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DATA-INTENSIVE STRUCTURAL HEALTH MONITORING IN THE *INFRAWATCH* PROJECT

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ABSTRACT

The InfraWatch project is a Dutch research project, aimed at developing novel techniques for large-scale monitoring of concrete infra-structures. The project involves a large bridge, fitted with multiple types of sensors that capture the high-resolution dynamic behavior of the bridge. With 145 sensors measuring at 100 Hz, a huge amount of data becomes available that describes various aspects of the bridge's response to traffic and weather conditions, both long and short-term. A single truck passing the bridge already encompasses almost 50,000 readings, such that detailed modal analysis can be performed. At the same time, this data-intensive monitoring continues around the clock, as well as the calendar, such that more gradual effects like changes in temperature and traffic conditions can be tracked as well. This wealth of information is being analyzed in various ways − which will be elaborated in this paper − combining both computer science and civil engineering expertise. The InfraWatch project is a central project in the Dutch national research program "Integral Solutions for Sustainable Construction (IS2C)", which is aimed at developing novel techniques for a next generation predictive simulation model for service life assessment. Other projects within this program are concerned with key degradation processes in structural concrete, such as ASR and chloride penetration. In the near future, the progress of such degradation processes will be measured by dedicated sensors, to be developed within these 'sister projects'. Such direct degradation measurements will complement the indirect measurements currently performed, which essentially only monitor the dynamic load on the bridge. A lab experiment is currently being developed in the Stevin II laboratory of Delft University of Technology, where ASR and chloride penetration will be measured alongside with the dynamic deformations of a test beam under load while focusing on the mutual interaction of both the materials degradation processes and the structural response.

KEYWORDS

Structural Health Monitoring, sensor data, concrete bridge, output-only modal analysis, lab tests, material and structural degradation.

INTRODUCTION

In the last decades, assessing the service-life of concrete structures is a theme that has gained an enormous interest. Despite the fact that concrete is a construction material that can last several decades to centuries, it has become clear that external influences may substantially (and often unexpectedly) shorten the service-life of civil infrastructures. More in detail, the factors that affect the service-life of civil infrastructures have various origins, such as traffic, climate conditions and the natural decay of the material phases. The complex interactions between these actions and the response of the infrastructural elements are the main topics to be dealt with, in order to assess the actual condition of our national stock of infrastructural assets. In this respect, a structural analysis that includes both traffic induced loading and material degradation and the interaction between these two actions is a major issue to be solved. In the Dutch STW perspective program called "Integral Solution for Sustainable Construction" (IS2C) (www.is2c.nl), these interactions between materials degradation, monitoring and sensing, and materials and structures are examined. The advanced knowledge is generated by 9 research projects forming together a consistent research program and will be used to develop a predictive simulation model for service-life assessment of infrastructure.

Figure 1: Hollandse Brug ("Bridge"). Monitoring system installed underneath the first span, seen from the left side.

One of the key projects within the IS2C program is the project called 'InfraWatch'. This project is a joint research project between Leiden University and Delft University of Technology and is scrutinizing the interpretation of real-time data. The data used for this project is achieved from the monitoring system that is installed at a major highway bridge called the "Hollandse Brug", in the Netherlands (Figure 1). The computational data analysis and data mining is conducted by researchers at Leiden University while the physical interpretation and matching with structural analysis models is conducted at Delft University of Technology. Within the framework of this project, the initial approach in Delft is to design a numerical simulation model that includes both the structural as well as the material aspects of the bridge. The model can be considered as the theoretical design tool that contains all the knowledge of bridge response representing the current state of the art. Matching the results of this model with the real data achieved from the real-time monitored bridge would provide a learning curve about the accuracy of the modelling approach as well as the long-term ability to simulate the interacting degrading and structural performance of the bridge. It is of particular interest to include degradation mechanisms such as ASR and chloride ingress in the numerical model and to account for their effects on the long-term durability performance.

