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Bridge Monitoring: A Pilot Project for Performance Assessment Management of Concrete Bridges

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ABSTRACT: The traffic intensity of the main highway network in the Netherlands has grown rapidly during the last decades. In order to be able to manage this infrastructural network more efficiently a full checkup of the total stock of existing bridge and tunnel structures has been performed with the main objective to examine whether their structural capacities still comply with the safety level of codes and standards, and to which extend they can deal with future demands. Efficient asset management requires insight in the short as well as in the long-term behaviour of infrastructural assets. In this respect, the “Hollandse Bridge”, situated in the Dutch highway A6, was upgraded with a concrete overlay in 2008 and accommodated with a comprehensive monitoring system, measuring all the mechanical degradation processes and structural aging effects during overlaying and operation of the execution works. At the same time, Strukton Civiel performed, in conjunction with Delft University of Technology, a research project with the aim to investigate the effect of traffic induced vibrations on hydration of early-age concrete. The motivation of this research was to examine the uncertainty that traffic vibrations may cause regarding the degradation of the young concrete overlay in relation to the conservative guidelines of civil engineering structures. As a consequence of this, it was decided to enforce a temporary detour during the execution and maintenance period, causing significant damage to the economy and many traffic delays. In order to investigate the necessity of this decision and to come up with recommendations for future projects and for improved service life design, both the research about the traffic induced vibrations and the monitored bridge response of the Hollandse bridge were combined and used as input for laboratorial scale research on the degradation of concrete loaded by traffic induced vibrations. The results of the research showed strong relationship between bridge response and materials performance. The monitoring system is now being used to monitor the condition of the bridge in terms of structural health monitoring.

1 INTRODUCTION

Asset management for infrastructure is the potential answer to the way our infrastructural assets can be managed while optimizing the operational & maintenance activities versus costs. In order to develop the necessary tools and knowledge for this, universities, contractors, private industries and governmental organizations have to work together in integral research initiatives. In line with the asset management approach it is considered that the technical state of a structure is the key information that provides the necessary data for computer models to simulate the desired optimum solution in terms of operational demands and maintenance costs. Structural health monitoring is the research direction that is aiming at developing the vital information to come to a system that enables the asset owner to manage and control the service-life condition and the maintenance demand proactively. It is the basis for the development of research projects like discussed in this paper where a 40 years old bridge had to be upgraded and where monitoring the bridge performance during and after the execution works and where the monitoring system is used afterwards as a pilot project for a structural health monitoring project in The Netherlands called IS2C ("Integral Solutions for Sustainable Construction").

One of the main reasons for changing the vision on maintenance demand and the economic consequences is the shift in the way the government will commence with contracting the construction of infrastructural assets. Within this approach responsibility is shifted from predefined governmentally imposed requirements towards a prescribed functional Operation & Maintenance system. This approach requires knowledge which is driven by different factors and among which the technical part is extended significantly from Design & Built towards an integral approach that includes construction upgrades and Operation & Maintenance. Besides these technical issues other factors that contributed to the motivation to shift the contracting approach have been:

- Lack of knowledge on the actual condition of infrastructural assets. In the United States several bridges have collapsed in the last decades, often due to unknown reasons;
- Most bridges in the Netherlands have been built in the years 1955-1975. Many of these bridges turned out to need significant maintenance on a short term, in order to comply with the national and European codes and safety standards.
- Enormous growth of traffic intensity and increase of average vehicle weights;
- Organizational mind shift associating with maintenance policy has evolved. Technical, contractual and organizational issues are to be encountered.

In order to demonstrate the issues that come along with the above mentioned shift of contracting, in this paper a detailed discussion will be reported on a case study called "Strengthening and maintenance of the Hollandse Bridge". This bridge has been maintained and strengthened by a concrete overlay, and widened with an extra lane in 2008. Along with the overlay execution stage, the main contractor Strukton Civiel initiated a research program in association with Delft University of Technology to investigate the effect of traffic induced vibrations on the microstructural formation of concrete overlays during hydration at early-ages. The research is subdivided into the following parts:

- Identifying dominant parameters for bridge management / bridge monitoring systems;
- Modelling and monitoring of traffic induced vibrations;
- Experimental program; examining traffic load and material consequence interactions.

In this paper, emphasis will be on the three main research parts addressed above. A detailed description of the research results achieved and the consequences for the design regulations will be provided.

