“Pocket-Monitoring” for fatigue safety verification of a RC bridge deck slab

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The fatigue safety of the reinforced concrete (RC) deck slab of a sixty-year-old steel-concrete road viaduct is questioned based on the results of code-based “re-calculation”. Since strengthening intervention would lead to major costs, detailed investigation of the fatigue safety was performed using data obtained from “pocket-monitoring” which is a rational and ready-to-use monitoring device for bridge engineers. The implemented “pocket-monitoring” concept for the determination of fatigue action effects in the RC deck slab is outlined. Results in terms of fatigue relevant stresses in steel rebars of the RC deck slab reveal that the fatigue safety requirements are largely fulfilled based on the proposed verification method using directly data from monitoring. In addition, uncertainties related to the “pocket-monitoring” concept, and in particular the influence of temperature effects, are outlined and analyzed.

1 INTRODUCTION

1.1 *Motivation*

Road and rail bridges and in particular their reinforced concrete (RC) or orthotropic steel decks are subjected to significant fatigue loading. Fatigue safety verification requires information about the fatigue resistance, the critical details to fatigue, and the fatigue loading including past and future traffic loads as well as environmental conditions.

Bridges show in many cases significantly higher structural resistance than calculated resistance using conventional code methods (Treacy and Brühwiler 2012). Moreover, the last development of the monitoring techniques with the high capacity of acquisition and storage is providing the possibility to examine bridges in real time for long-term monitoring. Consequently, there is a significant potential to use monitoring systems to investigate the current structural condition with the goal to verify the fatigue safety of existing bridges.

Structural monitoring provides relevant data and reduces the uncertainties of various involved parameters. This introduces a novel approach for structural engineers to verify the structural safety, based on monitored data rather than extensive engineering modelling and calculations.

1.2 *Approach and objective*

The verification of the fatigue safety must be based on direct measurements of the structural response at

Figure 1. View of the investigated steel-concrete composite viaduct

relevant locations since it is not economical nor practical to instrument the whole bridge structure. The instrumentation needs to be optimized by placing sensors at critical locations and reducing the number of sensors to the minimum such that the obtained information are reliable and sufficient to perform the fatigue safety verification. In this context, the methodology of “pocket monitoring” is proposed to characterize both the structural response and the effects of fatigue action.

The objective of this paper is to present the methodology of the fatigue safety verification using the “pocket monitoring” as applied to an existing bridge structure. The concept of this monitoring will be presented, with the data processing algorithms. The effect of temperature and its influence on the monitoring period and the reliability of the results will be discussed. The structural behavior and the fatigue safety will be examined.

Within this framework, a steel-concrete composite road viaduct in Switzerland, shown in figure 1, was instrumented according to the “pocket monitoring” approach with the objective to verify the fatigue safety. The viaduct is in service since 1957. It is composed of seven identical spans of 25.6m and one special span; the overall length is 195m. It has a reinforced concrete deck of 17cm thickness, fixed on two longitudinal steel box girders acting as a composite section (Fig. 2c).

2 “POCKET MONITORING” SYSTEM

2.1 *Conceptual idea*

“Pocket monitoring” is a rational system of non-destructive measurement techniques to collect data related to the structural behavior. The “pocket monitoring system” must be cost-effective (i.e., high gain in information with respect to cost) and easy to install, use and maintain. It shall be accessible to any engineering firm.

“Pocket monitoring” implements recent technology in data storage and high-frequency acquisition, to perform continuous real-time monitoring of structural response due to action effects such as traffic loading and temperature. It is performed for occasional inspections as well as for long-term monitoring.

2.2 *Installation*

2.2.1 *Monitoring system*

The present “pocket monitoring” system is composed of strain gauges and thermocouples for continuous long-term monitoring with the high-frequency acquisition of 100Hz. The installation of the monitoring system including a load test has been completed in three days.

The acquisition system is composed of three devices (Fig. 2.d). The first device is dedicated to thermocouples, the second to strain gauges and the third is for the data storage unit. The data is measured continuously and stored daily. Access to data is possible at any time, from any place with a 4G internet connection and a remote connection program. The instrumented spans 2 and 4 are presented below (Fig. 2).