In this paper, the state of the art of the project activities is reported. Emphasis is on the monitoring system of the Hollandse Brug and how the recorded data can be analysed using data mining techniques as well as structural analysis models. Modal analysis has been performed for both approaches and the mode shapes are compared. Moreover, the development of a lab-scale test-setup is briefly reported. With this set-up, tests will be conducted to evaluate the impact of materials degradation on the structural performance of a lab-scale reinforced beam. Finally, the proof loading activity of a full-scale concrete bridge which is affected by ASR is discussed briefly.

MONITORING HOLLANDSE BRUG

The Hollandse Brug is a reasonably old (over 40 years) highway bridge, with all the associated problems of bridges of that age. As the bridge's health was deteriorating, major refurbishment was undertaken in 2007-2008, at which time the sensor network was also installed on the bridge by contractor Strukton. The initial goal of the system was very much short-term, with emphasis on monitoring the curing conditions during refurbishing the bridge with a new concrete layer, and providing evidence for the renewed safety of the bridge in that period. As the monitoring system was a major investment, it was decided to make the system available to the publicly funded InfraWatch project after finishing construction activities, and allowing to develop research activities into the monitoring of infrastructure and the aging of concrete bridges. The sensor system has been handed over to the TU Delft and its collection of historic data is available within InfraWatch and the IS2C program as a whole. Parts of the strain data have been made public on http://www.infrawatch.com. The sensor system captures the moving loads on the bridge with much detail. Both from a strain as well as vibration perspective, measurements are collected at fairly high spatial and temporal resolutions. Additionally, local temperature sensors record the heating and cooling of the bridge, and a weather station provides general weather statistics at a low sampling rate. Combined, this data allows for a detailed analysis of the bridge's response to traffic, especially for large trucks and congestion, and weather conditions such as cold, wind, and sunshine. Besides monitoring the dynamic load on the bridge, deriving important parameters about the bridge's durability performance is also a topic of the project, in order to track the slow degradation of the bridge over time. This is a major challenge, as the sensors are predominantly affected by short-term changes such as traffic and seasonality, such that the gradual drift due to degradation is hard to recognize among the daily bridge dynamics.

The sensor system is installed underneath one of the spans of the bridge, measuring over 50 meters in length. A total of 145 sensors is placed along the width of the bridge, at three cross-sections of the span. At each cross-section, sensors of various types are placed at a variety of locations, for example attached to the bottom of the deck, under a girder, or embedded in the deck. Furthermore, sensors (especially the strain-gauges) are placed in various

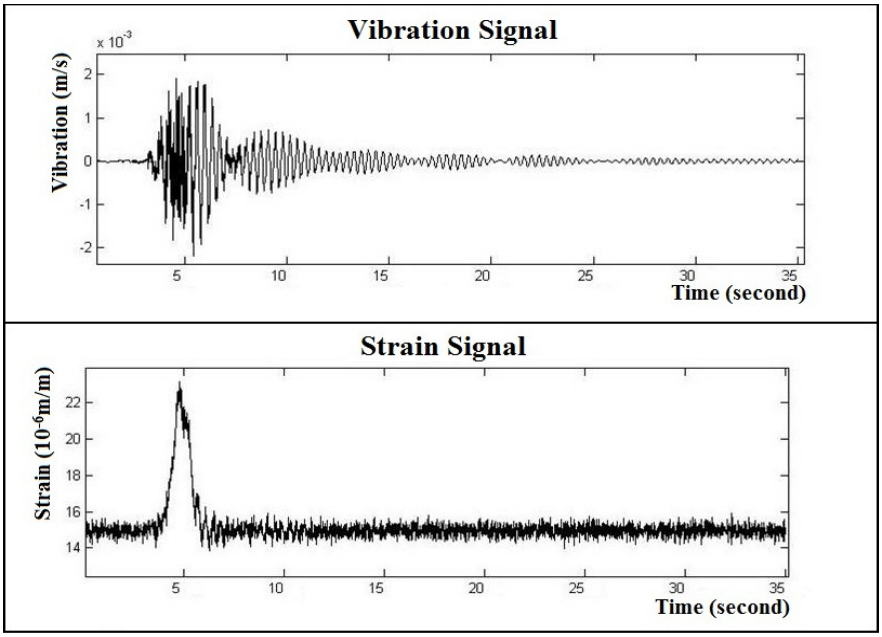

Figure 2: Detail of 35 seconds of strain and vibration data collected by two sensors, at 100 Hz.