2 BRIDGE MANAGEMENT FOR MAINTENANCE OF HOLLANDSE BRIDGE

The Hollandse Bridge (1969), situated in highway A6 in The Netherlands, is crossed by over 105.000 commuters, travelling between Almere and Amsterdam, every day (see figure 1). The bridge consists of seven statically determined spans with a length of approximately 50 meter. Each span consists of nine prefabricated, pre-tensioned concrete I-shaped beams of 3 meters height. The deck overlay is completed with in situ cast concrete at a thickness of 0.2 meter. The deck overlay as well as the in situ cast crossbeams situated perpendicular to the direction of the

Figure 1. Hollandse Bridge, subject to extended structural health monitoring.

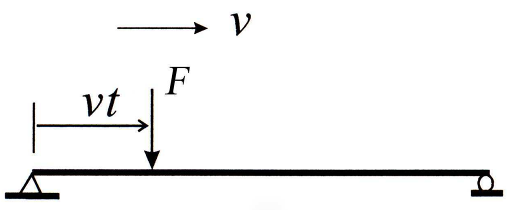
main I-shaped beams, are pre-tensioned as well. Upgrading the structural capacity of the bridge is executed by means of the principle of adding a new concrete overlay with improved performance. In order to achieve this, the existing asphalt layer has been removed and replaced by structural concrete layer. This construction principle only leads to an increased capacity of the bridge if the newly added concrete layer fully integrates with the existing concrete bridge deck. Therefore, the shear capacity of the interface should be large enough to withstand the shear forces ensuing from the solicitation forces (traffic, dead weight) and acting in the plane of interface. Great concerns arised from the influence of traffic induced vibrations on the bonding capacity of the concrete overlay during the hydration process. The execution of the overlay is subdivided into different stages, extending in transverse direction of the bridge. During each stage, two traffic lanes are taken out of operation and are covered with a climate facility (a tent). Inside this tent the lanes are upgraded one by one in longitudinal direction. This phased execution process allows it for traffic to use one of the other lanes, minimizing traffic obstruction and maximizing users (vehicle driver) comfort.

Problem description

Maintenance activities go along with a disturbance of the traffic flow due to the rehabilitation activities. During the execution process minimization of traffic obstruction is considered to be of paramount importance with respect to the users comfort and economic impact. Allowing traffic to cross the bridge and to pass the execution area at a close distance will affect the conditions at which the execution works will be conducted. Traffic induced vibrations will act on the bridge deck and, depending on the dynamic bridge resistance, impose the deck to respond at a certain frequency. Whenever the concrete overlay is freshly cast and still hardening, the effect of the traffic induced vibrations on the hardening process of concrete has to be taken into account. Guidelines that deal with this issue show a very conservative and inappropriate approach. The Dutch Directorate-General for Public Works and Water Management introduced vibration guidelines incorporated in the ROBK-6, the guideline for the design of concrete public works. The ROBK-6 guideline provides a strain limit of 35 microns and a Peak Particle Velocity (PPV) limit of 35 mm/s. Furthermore, differential displacement at the interface (existing to new concrete) is not allowed. In practice, the maximum strain limit is difficult to control. This also holds for other factors that associate with the hydration of the concrete, such as temperature and shrinkage and their effect on the actual strain. These effects and the lack of a specific measurement technique make the guideline unsuited for practical use. The limits addressed in the ROBK-6 guideline are mainly based on the results proposed by different researches which are combined in a publication of Ansell & Silfwerbrand in 2003. With this background it is questionable whether the ROBK-6 guideline is appropriate for the Dutch infrastructure. It can be concluded that these research results cannot fully answer the problem addressed. The Hollandse Bridge is, therefore, used as case study to examine the influence of traffic induced vibrations on the quality of the concrete overly (see Galenkamp 2009).

3 MODELLING BRIDGE RESPONSE

Before designing the Bridge Monitoring System the magnitude and origin of the traffic induced vibrations should be well understood. In order to achieve this, a theoretical model has been developed mimicking the bridge respond as a function of the traffic induced vibrations. The model includes traffic, bridge and environmental conditions and describes the bridge deflection as a function of location, time and dynamic load. With this model, vibration characteristics such as frequency and vibration magnitudes could be derived while interacting with the beam deflection. Quantifying the dynamic deflection of the bridge is done by using the modal analysis method. This method adopts the Euler-Bernoulli beam as a representation of the bridge (Fig. 2). The time and location dependent deflection u(x,t) is represented by an infinitesimal part of its natural modes of vibration. The most fundamental problem that should be solved is the dynamic response of a simply supported beam subjected to a single moving load and exists in a closed



$$u(x,t) = \frac{2FL^3}{EI\pi^4} \cdot \sin\frac{\pi x}{L}\left(\frac{\sin\beta_n t - S_n \sin\omega_n t}{1 - S_n^2}\right)$$

