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Monitoring of wind induced vibration on a tied-arch railway bridge.

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ABSTRACT: The ÖBB Rheinbrücke, situated in the vicinity of Lustenau, represents a novel approach to steel-concrete composite arch structure engineering, boasting a span of 102 meters. The primary supporting structure is a tied-arch comprising 12 round steel hangers, each with a diameter of 100 mm, situated on either side of the bridge. The maximum length of the hangers is 18.9 meters. In arch bridges of this type with steel hangers, wind-induced vibrations in the hangers can result in high-frequency, high-amplitude fluctuations in stress levels, particularly in the hangers and their connections. This can be problematic from the perspective of fatigue, particularly given that the hanger connections often have notch-sensitive details. Following the completion of the bridge, comprehensive monitoring was conducted in accordance with the original plan. This was done with the objective of acquiring data regarding the vibrations experienced by the hangers and the subsequent damage to the material. This data was then used to determine whether vibration-reducing measures were necessary. During the course of monitoring and subsequent evaluation, it was observed that wind-induced vibrations in the hangers could result in the occurrence of fatigue-relevant stress ranges. This article serves to emphasise the importance of structural health monitoring in confirming the efficacy of vibration reduction measures, which have the potential to extend the service life of railway bridges.

KEY WORDS: monitoring; wind-induced vibrations; fatigue.

1 INTRODUCTION

Railway bridges, integral to transportation networks, are subjected to diverse and dynamic loading conditions, necessitating diligent monitoring and maintenance strategies to guarantee their continued safety and operational efficiency. Specifically, the application of SHM to railway bridges enables the early detection of potential damage or deterioration, thereby averting catastrophic failures and extending the lifespan of these critical infrastructures. The implementation of SHM systems typically involves the deployment of various sensors, data acquisition systems, and communication networks to continuously monitor key structural parameters such as strain, displacement, acceleration, and temperature [1] By analyzing the data acquired from these sensors, engineers can identify anomalies or deviations from baseline behavior, which may indicate the presence of damage or deterioration [2] The integration of advanced data analytics, significantly augments the capabilities of SHM systems, enabling the detection of nuanced changes in structural behavior that might elude traditional inspection methodologies. These analytical techniques can discern patterns and trends in the data, thereby providing valuable insights into the underlying mechanisms driving structural degradation. [3]. In light of these considerations, this paper delves into the practical application of SHM in assisting the decision to apply correction measurements, with a particular focus on the ÖBB Rheinbrücke near Lustenau. the ÖBB Rheinbrücke is single-track and electrified. It is a total of 276.5 m long and 7.95 m wide and consists of a 102 m wide tied arch bridge over the Rhine as well as four trough bridges over the western foreland and two trough bridges over the eastern foreland (Figure 1).

Figure 1. ÖBB Rheinbrücke

The entire bridge has a continuous ballast bed. The tied arch bridge has two parabolic arches made of reinforced concrete, which are clamped in steel sleeves on the end cross girders. The bridge structure has twelve round steel hangers with a diameter of 100 mm on each side of the bridge. The maximum hanger length is 18.9 m. The connection of the hanger trapeziums to the connecting plate and the connecting plate to the upper flange of the longitudinal beam are designed as welded seams (Figure 2).

Wind-induced vibrations in these hangers can lead to high-frequency, high-amplitude stress fluctuations, particularly in the hangers and their connections, posing a significant fatigue risk. The susceptibility to fatigue is exacerbated by the presence of notch-sensitive details in the hanger connections, rendering them vulnerable to crack initiation and propagation under cyclic loading conditions [4]. Great attention was already paid to this issue during the planning phase of the bridge built in 2011. However, in order to gain experience of the phenomenon of hanger vibrations for this and future bridges, the hangers

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were initially designed without vibration-reducing measures. nevertheless, precautions were taken for the later installation of measures to reduce vibrations.

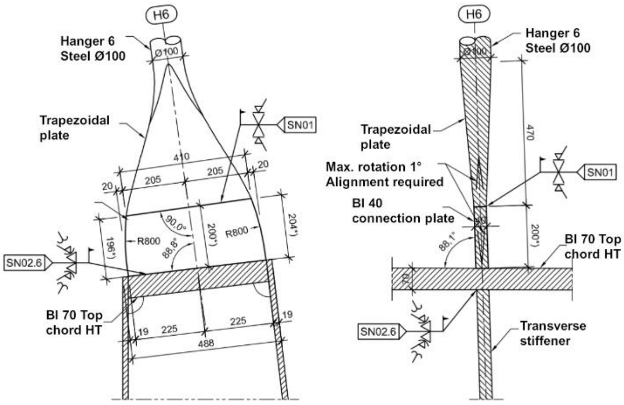

Figure 2. Detail of the hanger connection

Two wind related physical phenomena, vortex-induced transverse vibrations and rain-wind-induced vibrations, can appear during the structure's service life. Those characteristics of those phenomena are briefly described below.