orientations, such that the total network senses the bridge in many different dimensions and from a range of perspectives. The sensor network features a total of 91 strain gauges, 44 of which are embedded, and 47 are attached. Furthermore, there are 34 vibration sensors, as well as 20 temperature sensors. The sensors are connected to 5 data collection computers, sampling data at 100 Hz (Figure 2), and this data is finally recorded on-site in a central computer. With 145 sensors measuring at 100 Hz, a total of 14500 measurements are stored per second, which amounts to $1.25 \cdot 10^9$ measurements per day. Depending on the storage format, this translates to 5 to 10 GB of data per day, and over 2 Tb of data on yearly basis. To store this data over a longer period, a 72 Tb data storage has been reserved at the 3TU data center located at the Delft University of Technology, which includes 36 Tb working storage and 36 Tb back-up storage. Unfortunately, there is no live connection between the data center and the bridge, such that collected data only arrives at the data warehouse periodically. The above numbers indicate that even a simple event such as a truck passing the bridge is recorded in much detail, capturing the resulting deformation of the bridge as well as the vibrations induced by the dynamic event, which may last up to 20 seconds after the event. This results in roughly 350,000 data points related to a single truck passing, and will show details such as total strain during the event, bridge-suspension-truck interactions, induced vibrations (at various locations on the bridge), mode shapes, and damping ratios. On a larger time scale, the effect of temperature changes and day-night cycles can be observed clearly, which turns out to have a bigger impact on the (apparent) strain than individual trucks do. On a yearly scale, the temperature plays an even larger role.

With the bridge monitoring system installed on the Hollandse Brug, the simulated response characterization of the bridge is putting special attention to the analysis of the data recorded. Although the model results provided insight in parametric behavior of the bridge, the accuracy of results heavily depend on representation of load cases and corresponding bridge parameters. To overcome this, long term data analysis was performed to gain insight in the bandwidth of the measured data. By relating strain and vibration registrations to synchronized camera registrations, critical vehicles could be detected which helped data to be interpreted accurately. In this way, the type of vehicles causing critical strains or critical vertical velocities could be identified. In a later stage, this progressive insight was used to reselect the two typical vehicle cases and was also used to organize the normative loading program. For each run, vehicle characteristics such as axle loads were carefully recorded, while load and response data could be related and used for calibration of the bridge monitoring system. The calibrated bridge can now also be used as an alternative kind of Weight In Motion system for determining the weight and velocity of arbitrary vehicles crossing the bridge at any location (lane) (Figure 3).

