Development of Object-Specific Load Models for the "Donau-Wald-Brücke" at Winzer

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Abstract This paper presents the derivation of object-specific traffic load models, using the investigation of the bridge "Donau-Wald-Brücke" near Winzer as an example. Due to unsatisfactory results from recalculations, a structural monitoring campaign was launched, involving both short-term and long-term measurements. The goal was to obtain adjusted coefficients for the verification of the ultimate limit state (ULS) and fatigue design. The paper discusses the chosen approach and presents some key results. Although the investigations are not yet fully complete, it is already evident that the volume of necessary repair and reinforcement measures can be significantly reduced.

1 Introduction

The "Donau-Wald-Brücke" near Winzer carries State Road St 2119 over the Danube, approximately 20 km south of Deggendorf. The central river bridge is a haunched three-span beam girder structure with spans of 71 m, 152 m, and 54 m, constructed from steel with an orthotropic deck plate. Adjacent to this river bridge, a four-span prestressed concrete bridge crosses the floodplain area of the nearby Danube wetlands. Figure 1 provides a side view of the steel structure, while Figure 2 shows a photograph of the construction.

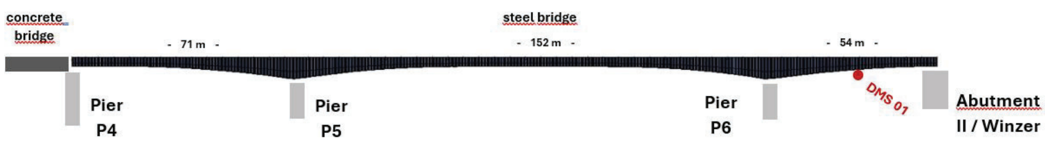

Figure 1: Side view of the central river bridge (steel construction)

The structural evaluation of the bridge, based on recalculation guidelines [1], revealed significant theoretical deficiencies con¬cerning both the ultimate limit state (ULS) and fatigue design. Before undertaking extensive reinforcement measures on the exis¬ting structure, the authors proposed a structural monitoring campaign. This campaign aimed to validate the structural behavior and assess the object-specific traffic loads.

Figure 2: Danube bridge Winzer (seen from the abutment Winzer to pier P6)

The monitoring campaign has now been completed. Based on extensive data analysis, object-specific characteristic traffic loads were determined. In comparison to the specifications of DIN EN 1991-2, this analysis indicated a significant reduction in traffic impacts for the examined bridge. The next step will involve recalculating the normative verifications using these object-specific values, from which any necessary reinforcement measures will be derived. These object-specific loads can also be applied to the recalculation of the adjacent prestressed concrete bridge. Although the data evaluation is not yet fully complete, key results from the monitoring campaign are presented, focusing on the strain gauge "DMS 01." This location is illustrated in Figures 1, 2, 3, and 4.

2 General Approach

2.1 Preliminary Investigations

In 2021, the steel bridge was recalculated according to Levels 1 and 2 of [1], considering the load classes BK60/30 and BK60. Significant exceedances of up to 85% in the ultimate limit state (ULS) were identified. Regarding the fatigue design, only isolated exceedances were found in the main structure. However, the normative fatigue verification could not be fulfilled for several crossbeam girders in the main span and parts of the deck plate.

The authors subsequently proposed further investigations, aligned with Levels 3 and 4 of [1], combined with a monitoring campaign, to obtain more detailed input values for structural evaluation and to optimize necessary reinforcement measures.

2.2 Development of the Monitoring Campaign

Based on the recalculation results, a monitoring campaign was designed. Its scope was deliberately minimized by focusing on key areas identified in the recalculation and leveraging the structure's symmetry. A total of seven strain gauges ("DMS") were installed on the main structure - five on the upstream main girder and two for comparative analyses and increased redundancy on the downstream main girder. Two additional strain gauges were placed on crossbeam girders.

To examine the deck plate and its components, further strain gauges were installed on the underside of the orthotropic deck plate. Figure 3 provides an overview of the measurement setup, excluding the strain gauges for the deck plate. The overall goal was to create a solid and reliable data basis for calibrating the structural model and conducting further analyses, without generating unnecessary data.