● Vortex-Induced Vibrations: These vibrations are caused by vortices detaching alternately from each side of the hanger. The frequency of this oscillating force is related to the Strouhal number, approximately 0.2 for cylinders. According to [5], the critical wind speed for the respective mode shape is calculated using equation (1)

$$v_{crit,i} = \frac{f_i \cdot D}{St} \quad (1)$$

Where D is the hanger diameter, f_i is the natural frequency of the respective mode shape and St is the Strouhal number.

● Rain-Wind-Induced Vibrations: These vibrations occur during simultaneous rain and wind events. They are characterized by low frequency and high amplitude, potentially leading to high stress amplitudes. According to [5], [6] the critical wind speed for this type of excitation can be calculated using equation (2).

$$v_{crit,i} = 73.5 \cdot D \cdot f_0 \cdot \left(\frac{f_i}{f_0}\right)^{0.6} \quad (2)$$

where D is the hanger diameter, f_0 is the reference frequency and f_i the natural frequency for the respective mode shape

Empirical studies [7],[8],[9] indicate these vibrations are most likely in light to moderate rain and wind speeds between 4 and 20 m/s.

2 MONITORING SYSTEM AND DATA EVALUATION

After the construction of the bridge, an extensive measurement program was started as planned. The monitoring system deployed on the ÖBB Rheinbrücke comprised an array of sensors strategically positioned to capture the dynamic response of the hangers. In the preliminary stage of the program, two cables of varying lengths were subjected to monitoring. H6, the longest cable on the bridge, measures 19 meters, while H4 measures 14 meters. The most critical element in terms of fatigue failure was used as the reference point for calculating the stresses. In the present case of the Rheinbrücke, they are the connections between the connecting plates of the hanger and the upper flange of the longitudinal girder (Fiure. 2) which present a notch type of 45 N/mm(2) ([10], Table 8.5, Design Detail 1). Strain gauges were affixed to these hanger connection plates to measure stress variations, while accelerometers were installed to capture vibrational frequencies and amplitudes on the hangers. In addition, temperature sensors were integrated into the system to account for thermal effects on the structural behavior of the bridge. The acquired data was transmitted in real-time to a central data acquisition system, where it underwent processing, analysis, and storage. Table 1 and Figure 3 show the number and location of the installed sensors.

Table 1. Sensors at the Rheinbrücke

	Ref.in Figure 3	Number of Sensors
Acceleration	AS	8
Displacement	Weg	2
Temperature (Component)	TEMP	4
Linear strain gauges	DMS-L	35
Rosette strain gauges	DMS-R	10
Wind speed		1
Wind direction		1
Rain intensity		1
Air temperature		1

In order to keep the amount of data reasonably limited, the strain values are recorded in a triggered manner; the recordings are started at accelerations greater than 0.4 m/s^2 at the hangers. The weather data and temperature, on the other hand, are recorded continuously.

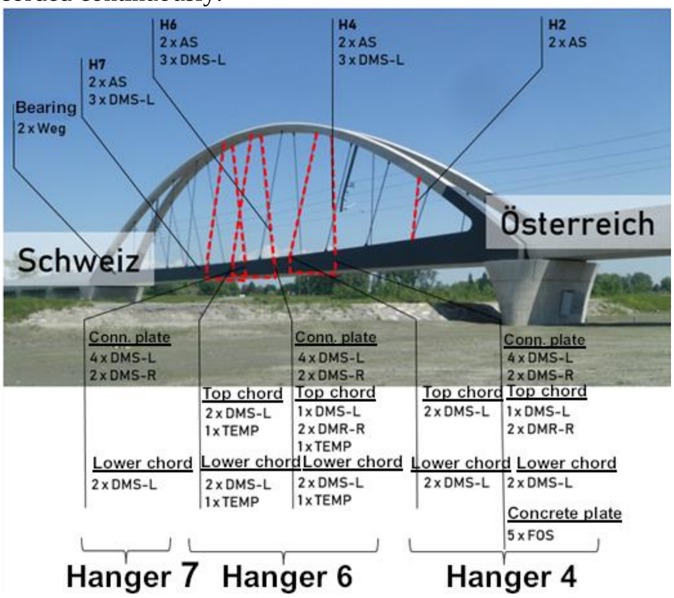

Figure 3. Position of the installed sensors

During the almost ten-year monitoring period (April 2013 to the end of 2022) on the Rhine bridge, numerous events with vortex-induced transverse vibrations and rain-wind-induced

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vibrations were recorded. To evaluate the recorded data, the critical wind speeds were calculated using formula (1) for vortex-induced vibration and formula (2) for rain-wind-induced vibration. The calculated speeds were useful for the analysis and classification of the different events.