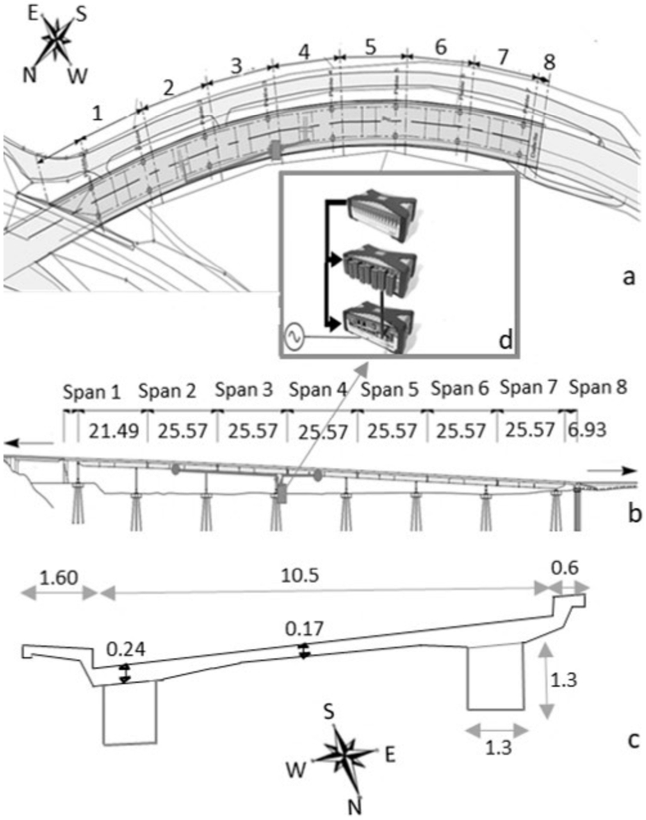

Figure 2. Drawing of the viaduct (a) plan view; (b) side view; (c) typical cross-section; (d) data acquisition and storage unit; dimensions in [m]

2.2.2 *Strain gauges*

Strain gauges are installed on the lower rebars at the mid-span of slabs 2 and 4 and the upper and lower flange of the steel girder of span 4. Four half-bridge strain gauges were installed at both locations to measure the strain of concrete.

As shown in figure 3, two gauges are located between the axis of the articulation and the axis of the support. The two other gauges are installed on the adjacent transverse and longitudinal rebars. Regarding the girder, the strains are measured using two gauges mounted on a ¼ bridge and installed in the upper and lower flange of the girder of span 4.

2.2.3 *Thermocouples*

Thermocouples are installed in various locations near the strain gauges and the central acquisition unit, to measure the temporal temperature variations. The thermocouples provide the temperature of concrete in spans 2 and 4, the temperature of steel in the girder of span 4, and the ambient temperature.

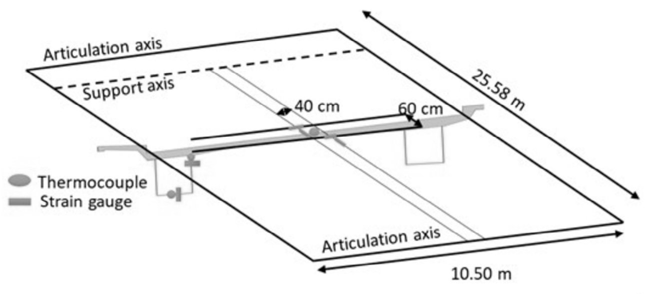

Figure 3. Location of the sensors

2.3 *Period of measurement*

During one year of measurements (from August 2016 to August 2017), data were recorded for 83% days. The missing measurement days are due to power cuts, problems of synchronization and memory of the acquisition system.

The frequency was initially set at 50Hz and later increased to 100 Hz for strain measurements in order to get a better signal. The temperature is recorded with 1Hz frequency.

The measured strain and temperature are saved every 24 hours. The data are then regularly repatriated and converted to a MATLAB file, for each day, from midnight to midnight. 44 GB of data has been collected and analyzed during this first year.

The long-term monitoring data provide an automatic record of strains due to traffic loading and allow to identify heavy vehicles, exceptional convoy, and vehicles exceeding the authorized load of 40 tons.