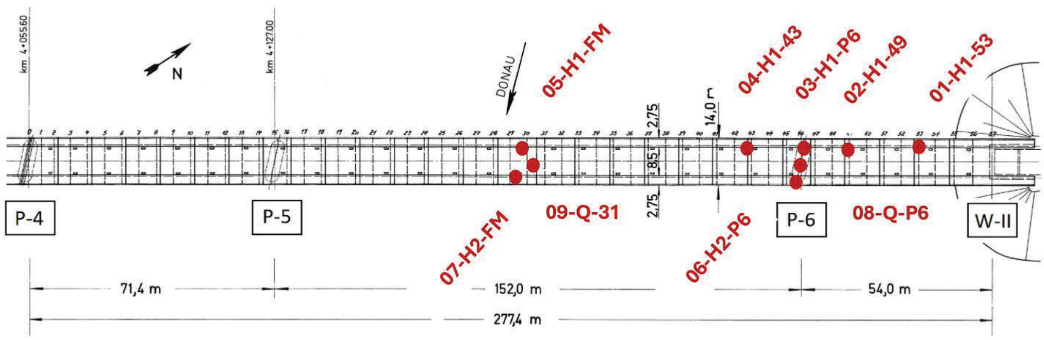

Figure 3: Overview of the strain gauges installed

The critical notch details in the structure are predominantly characterized by welds (joints of the flanges or attached secondary components). Since measurements cannot be taken directly at the notch, the strain gauges were installed in "undisturbed" sections close to the relevant notch detail. Transfer factors for this geometric deviation between the place of the strain gauge and the notch detail were calculated using the calibrated structural model (range between 1.00 and 1.16). The strain at each individual strain gauge is measured and recorded with a frequency of 125 Hz. Since the measured strains lie exclusively in the linear-elastic range they can be directly converted into stresses σ [N/mm^2] using Hooke's law.

The recording of strains or stresses is directly temperature-compensated through an appropriate electronic circuit. But - as the structure is a statically indeterminate system (three-span beam) - also real stresses occur resulting from constraint due to tempe¬rature fluctuations. They have to be taken into account, for example in fatigue relevant evaluations. For subsequent analyses regarding the stresses solely due to traffic impacts, temperature-related effects were compensated by additional data processing.

The data documentation is conducted using reduced "max-min-diagrams" which include re-spect¬ively only one maximum and one minimum value per minute of each strain gauge. These diagrams provide an overview representation even over longer measurement periods. Specific traffic effects, such as traffic jams, heavy transports or the effect of traffic light controls can be identified and temporally assigned. If necessary, such special events can later be selectively retrieved and further analysed in high resolution using the continuously recorded data.

2.3 Short-term Measurement and Calibration of the Structural Model

To evaluate the measurement data and compare them with normative load models, a structural model was developed using a combined framework and shell model. The beam-like elements, such as the main and crossbeam girders and the trapezoidal hollow sections beneath the deck plate, were modeled as finite element beams, while the deck plate itself was modeled using shell elements. The material distribution was derived in detail from the existing construction documents.

To calibrate this model, a short-term measurement was conducted on-site by having a truck weighing approximately 39 tons crossing the bridge several times. The axle loads and precise axle geometry were determined beforehand. The road was briefly closed for traffic to facilitate these measurements. The crossings were simulated as "moving" loads in a variety of single load cases, and the measured stresses were compared to the calculated stresses using stress-displacement diagrams. The results of these comparative calculations at strain gauge "DMS 01" are exemplified in Figure 4.

