t_0)) + B $$

In which ‘$$\omega$$’ and ‘$$t+t_0$$’ are related to the phase, and ‘$$A$$’ and ‘$$B$$’ to the impact of the load. In common SHM systems, deflections are stored with a high frequency, generating huge amounts of data, from which modal properties can be calculated. By increased measurement frequencies, more detailed information like higher order natural frequencies and damping ratios could be calculated as well. However, when applying the load according to equation (1), and all parameters of equation (1) are known, the load and the response can be reproduced analytically, while the data storage is limited, i.e. equation (1) needs only four data points instead of 6000 by a 100Hz geophone. Unfortunately, damping ratios can hardly be calculated by an analytical approach.

During the experiment, the range and the average value of the applied load is measured and stored. In equation (1), the load range is the difference between the minimum load and the maximum load, and is equal to two times the amplitude ‘$$A$$’. The load average is the baseline of the load and defined by parameter ‘$$B$$’. Due to fluctuations in oil pressure, environmental and ponding conditions, and in beam response, the force shows fluctuations with time as well. Since degradation is a slow process, it is not necessary to store data with a high frequency. Chosen is for a storage frequency of 0.017 Hz (one measurement per minute). This storage frequency could be lower during the first weeks of the experiment. However, during the last hours this frequency turned out to be necessary for an accurate recording of the beam failure.

### 3 Natural frequency

Natural frequencies can be derived from a standard single-mass-spring system [5], [6]. The first natural frequency of a single-mass-spring system can be calculated by

$$ f = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{K}{m}} $$

In which K is the stiffness and m is the mass of a structure. Note that in equation 2 the mass is concentrated. Equation (2) is often used in dynamic calculations. Equation (2), however, is only valid if the structure contains only one concentrated mass. In practice, structures have multiple (distributed) masses, which results in different derivations. Based on a multi-mass-spring system [5], the first natural frequency can be calculated by

$$ f = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{g \cdot \sum_{i} (m_i \cdot v_i)}{\sum_{i} (m_i \cdot v_i)^2}} $$

In which i is the number of permanent masses, g is the gravity acceleration, $$m_i$$ is the mass of element i, and $$v_i$$ is the deflection of element i as result of all permanent masses. With this, all permanent masses of a structure are included in equation (3) and consists the dead load of the structure, but also the permanent load. In the experimental setup the permanent load is defined as the minimum dynamic impact. The permanent load in real bridges can be considered as dead load, installations or traffic jams. Since the dead load is equally distributed and the applied loads are mostly concentrated loads, equation (3) can be rewritten as
Furthermore $v(x)$ depends both on the dead load of the beam and the minimum applied force, which makes an analytical approach unpractical to use.

The minimum impact of the load is approximately 2kN, which corresponds to 200kg. Since the dead load of the beam is 54 kg, and the dead load is equally distributed, the deflection due to the dead load is relatively small in comparison with the applied load. Because of this, small deviations in the dead load distribution have a minor impact on the calculated natural frequency. The distributed dead load is lumped in four nodes (Figure 2): two middle nodes are concentrated at the supports and have, therefore, no influence on the deflections, and two outer nodes which are concentrated at the same location at which the loads act on the beam, and can be simply taken into account in the calculation. Because of this mass lumping, equation (4) can be simplified into

$$f := \frac{1}{2 \cdot \pi} \sqrt{g \cdot \frac{2 \cdot F_{\min}}{2 \cdot g} \cdot v_A + \int_0^t \left[ q_{\text{dead load}} \cdot v(x) \right] \, dx}$$

$$f := \frac{1}{2 \cdot \pi} \sqrt{\frac{2 \cdot F_{\min}}{2 \cdot g} \cdot v_A + \int_0^t \left[ q_{\text{dead load}} \cdot v(x) \right]^2 \, dx}$$

Figure 2 Schematic impression of the load distribution, in which $M_1=54.2\text{kg} \times (0.300/1.500)$ and $M_2=54.2\text{kg} \times (0.450/1.500)$

A finite element (FE) calculation (Figure 3) is done with the software Scia Engineer, to check the results of the simplified equation (5). Table 2 shows the results of the FE calculations and the analytical approach. For the calculated examples, two permanent masses of 100 kg are applied. From the results it can be observed that equation (5) shows almost similar results than the FE calculations, and is, therefore, be used in further calculations.

Table 2 Calculation results first natural frequency

<table>
<thead>
<tr>
<th></th>
<th>FE (equal distributed)</th>
<th>FE (concentrated)</th>
<th>Equation (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_1$</td>
<td>47.77 Hz</td>
<td>47.81 Hz</td>
<td>47.91 Hz</td>
</tr>
</tbody>
</table>
3.1 Measurements

Due to the effect of structural and chemical degradation (ageing), deformations of structures will change with time. In this section the recorded measurements are analysed on this influence. Equation (5), shows the deflection $\Delta$ which is the difference in deflection between the unloaded ($F=0$ kN, and no dead load) and the permanent loaded situation ($F=12$ kN, and dead load). Due to creep, shrinkage, and other aging properties, some deformations are irreversible and do not influence the natural frequencies. Since the unloaded situation is not measured, these values need to be calculated from the recorded data ($F=2$ kN and $F=12$ kN). It is assumed that the relation between the force and the deflection shows a linear behaviour, since the force is limited to 50% of the failure load. To calculate the unloaded situation, the relation between the load range, the deformation range, and the permanent load is calculated (Figure 4) by

$$\Delta_{A, perm. load} = \Delta_{range} \cdot \frac{F_{permanent}}{F_{range}} \quad (6)$$