2.4 *Load test*

A load test was performed after the viaduct's instrumentation. A truck of five axles with a total weight of 40 tons crossed the viaduct in eight passages when the road was temporarily closed to traffic. Three passages with different trajectories and speeds in each direction provided the strains due to the truck. One repetitive passage was performed in each direction to reveal uncertainties related to the measurements. Each truck axle has been weighed separately, and the precise axle spacing has been measured. The results of the load test serve as a reference.

The typical structural response of a truck passage for the rebars and the steel girder is shown in figure 4.

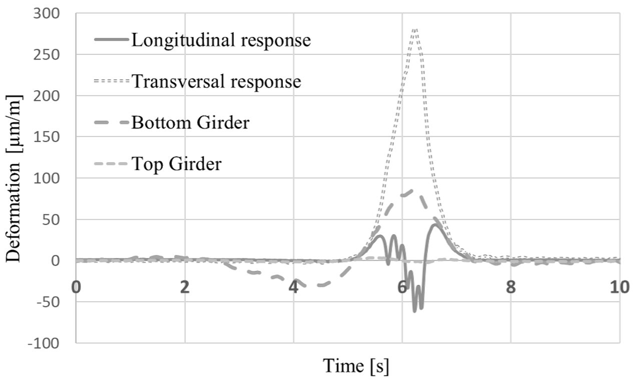

Figure 4. Strain due to a moving load (35km/h)

The transverse rebars are loaded in tension during the passage of a vehicle. In the longitudinal bridge direction, the girder and the longitudinal rebars show the expected stress reversal, i.e., both tensile and compressive stresses due to vehicle passage (Fig. 4). The five peaks in the longitudinal response present the passage of the five axles of the truck.

From the load test, it was found that:

The measured strains are mainly influenced by the truck position and by the slab slenderness that accentuates local strains under the wheels.

Repeatability, i.e., identical structural response, was obtained from passages that follow the same trajectory.

Reference strain values were identified from the load test for the detection of heavy and overloaded vehicles, and their position on the bridge deck.

3 EFFECT ON THE MONITORING PERIOD

3.1 *Temperature measurement*

During winter, the temperature of concrete is different from ambient temperature because of the high thermal inertia of the relatively massive concrete slab. However, the temperature of the steel girder follows the same variations as ambient temperature, which is due to the good thermal conductivity of steel.

The response time of temperature in the concrete slab is from 3 to 6 hours, depending on the season. Figure 5 illustrates this response time for the steel girder and the slab during 24 hours of continuous monitoring in February.

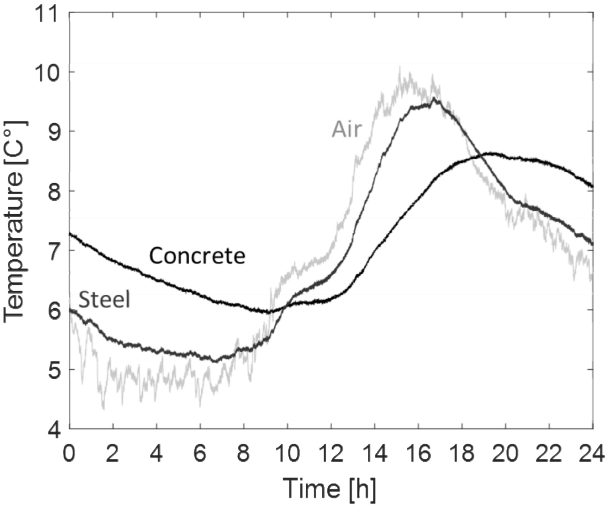

Figure 5. Daily temperature variation of the air, steel girder, and the concrete slab as obtained on 21 February 2017.

These temperature variations may significantly affect the overall behavior of the viaduct, through thermal expansion and changes in the modulus of elasticity.

To understand the temperature effect, it is important to investigate in detail the recorded strain and temperature.

3.2 *Data processing*

Temperature balance in the viaduct takes time. The variations in temperature during few seconds, minutes and even hours present rapid fluctuations, which create a non-stable thermal action. For example, several strains value can correspond to the same temperature value.