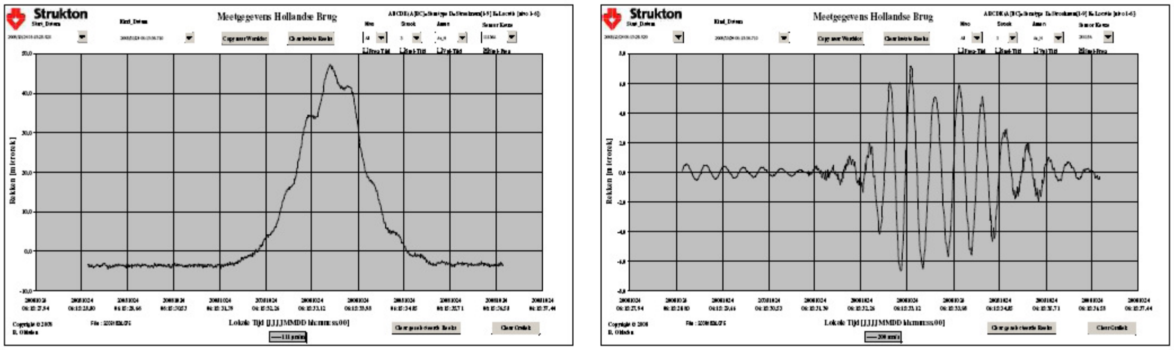

Figure 3: Data capture of strain (Left) and particle velocity (Right) of a large truck crossing the bridge.

Long term stain recordings showed that the absolute strain at the topside of the bridge did not exceed 20 micro-strains. Analysis of camera registrations showed that extreme strain values are repeatedly caused by heavy trailer trucks carrying ballast loads for cranes. Remarkable is the fact the dynamic contribution has on the total strain that alternates on top of the quasi-static strain. This additional deflection is a result of the combined effect of the vertical acceleration of the vehicle and the horizontal velocity effect. By taking a closer look to local strain registrations on the bridge, individual axes of a vehicle can be recognized as well. On a larger time scale, we are seeing the effect of temperature changes and day-night cycles, which turn out to have a bigger impact on the (apparent) strain than individual trucks do. On a yearly scale, the temperature plays an even larger role (see Figure 4).

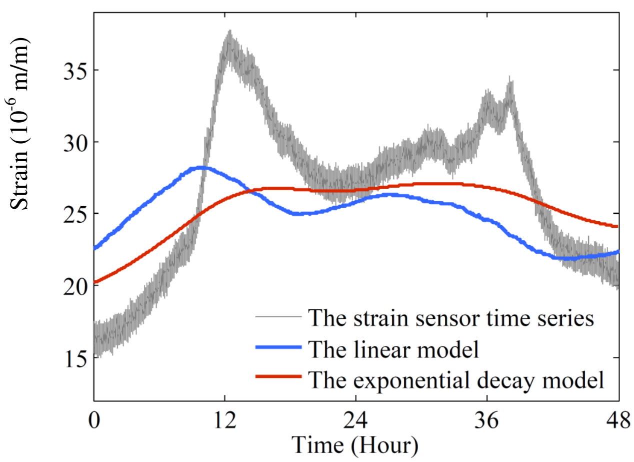

Figure 4: One day of strain data, showing the large effect of temperature (individual trucks are hidden in the small fluctuations). The blue line indicates the local temperature, and the red line a first-order differential equation model that to some extent explains the (delayed) effect of temperature on the apparent strain.

DATA ANALYSIS

Because of the richness of the data, many different kinds of analyses can be performed on the data, each demonstrating a particular aspect. These analysis experiments can be simply aimed at better understanding the nature of the collected data, and how the different sensors measure the same events in slightly different ways. Alternatively, some of the analyses are more goal-oriented, and aim to capture key performance indicators that can point to the long-term degradation of the bridge. In the text below, some of the data analysis performed on this data has been outlined briefly, neither attempting to be complete, nor excluding any future analysis that might be performed within InfraWatch or by other research groups.

Modelling Sensor Dependencies

As one of the first activities within the project, the dependencies between sensors were modelled. With the amount of available sensors, and the relative density of sensors on the bridge span, there will be a significant redundancy possible within the recorded signals. In fact, the sensor system was designed to capture data at a higher spatial (and temporal) resolution than strictly necessary. This was done with the objective to evaluate this potential redundancy, and also to better understand the monitoring intensity necessary in future SHM application. If it turns out that the same information can be obtained with fewer sensors than currently employed, then the costs of future monitoring systems could be reduced significantly. However, in order to reach this goal, an abundant set of sensors, from variation in types, attachments and orientations, will be needed help to scale down to this ideal sensor set-up.