The measured deformations are the differences between midspan and the load location (while under loading). An analytical model and a numerical calculation are performed to calculate the relation between the deformations at the load location and the deformation at midspan. For this approach, it is assumed that the stiffness of the beam is constant over the length. Equation (7) shows the deformation at the load location; equation (8) shows the deformation at midspan. Due to the loading direction at the beam edges, the deformation at midspan is directed upwards and negative in the formulae.

$$\Delta_{F=0} = \Delta_{F_{min+DL}}$$

$$\Delta_{F_{max+DL}}$$

Figure 4 Relation between the load range, the deformation range, and the permanent load
Using equation (7) and (8), the ratio between the deflections can be calculated and is defined as

$$\alpha := \frac{2 \cdot a \cdot (a + 3 \cdot b)}{2 \cdot a^2 + 6 \cdot a \cdot b + 3 \cdot b^2}$$  (9)

$$\beta := \frac{3 \cdot b^2}{2 \cdot a^2 + 6 \cdot a \cdot b + 3 \cdot b^2}$$  (10)

In which $\alpha$ is the deflection at the load location relative to the total deflection and $\beta$ is the deflection ratio which is related to the deflection of the midspan. With $a=475\text{mm}$ and $b=225\text{mm}$ (see Figure 2), $\alpha=0.88$ and $\beta=0.12$, which means that 88% of the measurements are caused by the deflection at the load location, and 12% by the midspan deflection. According to these calculations, the measured deformation was multiplied by a factor 0.88 to calculate the deflection at the load location, which needs to be applied in equation (5).

4 Results

During the test, the range and the average values of the force and the deflection of both beams are measured and stored every minute. Due to different crack patterns, the deflection is not equal in both beams. In the primary stage of the test, the beams are loaded statically to initiate the cracks. The beams are not yet exposed to Cl and/or water solution in this stage, so corrosion could not influence the crack locations. In the beam that is later exposed to the chloride-solution eight cracks are observed, while in the second beam nine cracks developed. The number of cracks influences the crack width and the deflection. The maximum deflection of both beams with time is plotted in Figure 5.
linear regression line [7] is calculated for the deflection development. This regression line was plotted in Figure 6 as well. The properties of the linear regression line can be found in Table 3.

Table 3 Properties linear regression deflection development

<table>
<thead>
<tr>
<th>Beam 1 (tap water)</th>
<th>Beam 2 (Chloride solution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ Y = 1.014 + 9.250 \times 10^{-8} \times n \text{cycles} ]</td>
<td>[ Y = 1.005 + 1.075 \times 10^{-7} \times n \text{cycles} ]</td>
</tr>
<tr>
<td>Standard deviation: 1.177 \times 10^{-4}</td>
<td>Standard deviation: 2.430 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Figure 6 Development of deflection (deflection(t) / deflection(t=t0)), the tap water exposed beam left, the chloride-affected beam right

Table 3 and Figure 6 show that the slope of the linear regression of the deflection development is 16% higher in the chloride affected beam compared to the beam that was exposed to tap water only. Scatter in material properties and inaccuracies in measurement equipment may lead to a comparable difference, which make it hard to observe this phenomenon in real structures. Furthermore, the standard deviation is relatively high.

The total deflection can be divided into initial deformations and in variable deformations. Initial deformations are irreversible and do not influence modal properties. These deformations are analysed and not considered in the calculation for the first natural frequency. Furthermore, the linear regression line is calculated for both beams and shown in Table 4. Figure 7 shows the first natural frequency as function of the number of cycles.

Table 4 Properties linear regression first natural frequency

<table>
<thead>
<tr>
<th>Beam 1 (tap water)</th>
<th>Beam 2 (Chloride solution)</th>
</tr>
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<tbody>
<tr>
<td>[ Y = 26.88 - 1.40 \times 10^{-7} \times n \text{cycles} ]</td>
<td>[ Y = 27.31 - 5.90 \times 10^{-7} \times n \text{cycles} ]</td>
</tr>
<tr>
<td>Standard deviation: 0.127</td>
<td>Standard deviation: 0.170</td>
</tr>
</tbody>
</table>

After analysing the first natural frequency, it is discovered that the difference between the tap water affected beam and the chloride solution affected beam is significant. The chloride affected beam shows a clear decrease of the first natural frequency while the first natural frequency of the second water exposed beam hardly decreases. Since the standard deviation of the chloride affected beam is relatively high, measurements need to be analysed carefully.
5 Conclusion

During a dynamic four-point-bending test, two comparable beams are loaded simultaneously. The range and average value of the load and deformations are measured during testing. One beam is affected with a Cl-water solution while a second beam is exposed to tap water only. The load and deflections provide information about the stiffness and natural frequencies of beams.

The number and location of the cracks are not equal for both beams. Because of this, a sound comparison between the responses of the beams is not possible. The development of the deflection at midspan is calculated for both beams. It is found that the deflection development of the chloride affected beam is slightly higher than the beam that is exposed to tap water only. However, the differences are small and the material properties and measuring equipment may show uncertainties in the same order of magnitude.

Based on the range of deflection and applied load, the initial deformations of the beams could be subtracted from the measured data. The remaining data is used to calculate the first natural frequency using an analytical model. A linear regression line is calculated to understand the development of the natural frequency with time. It is observed that the natural frequency in the chloride affected beam shows a clear decrease with time while the natural frequency of the tap water exposed beam shows barely any change. However, temperature and humidity, including exposure conditions, influence the natural frequency significantly. The standard deviation of the first natural frequency is relatively high which may influence the observed results as well.

6 References