The variations in temperature have two characteristics: permanent and instantaneous. On the one hand, the movement of the sun creates a permanent system, with the daily and seasonal cycles. On the other hand, wind and traffic can create an instantaneous system with local thermal variations. Consequently, it is important to understand the mechanism of thermal balance to process the data efficiently.

The monitoring system is providing high-frequency measurements of strain and temperature in the structure for local points. Investigating the impact of temperature requires the study of the permanent system response. The local effects of the instantaneous system response are thus not analyzed.

A compensation algorithm is developed to extract the strains due to temperature. The algorithm calculates the moving average of the signal for ten minutes. Figure 6 includes the data of the raw signal before and after removing the strain due to temperature. The signal presents the daily recorded strain of the longitudinal rebar in span 4.

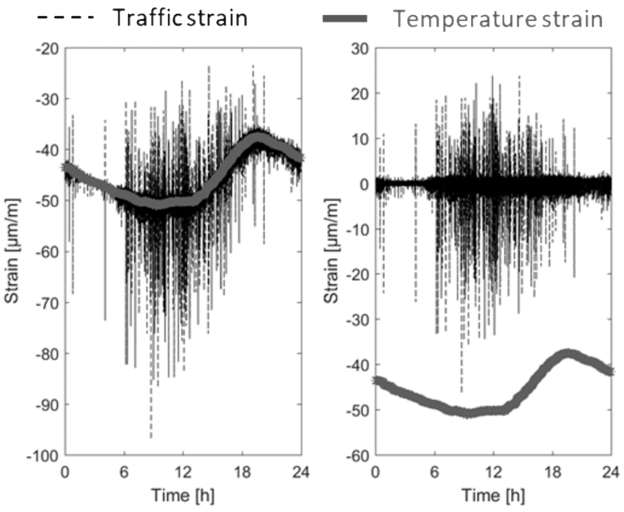

Figure 6. Total strain, temperature strain, and traffic strain

The reversal stresses in the longitudinal rebar are clear, for each passage the rebar is loaded under tensile followed by a compression stress.

3.3 *Effect of the temperature on the period of monitoring*

The thermal effect on structures is important. Penka (2005) had shown the strong influence of temperature in the longitudinal behavior of prestressed box girders. Treacy (2014) had found that thermal actions have substantial effects on quasi-static strain and induce significant internal forces. Therefore, the mechanical effect of temperature sould be analyzed in detail.

When extracting the strains due to temperature from recorded data, it is found that they are not due to the thermal response of the materials, but rather a structural response. In fact, thermal variations due to the material response are compensated with the ½ bridge strain gauges using an expansion coefficient of 10^{-6} K^{-1}, like the one for concrete and steel.

Figure 7 includes the monthly average of thermal strain versus the monthly average of temperature, for the transverse and the longitudinal rebars. In the longitudinal rebars (Fig. 7b), there is compression during winter and tension during summer, which is the opposite for the transverse rebars (Fig. 7a), where there is compression during summer and tension during winter. This is due to the double thermal bending of the slab.

The isostatic longitudinal static system of the viaduct allows unrestrained expansion of each span. In the longitudinal section, the neutral axis is above the longitudinal rebars which lead to compression during the thermal bending. In the cross-section where the neutral axis is below the transverse rebars, the resultant stress due to thermal bending is tension. Therefore, the temperature is a good indicator of the structural behavior.