The first dependencies between sensors considered were among sensors of the same type. Specifically between strain gauges, there was a high level of correspondence, with the dependence dropping as a function of the distance between the sensor locations, as could be expected. Although all strain gauges were correlated, the placement of the sensor turned out to be of importance in the amount of noise being captured, and hence the clarity of the signal. By far, the most reliable measurement of strain was obtained from sensors located underneath the girders, which is due to the bottom fibre, which is most affected by changing loads, and thus results in the highest signal-to-noise ratio. Sensors embedded in the new bridge deck were very sensitive to local pressure from heavy vehicles, and tended to fail easier.

Moving on to dependencies between sensors of different types, the relation between the temperature and strain signal was quite obvious. As Figure 4 also demonstrates, the signal produced by the strain gauges moves up and down with the local temperature measured. According to the measurements of the temperature sensors, the concrete temperature has a significant effect on the strain. However, the temperature of the concrete section is not equal to the outside temperature. Volume, surface, and concrete properties affect the spread of heat inside the concrete girder. Because of this temperature penetration, the temperature inside the concrete is delayed compared to the outside temperature, which is also measured by the temperature sensors. In a recent publication (Miao 2013b), a model for predicting the baseline drift of the strain signal as a function of the measured temperature has been obtained, which is based on a first-order differential equation essentially modelling the drift as an exponential decay of temperature effects (see Figure 4). Although the model nicely explains how the temperature affects apparent strain, it is not yet accurate enough to remove this effect from the measured strain signal, in order to arrive at a clear measurement for load-induced strain. For this purpose, it turned out that various baseline removal methods that separate long-term changes from short-term ones perform much more reliably.

The analysis of these dependencies was extended by a meta-level analysis that included the location, orientation and type of attachment of the strain gauge and temperature sensor, respectively. Essentially, if the level of influence of each temperature sensor on each strain gauge is computed, it is possible to determine what properties of the sensors determine this correspondence. It turns out that strain gauges embedded in the deck, and especially those oriented along the y-axis of the bridge (longitudinal), were most affected by temperature changes.

Miao *et al*. (Miao 2013b) also discusses the modelling of changes in the vibration signal, caused by temperature changes. Specifically, changes in modal frequencies are considered, and whether these correlate with changes in outside temperature. Although temperature in theory influences stiffness, and thus modal frequencies, such influences were hard to detect in the data considered, possibly because the modal frequencies were significantly perturbed by differences in traffic (speed, weight, number of axles) to show a clear correlation, at least for the lower modes. The paper does observe a relationship between temperature and frequency of higher modes. A more sophisticated method for obtaining spectra from *free vibration periods* has been adopted since (Miao 2013a, Miao 2013c), which may show such an influence also for the lower modes.

Modal Analysis

Understanding the dynamic behaviour of a bridge is considered an important aspect of assessing its structural health. Unfortunately, it is not practical to close civil infrastructures for controlled testing or proof loading, especially when the bridge is a main highway connection, as is the case with the Hollandse Brug. Therefore, analysis of the bridge's behaviour has to be fulfilled during *in-service* conditions. The behaviour is primarily studied by means of modal analysis. Based on the vibration sensors, located at various intervals along and across the bridge, detailed information about the mode shapes, natural frequencies and damping ratios could be obtained (see Figure 5). This analysis was done using *Stochastic Subspace Identification* (Peeters, 1999). A comparison between these results and an FEM model of the Hollandse Brug is presented in (Miao 2013c). Modal analysis is of importance, because it produces information related to the stiffness of the bridge. Tracking mode frequencies and damping ratios over time, while accounting for the influence of temperature, will point to any potential drift in this stiffness, and potentially any underlying degradation of the bridge.