To assess the effects of the wind induced vibrations on the fatigue resistance of the structure, the cut-off limit for the fatigue strength was calculated according to [10], resulting in a value of 15.8 N/mm2. This implies that every stress range above this limit is relevant for the fatigue resistance. and must be considered for the damage accumulation. The process of damage accumulation is an important aspect of fatigue analysis as it is used to predict the remaining service life of a component or structure. The Palmgren-Miner rule [11,12] has been used to calculate the amount of damage produced by a given loading history by summing the damage caused by each loading cycle.

The following sections describe one event of each type, providing a better insight into the effects of these events on the structure.

2.1 *Vortex induced vibrations*

Table 2 shows the calculated frequencies for the monitored hangers.

Table 2. Natural frequencies

Hanger Mode Shape	H4 f[Hz]	H6 f[Hz]
1	4.0	3.5
2	8.7	7.4
3	14.5	11.9

The measurements carried out show that the critical wind speed calculated for the 3rd natural frequency wind speed $v_{crit,3}$= 6 m/s caused the hanger H6 to oscillate over longer periods of time with stress oscillation amplitudes above the fatigue strength threshold value, as the stress history plot in figure 4 shows. During the duration of the event, the condition for vortex-induced vibration excitation was fulfilled by a constant wind speed around the calculated critical speed for a long period of time (over two hours in this event).

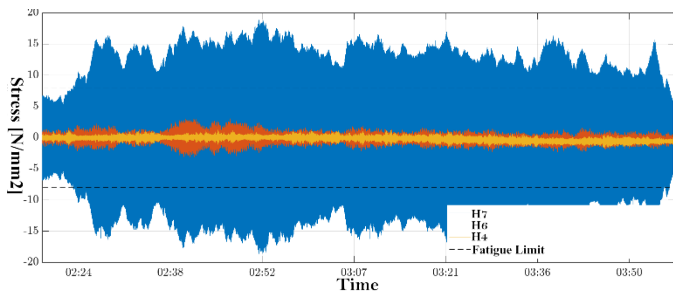

Figure 4. Stresses caused by a vortex-induced vibration event

Figure 4 shows that the stresses measured on cable H6 are much higher than those measured on cable H4. The stresses on cable H4 are irrelevant for fatigue damage. Figure 5 clearly shows that the measured frequencies are close to the calculated third natural frequency. This indicates that higher natural modes than the first must be considered when evaluating fatigue damage.

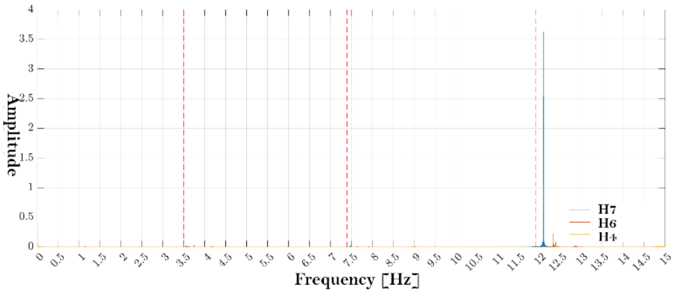

Figure 5. Frequency of the vortex-induced vibration

2.2 *Rain-wind induced vibration*

To detect and characterize event of this type, a criterion based on the calculated critical speed (table 2) for the first natural frequency and the presence of persistent precipitation has been applied. A typical stress history for this type of events is presented in figure 6.

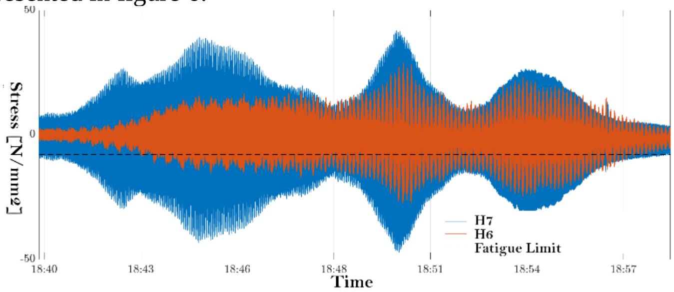

Figure 6. Stress history over a rain-wind induced vibration event

During the duration of this event, the wind speed was only occasionally in the range of the calculated critical wind speed vcrit,1= 15.7 m/s, the damaging vibrations nevertheless occurred for a longer period of time. It should be also noted that it rained unusually heavily (over 50 mm/h) shortly before the build-up. Generally, from the recorded rain-wind-induced events, it can be inferred that the stress range of hanger H6 is significantly higher than in events in which vibrations are caused solely by vortex-excited transverse vibrations.