Figure 2. Left: mathematical scheme of the dynamic model; Right: formula describing the response of an elastic beam under a moving load.

form. The single load F represents one vehicle axes acting on the bridge and vt its actual position. By superposition of several axes, a realistic model of the traffic acting on the bridge can be obtained. This is allowed since the moving load problem is a linear system. The model is used to evaluate the dominant parameters involved in the bridge respond when loaded by moving traffic. From the model results it turned out that two typical systems could be distinguished representing generic traffic flow. These two cases are 1) single vehicles crossing the bridge and 2) a traffic jam. In Figure 3, modelling results are presented for the two cases. In the first case (Left), the mass and velocity of the passing vehicle is dominant and determines the maximum particle velocity of the bridge. The second case (Right) shows the deflection during congestion leading to the maximum bridge deflection induced by slowly moving traffic. From the simulations it turned out that the highest particle velocity and the highest strain don't occur at the same time. The highest particle velocity was found for heavy vehicles with high

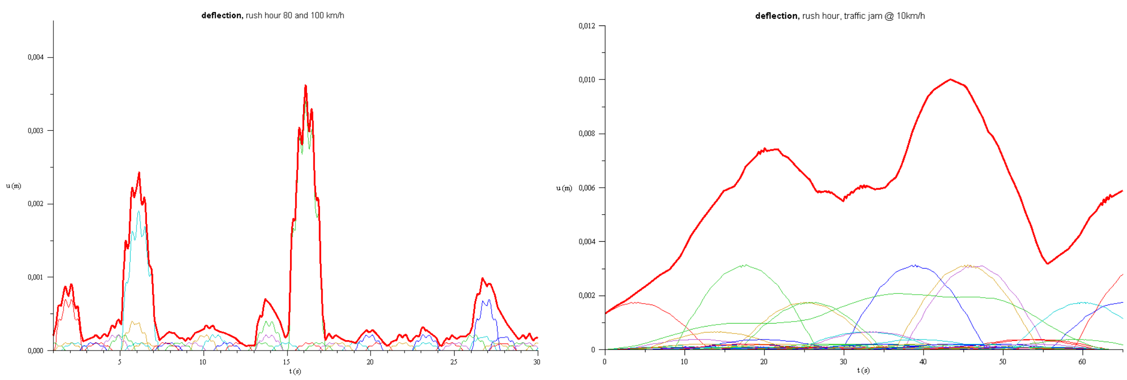


Figure 3. Left: Case 1) Typical deflection during intensive traffic including heavy cargo vehicles; Right: Case 2) Typical deflection during congestion.

velocities whereas the highest strains were found during congestion on the bridge. This leads to the conclusion that possible failure mechanisms could occur due to two different loading types and they should therefore be investigated separately to identify the individual contribution of both strains and particle velocities. The results obtained from the simulations were also taken into account by the design of the bridge monitoring system and will be discussed next.

4 DESIGN AND FUNCTIONALITIES OF THE BRIDGE MONITORING SYSTEM

Bridge response, including external influences, can be measured with a bridge monitoring system. Three main categories of variables have been identified: traffic load variables, variables that define the structural response and variables indicating the external influences. The bridge monitoring system is schematically shown in figure 4. Instead of using a weight in motion system (WIM) for measuring the actual vehicle loads, the measured structural response of the bridge is used. For this, the measured data has been converted from strain into traffic load information using the structural response of the bridge and by calibrating the system using normative loads. Therefore, heavy trucks have been mobilized that were loaded by a predefined weight and were directed to cross the bridge at a predefined sequence, speed and lane. For the measurement of the structural response, the system is equipped with nearly 150 sensors in normative cross-sections. Different types of strain gauges, geophones and temperature sensors are used. The maximum sample rate of the system was 500 Hz, where in practice 100 Hz turned out to be already sufficiently accurate. The monitoring system is built around a main PC, which communicates with and receives data from the different data loggers. The data loggers, video camera and the weather stations are connected with the main PC via a network cable. The data loggers consist of a National Instruments Compact-Rio system. The different Compact-Rio's are spread over the bridge and the backplane of these systems can be equipped with different I/O modules for different sensors. The main PC controls data loggers, time synchronization and online visualization of the recorded data. The main PC can be accessed and controlled from any internet connection. The quality control of the recorded data is executed using a data viewer, developed in Labview software. This viewer represents the values online in graphs. The data analysis is executed with Visual Basic and Excel. Visual Basic code is used for the mathematical calculations and filtering of the data. This data can be visualized with custom made Excel applications, which shows the selected data in graphs. Data interpretation is performed by combining the information from graphs, camera views and the recorded data.