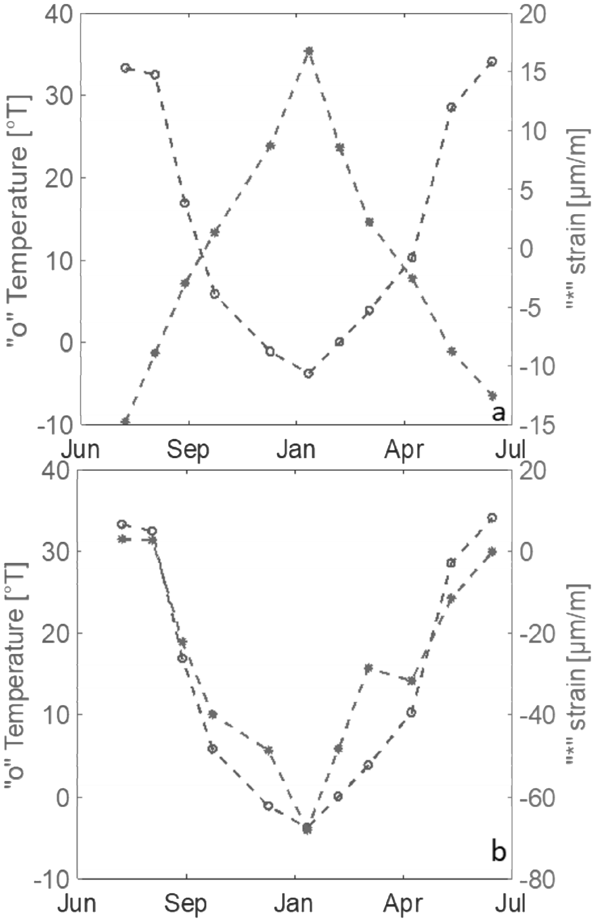

Figure 7. Annual variations of temperature strain; (a) transverse rebar; (b) longitudinal rebar

Another temperature effect is the change in the modulus of elasticity. The elasticity modulus variations for concrete and steel can be neglected in front of the elasticity modulus variation of the asphalt. It was found that the apparent modulus of elasticity of the asphalt layer on the top of a RC deck slab significantly depends on temperature, according to logarithmic or linear equations (AASHTO. 1993 and Hassan et al. 1995)

In general, the higher the temperature applied to the flexible pavement layer the lower the elastic modulus value will be. (Taha et al. 2012).

This effect is not detectable with few days or weeks of monitoring. Only the annual strains show the clear dependency on temperature variations. The highest measured strains were recorded during summer and the lowest ones during winter (Fig. 7). This means that even after processing the signal and deleting thermal strains, some indirect temperature effects remain on the strain measurements due to the variation of asphalt-layer rigidity.

This effect was depicted by Burdet (1993) who showed the significant structural contributions from the asphalt layer based on 200 load tests on Swiss bridges. The asphalt layer was found to significantly reduce the stress level in bridge decks during the winter season, like in the present case.

In figure 8, the maximum strain per month recorded in the longitudinal rebar, the transverse rebar and the steel girder versus the monthly average of ambient temperature are presented.

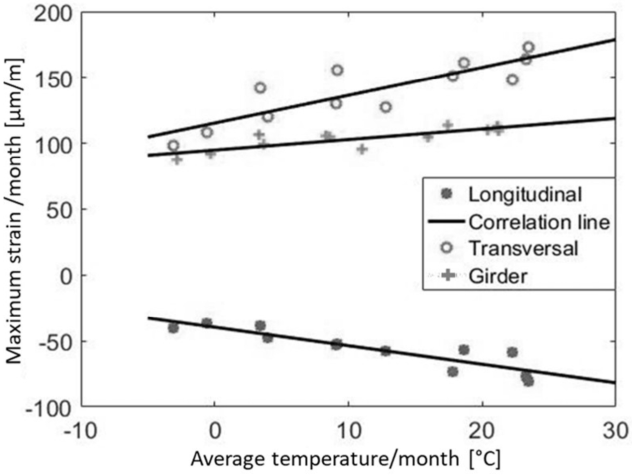

Figure 8. The thermal effect of the bituminous layer, transverse and longitudinal rebars, and the girder

It is shown that the 10-centimeter bituminous layer increases the level of strain by 50 µm/m when the temperature increases from 0°C to 30°C, in the longitudinal and transverse rebar.

Therefore, it is not possible to compare data recorded during summer with those recorded during winter for a road bridge with short-term monitoring since the effect of the bituminous layer cannot be directly removed from the signal. The effect of thermal variations on the rigidity is detectable only with long-term monitoring.

Moreover, thermal variations can create higher stresses (Raw signal, Fig. 9) than heavy vehicles (Processed signal, Fig. 9). In fact, the recorded strains are shifted from the zero-value because of temperature which make the strain higher.