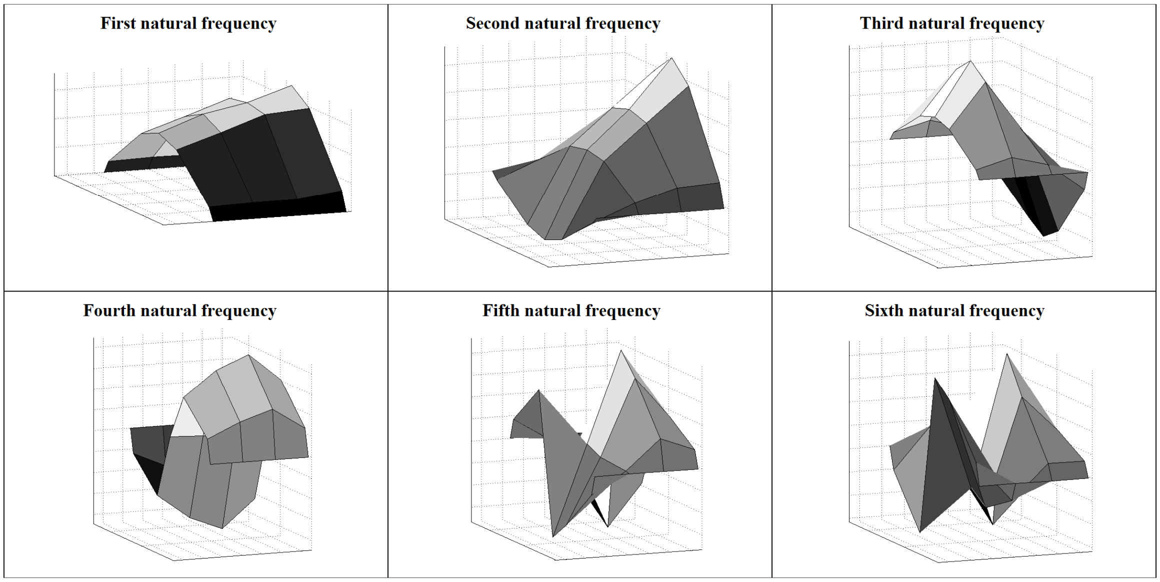

Figure 5: Mode shapes obtained from the vibration data for the first six modes: the first natural frequency is bending, 2.51 Hz; the second one is torsional, 2.81 Hz; the third one is bending and torsional, 5.74 Hz; the fourth one is bending, 10.09 Hz; the fifth one is torsional, 11.47 Hz, the sixth one is bending and torsional, 11.99 Hz.

Beating Phenomenon

As shown in Figure 1 (top), after the external loading (vehicle) has been passed, a beating phenomenon occurs during the free vibration period. The beating phenomenon is caused by the presence of two closely-spaced natural frequencies, shown as Figure 6, one of them is 2.51Hz and another is 2.81 Hz.

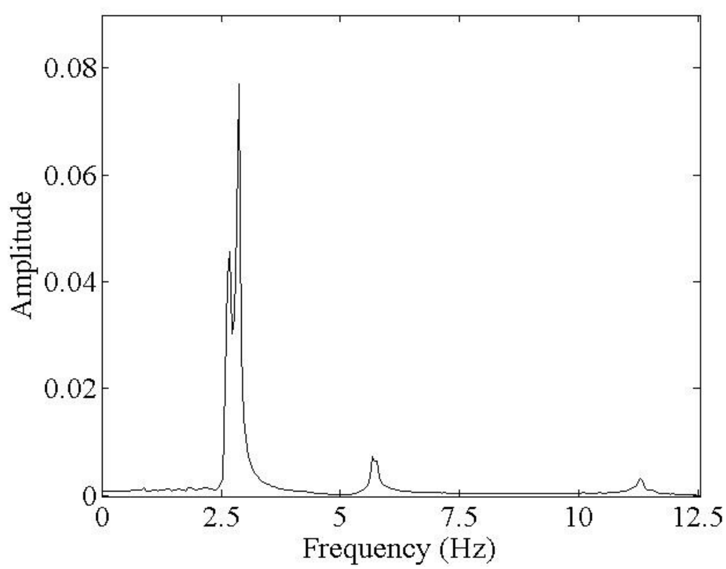

Figure 6: The spectrum of a free vibration signal: there are two natural frequencies, 2.51 Hz and 2.81 Hz, that are close to each other, which produce beating phenomenon in the free vibration period.