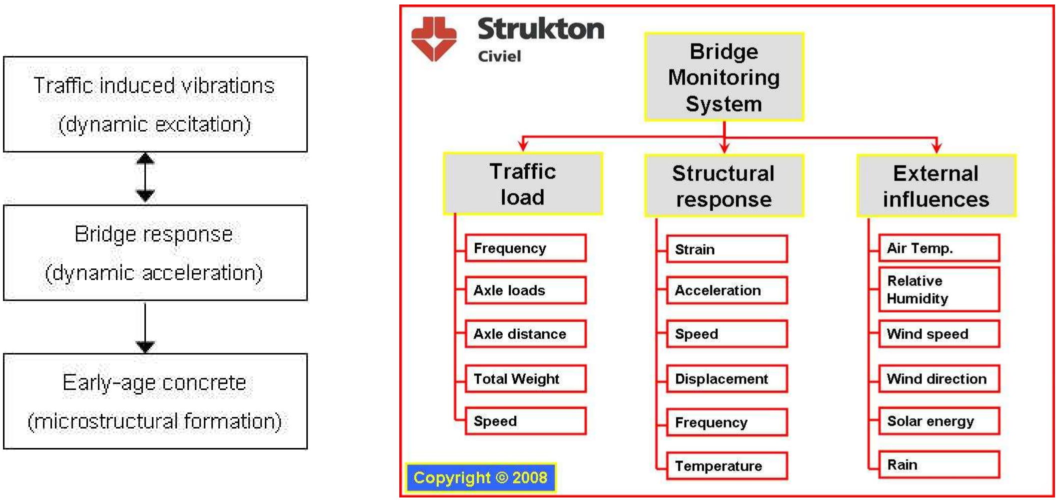


Figure 4. Left: Schematic representation of the relationship between traffic induced vibrations and its effect on early-age concrete; Right: Structure of the bridge monitoring system.

5 MONITORING VEHICLE-BRIDGE INTERACTION

With the bridge monitoring system installed at the Hollandse Bridge, the simulated response characterization of the bridge put special attention to the analysis of the data recorded. Although the model results provided insight in parametric behavior of the bridge (Fig. 3), 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 stadium, this progressive insight was used to reselect the two typical vehicle cases and was also used to organize the normative loading program (Fig 5). For each run, vehicle characteristics such as axes 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 be used as an alternative kind of weight in motion WIM-system for determining the weight and velocity of arbitrary vehicles crossing the bridge at any location (lane).

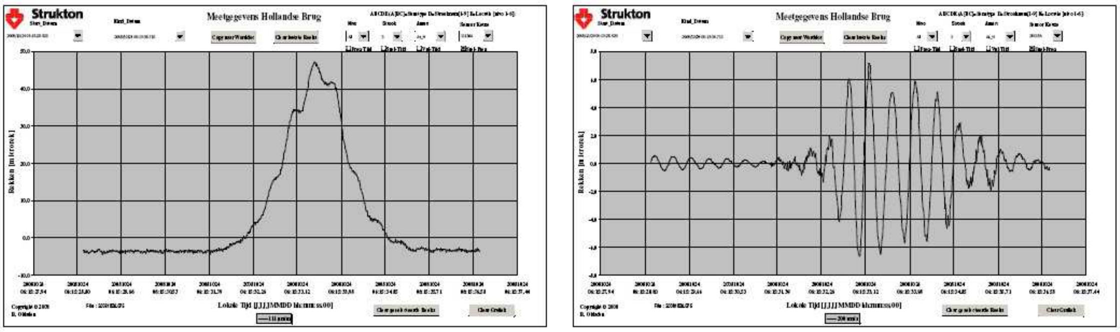


Figure 5. Data capture of strain (Left) and particle velocity (Right) of a large truck crossing the bridge.