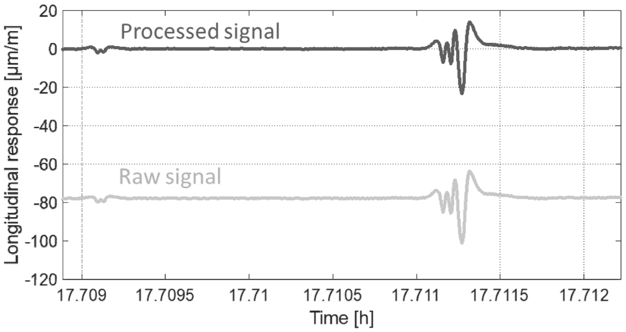

Figure 9. Recorded strain in the longitudinal rebar during the passage of a truck

Consequently, it is important to take thermal effect into account during monitoring and data processing.

Thermal actions significantly influence the mechanical behavior. Occasional inspections should thus be performed during the same periods of the year. Otherwise, the separation of strains due to traffic and those due to temperature will be difficult. The period of monitoring can be fixed based on the thermal effect. Recoding data one day each month for one year is sufficient to identify and analyze the thermal effect on road bridges.

For fatigue investigation, the effect of temperature on the structural response is not relevant since measured strains are just shifted. However, the effect of temperature on the bituminous layer affects the maximum stress values used for fatigue safety verification, with stresses being higher during summer and lower during winter.

4 MONITORING RESULTS AND STRUCTURAL ANALYSIS

4.1 *Fixity and neutral axis*

Monitoring data is used to understand the structural behavior and to verify the structural safety of the viaduct. The position of neutral axis and the fixity of the concrete slab in the steel girder are evaluated.

Theoretically, assuming full composite action, the neutral axis is located close to the upper flange of the steel girder for the longitudinal section.

The analytical calculation using monitoring data shows that the section acts as a full composite section and that the neutral axis is located 6cm below the upper flange of the steel girder (Fig. 10).

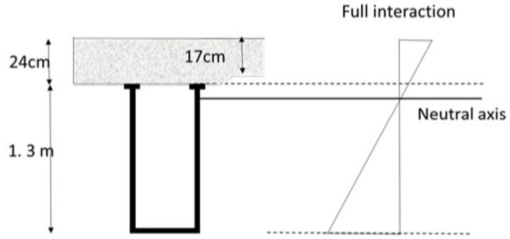

Figure 10. Neutral axis of the longitudinal section

As for the degree of fixity of the slab in the steel box girder, the recorded stress levels are too small to damage the connection between the slab and the girder. The slab is thus fully fixed.

During the load test with the truck of 40 tons, the vertical displacements returned to their initial value after each passage showing the expected reversible elastic behavior of the deck slab.

4.2 *Fatigue safety verification*

4.2.1 *Fatigue verification*

To verify the fatigue safety of the composite structure, the reinforced-concrete slab is examined. The slab is identified to be the most critical element regarding fatigue since it is relatively slender and fixed to the steel girder via welded rebars. As such, the fatigue safety of the longitudinal and transverse rebars in the mid-span, as well as the rebars welded to the steel box girder are investigated.

Fatigue safety is verified following two levels. First, the endurance limit is verified, i.e., the maximum value of measured stress range must be smaller than the endurance limit of the rebar fatigue detail. If level 1 of verification is not conclusive, damage accumulation according to Palmgren-Miner's rule is performed using the recorded histograms of stress cycles and the appropriate S-N curve for the rebar fatigue detail.

4.2.2 *Rebars*

According to the Standard SIA 269/2, the fatigue resistance of passive steel rebars, with a diameter less than 30mm, is equal to $\Delta\sigma_{sd,\ fat} = 150$ N/mm^2. The slope of the S-N curve is equal to m=4, and thus the endurance limit is equal to 80% of the fatigue limit, $\Delta_{\sigma sD} = 120$ N/mm^2, (Fig. 11 and Tab. 1).