If each mode is treated as a damped single degree of freedom system, shown as Figure 6, which can be represented:

$$Y_i(t) = A_{i0} e^{-\xi_i \omega_{in} t} \cos(\omega_{id} t - \varphi_{i0}) \tag{1}$$

where ξ_i is the damping ratio, which can be estimated by two adjacent amplitude, also shown as Figure 7, ω_{in} is the natural frequency, ω_{id} is the damped vibration frequency, A_{i0} is the initial amplitude, and φ_{i0} is the initial phase, which is normally assumed to be zero. The relationship between ω_{in} and ω_{id} is:

$$\omega_{id} = \sqrt{1 - \xi_i^2}\, \omega_{in} \tag{2}$$

When ξ_i is small enough, we can assume that $\omega_{id} \approx \omega_{in}$. he structural system can be represented as a damped multiple degrees of freedom system:

$$Y(t) = \sum_{i=1}^{m} A_{i0} e^{-\xi_i \omega_{in} t} \cos(\omega_{id} t - \varphi_{i0}) \tag{3}$$

where m is the number of modes (natural frequencies). With the equations mentioned above, the beating phenomenon can be moderately modelled, but is not the same as the original signal. This may be caused by the initial phase of each mode, which is assumed to be zero. In practice, it can be a different value.

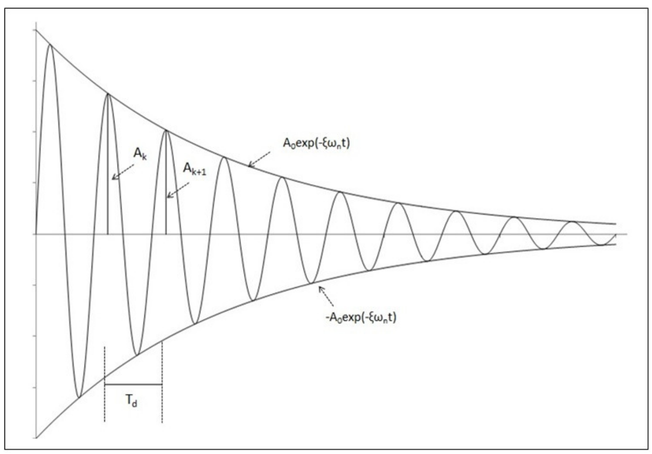

Figure 7: The damped single degree of freedom system

LAB EXPERIMENTS

The objective of the IS2C program is to generate advanced knowledge for the elements necessary to develop a next generation "Predictive simulation model for service-life assessment". Understanding the impact of chemical degradation mechanisms, such as chloride penetration and Alkali Silica Reaction (ARS), on the structural degradation of civil infrastructure is part of the research program. The Hollandse Brug is used as a test case to evaluate the data achieved from real-scale bridge monitoring systems. However, since the Hollandse Brug is recently being refurbished, and chemical degradation mechanisms are not likely to develop in the near future, lab-scale experiments are planned, with emphasis on the impact of materials degradation on the structural performance of concrete elements (Veerman 2013). Lab-scale tests also avoids uncertainties in the monitored data which are caused by the unknown traffic loads and climate conditions, which may affect the accuracy of the measurements. Therefore, to improve understanding about the effect of chemical degradation on structural performance in controlled conditions, a test-setup is currently under development at the Stevin II laboratory of Delft University of Technology.

The laboratory test has two objectives. The first objective is to measure and numerically analyze the mechanical and chemical degradation of a simply supported four-point-bending beam, while under a dynamic load. The second objective is to analyze the monitored data and to evaluate the overall beam monitoring system, which will be performed by the Leiden University. Obtained knowledge can be used for better understanding the degradation in real time bridges.