Long term stain recordings showed that the absolute strain at the topside of the bridge did not exceed 20 microstrain. 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. In Fig 6, 10 axes were counted, and the configuration of the vehicle could be recognized from the strain registration. By differentiating two points of the recordings, velocity of the vehicle, the axe configuration (vehicle length) and load per axes can be determined, including the total vehicle weight.

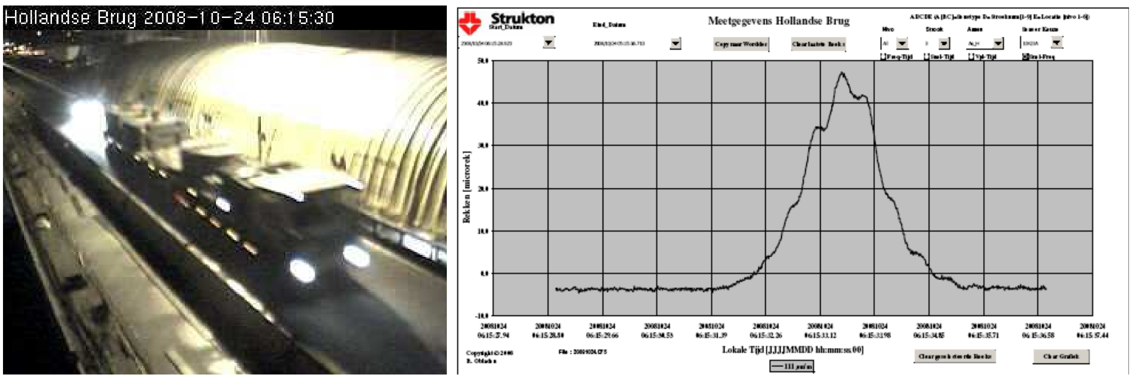


Figure 6. Left: Image of ballast truck 100 mT; Right: Strain registration of main girder during passing.

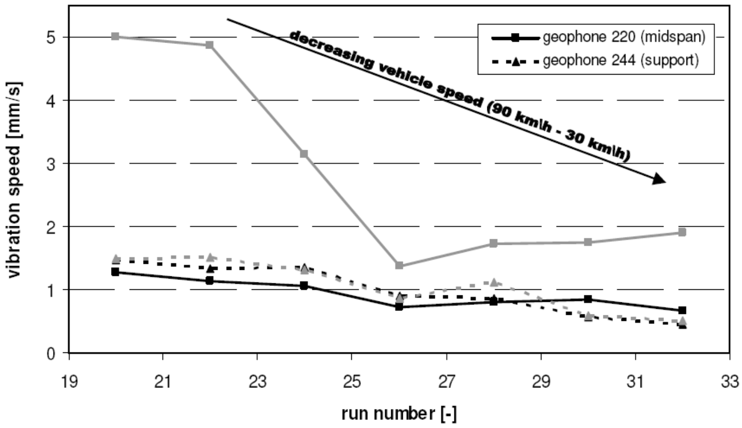


Figure 7. Influence of the velocity of the vehicle on the magnitude of bridge vibration (acceleration) for different runs, while reducing the velocity from 90 km/h to 30 km/h.

The effect of the vehicle velocity passing the bridge at vibration speed (acceleration) of the deck is considered the second important indicator for vibration susceptibility of the bridge (Fig. 7). The vibration speed is expressed in terms of the vertical velocity of the bridge which corresponds to the acceleration and is a measure for the particle velocity (see case 1, fig 3). It was expected that the heaviest vehicle will cause the largest vertical velocity of the bridge. However, data-analysis revealed that the vibration magnitude primarily depends on the type of vehicle. Long term analysis of recorded data showed that the largest vertical velocity was caused by trucks of only 13 tons. For those trucks, the vibration magnitude was almost 30 mm/s.

6 EXPERIMENTAL PROGRAM

In order to examine the influence of the bridge deflections and deck accelerations on the quality of the freshly cast overlay an experimental program has been developed. The program consisted of load cycle simulations of concrete specimens on top of which a layer of young concrete was cast and hardened during testing. After the cyclic loading test, samples were distracted from the specimen and used for tensile tests and optical microscopy investigations. The objective of the tensile tests was to investigate the effect of the dynamic loadings on the tensile strength capacity of the overlay as well as to evaluate the strength of the interface. The specimens were scaled to match the characteristics of several bridge types that were considered in this research project and the loading program was based both on experiences achieved from the in-situ measurements and from the model simulations (see section 3). It was the objective to couple the experimental data received from traffic induced vibrations directly to the consequences for the quality of the overly. The model simulations were used to provide insight in generic vibration susceptibility of the bridge and to deduce the boarder limits that could be used for the experimental tests.