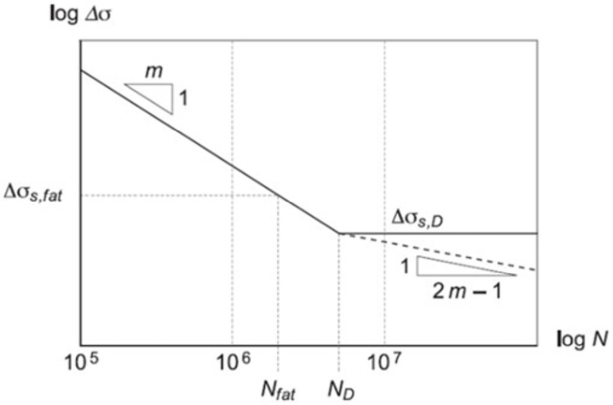

Figure 11. S-N curve from SIA 262, 2013

	SIA 269/2 straight bar ø ≤ 30 mm	SIA 269/2 Welded rebars
$\Delta\sigma_{sd,\ fat}$	150 MPa	70
$\Delta\sigma_{s,\ D}$	120 MPa	56
N_{fat}	$2*10^6$	$2*10^6$
N_D	$5*10^6$	$5*10^6$
m	4	4

Table 1. Fatigue resistance of passive and welded rebars (SIA 269/2)

The stress cycles were calculated from the measured strains using the Rainflow counting method and the steel rebar modulus of elasticity of 210 GPa. Figure 12 includes the histograms of stress ranges in the instrumented rebars at mid-span.

The measured maximum fatigue stresses in the transverse and longitudinal rebars at mid-span of the slab do not exceed 70 MPa which is largely lower than the endurance limit (of 120 MPa). Therefore, there is no fatigue damage in these rebars.

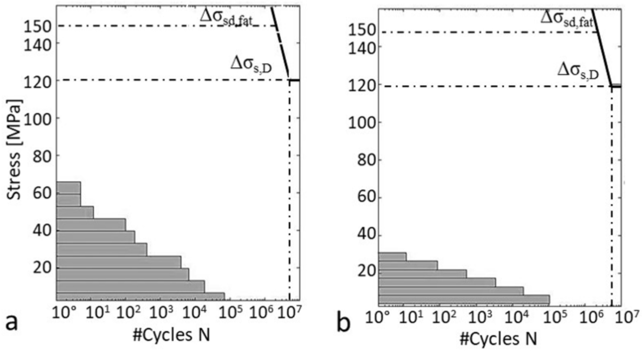

Figure 12. Stress cycles (a) transverse rebar; (b) longitudinal rebar

4.2.3 *Welded rebars*

The reinforced-concrete slab is fixed in the steel girder via welded rebars (Fig. 13). The welded rebars are not easily accessible for monitoring. However, they are a critical detail for the fatigue safety. In fact, the flexural behavior of the transverse section of the slab is mainly dependant on the capacity of the welded rebars to ensure the full fixity in the girder, and thus the fatigue safety of the welded rebars need to be examined. For this aim, a structural model is used to extrapolate measured data from mid-span to the welded rebars. The length of the weld is 150 mm, and thus the weld is considered as longitudinal and continuous.

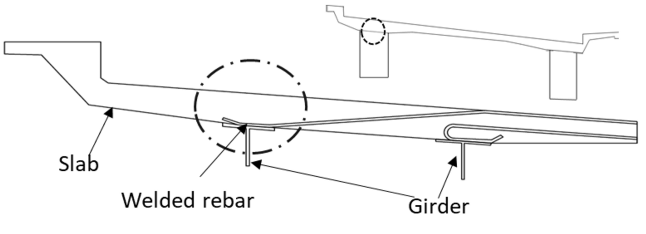

Figure 13. Welded rebar

According to SIA 269/2, the fatigue resistance of the welded rebars is equal to $\Delta\sigma_{sd,fat} = 70$ MPa, the slope of the S-N curve is equal to m=4, and the endurance limit is equal to 80% of the fatigue limit, either 56MPa (Tab. 1 and Fig. 11).

To get the strains in the welded rebars, a model of the cross section provides the influence-line in the mid-span and the welded rebars. The ratio between the moments is then calculated for various positions of traffic, and the ratio between the measured rebar strain at mid-span and the strain in the welded rebars is deduced from the moment ratio.

The recorded strains in the transverse rebars were linked to the position using the reference values defined during the load test to determine the position of the traffic. An algorithm was then developed to extrapolate the measured strains and calculate stress cycles using the Rainflow algorithm in the welded rebars. The resulting stress cycles are presented in figure 14.