3 FATIGUE DAMAGE AND LIFE CYCLE

During the entire bridge monitoring period, regular calculations of the remaining service life of the critical weld seam between the connecting plate and the top chord of the longitudinal girder were carried out on the basis of the Palmgren-Miner rule. In order to be able to make a statement as to whether the observed stresses could become a problem for the hanger connections over the years, the stress range collective recorded during the measurement period was extrapolated to a service life of 100 years in this work. For this purpose, it is assumed that exactly the same stresses occur during the extrapolation period as during the period in which the monitoring was carried out. Under this assumption, the collective stress range measured can simply be multiplied by a corresponding factor and thus a forecast for the theoretical service life can be created using the Palmgren-Miner hypothesis. No distinction was made between individual vibration types in these forecasts; all vibration sources such as

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rain-wind-induced vibrations and vortex-induced transverse vibrations, as well as train passages, are therefore included here. The data are added together to obtain a statistically sound statement about the remaining service life of the monitored hangers. It should be noted at this point that only heavy freight trains can cause stress oscillation amplitudes relevant to fatigue, and that these do not significantly reduce the remaining service life, due to their low frequency. The history of the theoretical residual service life is shown in Table 3

Table 3. Progress of theoretical service life (years)

Hanger	Marz 2018	July 2019	June 2020	June 2021	June 2022	Nov. 2022
H4	465	269	394	475	573	626
H6	42	40	21	18	22	23
H7	207	360	265	353	461	518

The remaining service life forecasts show that the influence of wind induced vibrations, on the hanger H6 is remarkable, while the influence on the shorter hanger (H4) plays a subordinate role with regard to the planned service life.

4 VIBRATION-REDUCING MEASURES

Following the results of the monitoring campaign, it was decided to install a system to reduce the effects of vibration on the Rheinbrücke. Interconnecting adjacent cables using cross-ties is a method that has been experimentally tested on numerous suspension bridges [13], which simply and effectively mitigates the effects of wind-induced vibrations. In addition, this vibration reducing measure was already proposed during the planning phase in case of need. It consists of connecting the bridge hangers with small-diameter cables. In this way, the vibration energy is distributed over several hangers with different natural frequencies. In this manner, unexcited hangers act as dampers [13,14].

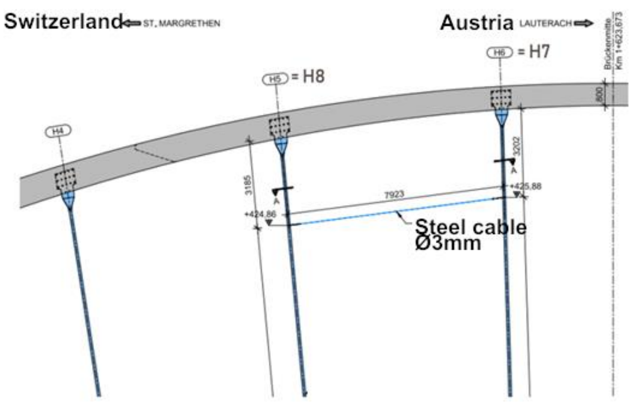

Figure 7. Vibration reducing cable

In May 2017 such measure was implemented by installing a 3 mm cable connecting hanger H7 and hanger H8 (Figure 7). After installation, H7, which has the same length as H6, was also monitored to evaluate the effectiveness of the procedure. As can be seen in figures 3 and 4, the amplitude of the measured stresses is significant reduced when compared with those in hanger H6. Using this method, it is possible to improve the issue of fatigue damage in the structure, as can be seen from the calculation of the theoretical service life in Table 3. In the summer of 2021, the measure was installed on the remaining bridge cables. The data presented in Table 3 unequivocally reveals a trend change in the theoretical service life of cable H6 since the installation of the connecting cable. This finding is confirmed by calculations for the subsequent years, thereby underscoring the beneficial effect of this measure.

5 CONCLUSION

This article presents the effects of vortex-excited transverse vibrations and rain-wind-induced vibrations on the ÖBB Rheinbrücke near Lustenau. Data collected during a long and extensive monitoring campaign on the bridge were used for this purpose.

The following conclusions can be drawn from the analyzed data:

- Wind-induced events cause fatigue-relevant stresses that are dependent on the weather conditions
- The effects of vortex-induced and rain-wind-induced events on the fatigue strength are much more pronounced for the hangers with greater length.
- The damaging effect of such events can be effectively reduced by installing cables joining adjacent hangers The theoretical service life increases progressively, which confirms the positive effect of the measure against fatigue failure.

These findings underscore the critical importance of considering wind-induced vibrations in the design and maintenance of arch bridges, especially those with slender steel hangers. The implementation of a structural health monitoring system proved invaluable in detecting and quantifying these vibrations, allowing for timely intervention and mitigation strategies. The SHM system enabled the detection of wind-induced vibrations in the hangers, which could have led to fatigue damage and premature failure, thus contributing to the mitigation of potential risks.

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