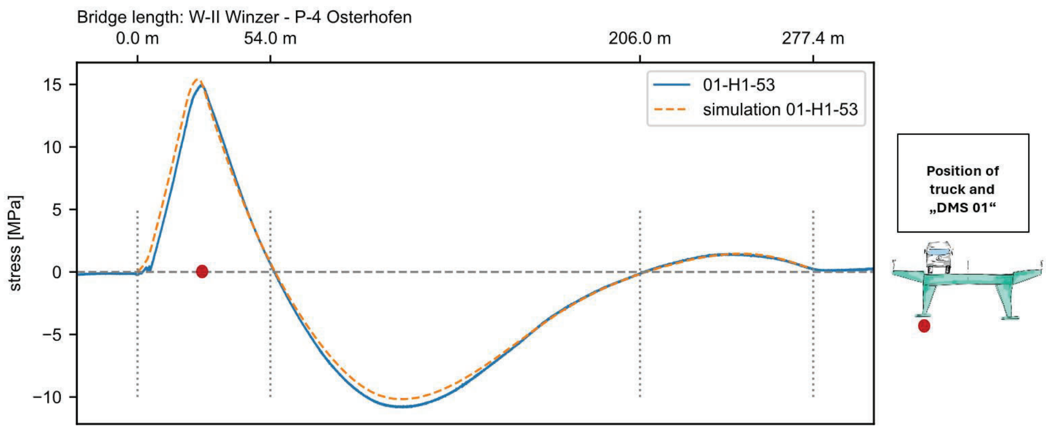

Figure 4: stress-displacement-diagram for “DMS 01” during a crossing from Winzer towards Osterhofen

Following several optimization steps, an excellent agreement was achieved between the measured and calculated stresses. The calibrated model is essential for many evaluations, including comparing the effects of normative load models with object-specific traffic. It also ensures that stress peaks and model stiffness align with real structural behavior, identifying and assessing compu¬tational effects from discretization choices. The short-term measurement provides a valuable reference for evaluating special or extreme load events. Conclusions regarding truck weights during the measurement can also be drawn from the determined stress amplitudes, with some examples presented further below.

2.4 Long-term Measurement

The long-term measurement was conducted over a period of one year to capture seasonally variable traffic effects (e.g., agri¬cultural or construction activity), holiday and vacation influences, and seasonal temperature fluctuations. Continuous data recording was maintained throughout the measurement period, and all evaluations and data reductions were conducted sub¬sequently.

For the fatigue safety assessment, the recorded data was analyzed using the rainflow method to count the stress ranges ($\Delta\sigma$). As a result, fatigue-relevant load collectives could be derived and further evaluated.

To investigate traffic loads, the data was first reduced to one-minute extreme values, represented in "max-min-diagrams." An example is shown in Figure 5, depicting data for one week (seven days starting Monday at 00:00). The upper part of Figure 5 shows raw data affected by daily temperature changes, with significant temperature effects visible on the first two days (Monday and Tuesday, indicated by the area marked "T") and on Sunday. In contrast, the lower part of Figure 5 shows the data after correction for temperature influences, isolating traffic-related loads.