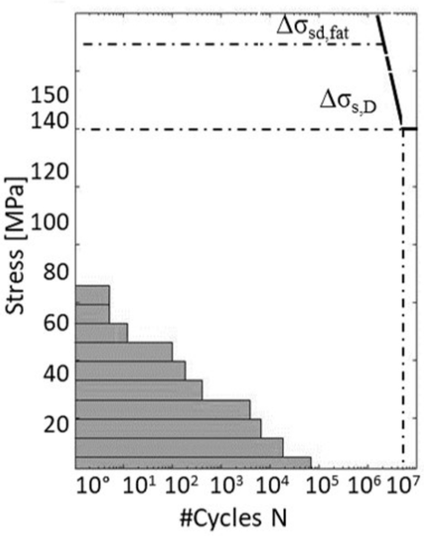

Figure 14. Stress cycles, welded rebar

The stresses are found to be 30% higher than those measured in the mid-span. They are exceeding the endurance limit 56 MPa.

Palmgren-Miner damage rule is thus applied to calculate the damage accumulation rate, according to the equation 1:

$$d=\sum(n_i/N_i) \quad (1)$$

where d is the cumulative damage, n_i is the number of cycles for the constant stress $\Delta\sigma_i$, and Ni is the total number of cycles to failure under the constant amplitude stress $\Delta\sigma_i$ [MPa].

The damage was calculated based on the recorded data for 30, 90, 250, and 303 days. The results are presented in figure 15 below.

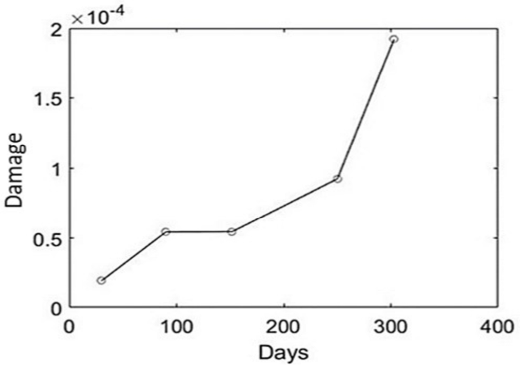

Figure 15. Annual cumulative damage in the welded rebar

The calculated damage value during the monitoring period is very low. With 60 years of service duration in the past and the conservative assumption that traffic load and volume were the same in the past, the total current damage is estimated being equal to 1.15 10^{-2}, thus considerably lower than 1 usually considered to correspond to fatigue failure. Adding 100 years of future service duration to the viaduct, the damage would be equal to 3.18 10^{-2}, still very much smaller than 1.

The evolution of damage during the summer is largely higher than the one occurring during winter This is mainly due to the contribution of the 10-centimeter-bituminous layer (Part 3.3). The rigidity of the bituminous layer follows temperature variations, which gives low strains during winter and higher strains during summer for the same volume of traffic.

5 CONCLUSION

“Pocket monitoring” is a ready-to-use monitoring system that provides information about the structural behavior and features of loadings. Monitoring data is analyzed using calibrated algorithms to obtain stress values allowing to verify the structural and the fatigue safety and to characterize features of traffic and thermal loading effects. A load test was carried out to calibrate the measurements and to define reference values for traffic characterization. It was found that “pocket monitoring” is easy to use and has a good cost-benefit ratio.

The one-year data provides a real-time record of environmental temperature actions and the related structural behavior. The viaduct is found to be in good condition after 60 years of service. The fatigue safety of the reinforced concrete deck could be verified with respect to the fatigue endurance limit of the critical fatigue details. There is no fatigue issue although initial code-based “recalculation” indicated insufficient fatigue safety. This means that current code provisions are unnecessarily over-conservative and should not be used for the given bridge structure and probably also for any other existing bridge structure since these provisions do not reflect reality.

The period of monitoring was investigated based on temperature effect. It was found that temperature can create higher strains than traffic loads. Therefore, inspections should always be conducted during the same period of the year. Monthly measurements for a year provide valuable information to follow the thermal effect of the daily and seasonal cycles.

6 ACKNOWLEDGMENT

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