Since maximum strain and maximum velocity never occur at the same time, these two traffic induced phenomena had to be determined in two different configurations of the test setup. The stain alterations were simulated in a snap-back system where the force on the specimen was constantly adjusted based on the measured deformation. De desired velocities were imposed by pre-programming the displacement of the hydraulic jack piston as a function of time. Each specimen consists of a concrete substrate that will be covered by a concrete overlay just before starting the test, i.e. applying the force to the specimen with overlay. This overlay is cast on top of the substrate in a pivoting formwork that is attached to the substrate. In this way, the concrete overlay hardens on top of the substrate while loaded dynamically. The setup and the tensile test results are shown in figure 8. From the results it can be observed that traffic induced vibrations

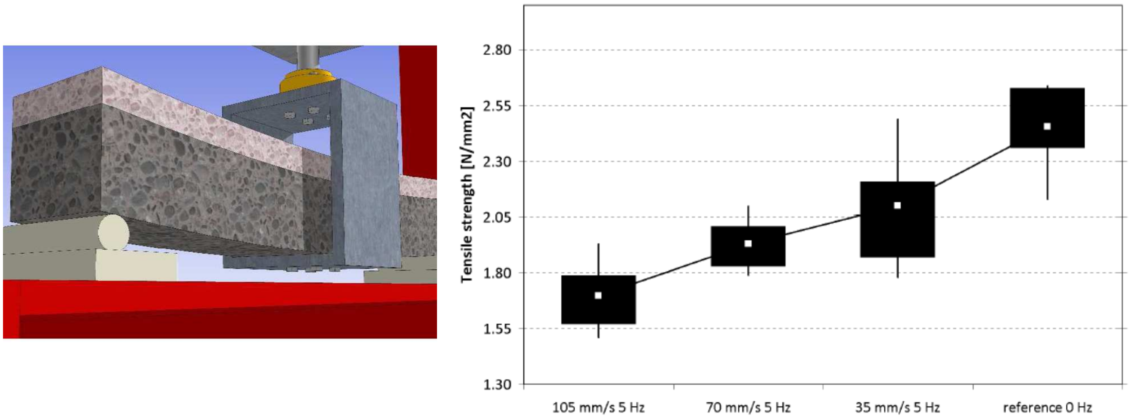


Figure 8. Left: Impression of the test setup; Right: Tensile strength versus different dynamic loadings.

do effect the ultimate tensile strength reached for overlays while under dynamic loading. The results of the tensile tests show a decreasing strength with an increasing magnitude of the vibration. The relative strengths for vibration velocities of 70 mm/s and 35 mm/s reached 79% and 86% with respect to the control specimen, respectively. In figure 8, results are plotted for extreme load cases up to 105 mm/s and achieved a relative strength of 72%. The results suggest a linear relation between strength and vibration speed. The material structure was investigated by optical microscopy of impregnated plane sections. Detection of the UV-sensitive epoxy resin indicated weak spots with crack formations, bleeding, segregation and porous zones around the larger aggregates where interconnection of such porous zones may induce failure planes.

7 CONCLUSIONS AND ACKNOWLEDGEMENTS

-The current research project has shown that the combination of modelling, monitoring and laboratorial research gave fruitful results. In this case, traffic disturbance could be minimized based on insight in the direct relation between traffic loads and quality of the concrete overlay.
- The developed bridge monitoring system can be used for the registration of traffic by weight in motion, as a structural health monitoring system and for research purposes.
- Traffic vibrations of sufficient magnitude negatively affect the (tensile) strength of concrete.

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REFERENCES

Strukton Bridge Monitoring system, 2009, (internal communication Strukton Engineering, in Dutch), Data acquisition on the “Hollandse Brug”.

Directorate-General for Public Works and Water Management, 2006, ROBK-6 – Richtlijn voor het Ontwerp van Betonnen Kunstwerken 6 the Netherlands (in Dutch): Directorate-General for Public Works and Water Management.

Ansell A., Silfwerbrand J., 2003, “The vibration resistance of young and early-age concrete”. *Structural Concrete*, Vol. 4, No. 3, pp. 125 - 134.

Galenkamp, H.F, 2009, *“The Influence of Traffic Vibrations on the Hydration Process of Earlyage Concrete”*, Master Thesis, Delft University of Technology, M&E Publication MT17.