Figure 8: Test setup for dynamic loading of 1) a chloride induced specimen and 2) a non-chloride induced specimen that acts as a reference, to analyse the effect of materials degradation on the structural performance of elements.

In the lab-scale test set-up, chloride induced corrosion is considered as the chemical degradation mechanism. To make a comparison between a corroded sample and an uncorroded sample possible, at least two beams need to be tested simultaneously. Therefore, since corrosion induced degradation is a slowly-running process and, more important, in order to have a reference sample which is not affected by corrosion, the set-up has been designed in such a way that the two beam specimens are situated on top of each other (see Figure 8). The biggest advantage for this setup is that both samples are loaded equally, which makes comparison of the data possible and enables the possibility to measure the contribution of materials degradation on the structural performance of concrete beam elements explicitly.

Corrosion will be generated at the top surface of specimen 1) by applying a bath of chloride-solution on top of it. The chloride solution penetrates into the concrete specimen through the cracks and corrodes the reinforcement bar, which is located in the top layer of this sample. Specimen 2) is unaffected by chlorides and only contains a reference bath filled with water and will only show materials degradation which will be mainly caused by fatigue and de-bonding of the reinforcement. The system will be loaded dynamically with a frequency that mimics real traffic. Due to this dynamic loading and the chloride induced corrosion of the rebars, the cracks in the beam specimens will increase and will affect the structural performance, i.e. deflection and frequencies. It is expected that due to the active movement of the beams and the associated ingress of the chloride solution into the cracks, that corrosion will develop in a shorter time span compared to a statically loaded situation.

To understand the effect of materials degradation on the structural properties of the beam, it is necessary to measure both degradation and response. Therefore, the beam deformations, the actual crackwidth and the corrosion rate will be measured continuously during testing. This also holds for the deflections and accelerations, which are the response measurements of the system. All the readings will be stored at the 3TU Data Center, along with the Hollandse Brug data. This data will be analyzed to evaluate the overall performance of the beam monitoring system.

PROOF LOADING OF AN ASR-AFFECTED BRIDGE

The IS2C projects that deal with the chemical degradation mechanisms, including the InfraWatch project, are limited to two degradation mechanisms, i.e. chloride ingress and Alkali Silica Reaction (ASR). The explicit effect of chloride ingress on the structural performance of the measured bridge data will be investigated by means of lab experiments as discussed above. However, for ASR, experimental testing at lab-scale is more difficult. As ASR is a complex chemical process and hard to mimic in a short period of time, alternative routes had to be considered. Therefore, in order to achieve more information of the effect of ASR on the structural performance of civil infrastructure, Rijkswaterstaat, which is part of the Dutch Ministry of Infrastructure and Environment, proposed to investigate a full-scale bridge which is affected by ASR. One of these ASR-affected bridges in the Netherlands is called the Vlijmen-Oost bridge, and has been monitored for more than 10 years. The recorded data is also considered by the InfraWatch research team and is used to study the effect of ASR on the structural performance of bridges.

CONCLUSIONS

The InfraWatch project is an IS2C project that has the ambition to generate usable asset management information from the data obtained from bridge monitoring systems, and which includes both material and structural degradation, as well as their interaction. Several activities are running at this moment at the Leiden University and Delft University of Technology. The modal analysis studies show that monitored data from complex bridge structures can be used as basis to evaluate bridge degradation using data mining techniques. The comparison with the results achieved from structural FEM simulations show a good agreement and give confidence to the approach followed. However, in order to gain more insight in the explicit contribution of materials degradation on the structural performance of concrete beam elements, laboratory tests will be conducted in the coming months. For these tests, chloride ingress is considered as the main degradation mechanism. The full-scale bridge called Vlijmen-Oost will be used to study the effect of ASR and its effect on the long term structural performance of bridges. Results of all reported activities will become available soon and can also be found at the websites www.is2c.nl or www.infrawatch.com.

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