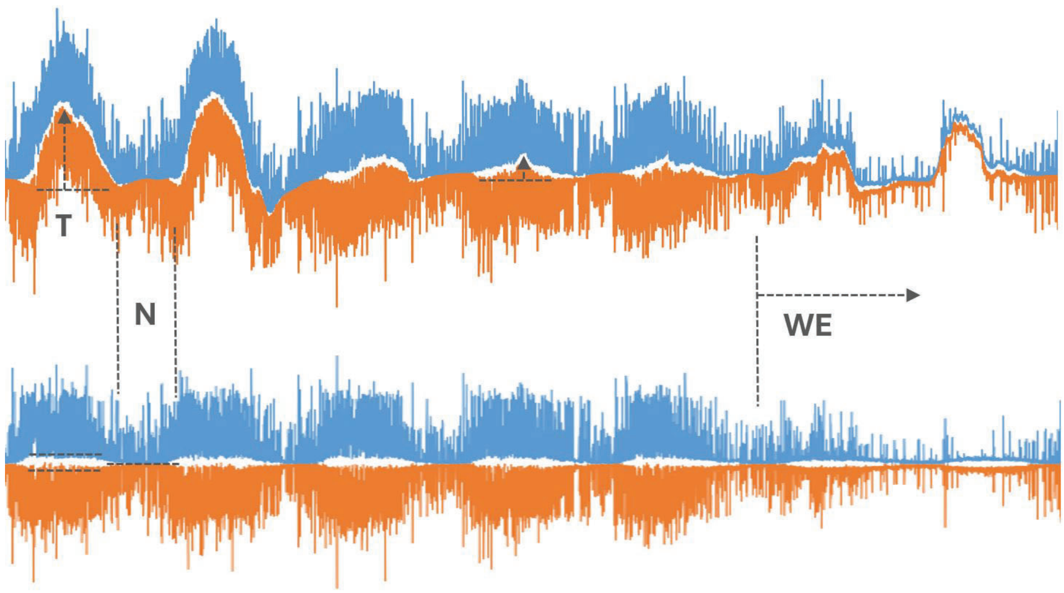

Figure 5: "Max-min-diagram" for one week with (upper part) and without (lower part) temperature influence

The working days from Monday to Friday are clearly visible due to larger maximum and minimum stress values caused by traffic. A decrease in fluctuations is noticeable from Friday night, corresponding to reduced traffic loads during the weekend (area marked "WE"). The general driving ban for trucks over 7.5 tons on Sundays is evident from sporadic larger stress peaks, which increase again on Sunday night into Monday. Low-traffic nighttime hours are characterized by minimal traffic loads, leading to very small differences between the maximum and minimum values (see area "N").

3 Evaluations Concerning Fatigue Design

3.1 General Approach

For fatigue design assessments, the continuously recorded data from each strain gauge was evaluated using the rainflow analysis method. The derived load collective includes the number of identified stress ranges ($\Delta\sigma$) over the entire measurement period. The total damage can then be calculated using the Palmgren-Miner linear damage accumulation hypothesis, which considers the sum of all partial damages at the respective notch detail. The evaluations are based on the S-N curves specified in DIN EN 1993-1-9, considering the fatigue endurance limit and the cutoff range. Using this data, the calculated service lifetime can be directly extrapolated.

By measuring the stresses, object-specific influencing factors - such as stress levels, traffic composition, volume, number of lanes, oncoming traffic, dynamic effects, etc. - are directly captured. For comparison with normative verification procedures, an overall damage equivalence factor (λ_{mess}) can be directly determined from the measurements. This factor ultimately allows the actual (object-specific) fatigue loads to be compared with the normative approach.

3.2 Results of “DMS 01”

According to Eurocode 1993-1-9, the examined location at strain gauge “DMS 01” corresponds to notch group $\Delta\sigma_c$ = 50 N/mm². A partial safety factor of 1.15 is applied to elements of the main structure. Normative verification cannot be fulfilled at this point using a $\Delta\sigma_{LM3}$ = 28.2 N/mm² and a $\lambda_{total-EC} = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4$ = 1.57. The calculation of λ already includes a reduced value for $N_{obs} = 0.2510^6$, derived by the structural engineer from a traffic count. Altogether, this results in a damage-equivalent $\Delta\sigma_{E2}$ = 44.3 N/mm², slightly exceeding the verification limit of $\Delta\sigma_{cd}$ = 50/1.15 = 43.5 N/mm².

The position of strain gauge “DMS 01” is shown in Figures 1, 2, 3, and 4. Figure 6 illustrates the stress collective derived from the rainflow analysis conducted over one year at this location. The theoretical service lifetime at this point is estimated at around 500 years. Overall, the steel bridge provides sufficient fatigue design (>100 years) for the actual traffic conditions.

A reference to the normative load model LM3 can be made through supplementary considerations. A fictitious notch group was recalculated iteratively from the measured stress collective, yielding a service life of 100 years. Instead of the normative classification with $\Delta\sigma_{cd}$ = 43.5 N/mm², an object-specific ("OS") minimum notch group of $\Delta\sigma_{cd,OS-100}$ = 31.9 N/mm² was found to be sufficient. By comparing the exceedance in the normative verification with the safety reserve from the actual stress collective, a normative overestimation of the actual traffic situation of about 39 % was identified. For future recalculations, the object-specific effects for fatigue design allow a reduction of normative specifications to approximately 72 %, or the use of a total damage equivalence factor $\lambda_{total-OS}$ = 1.13.

The data evaluation was not fully completed at the time of publication. Further investigations regarding fatigue design and global safety assessments of the construction are still in progress.

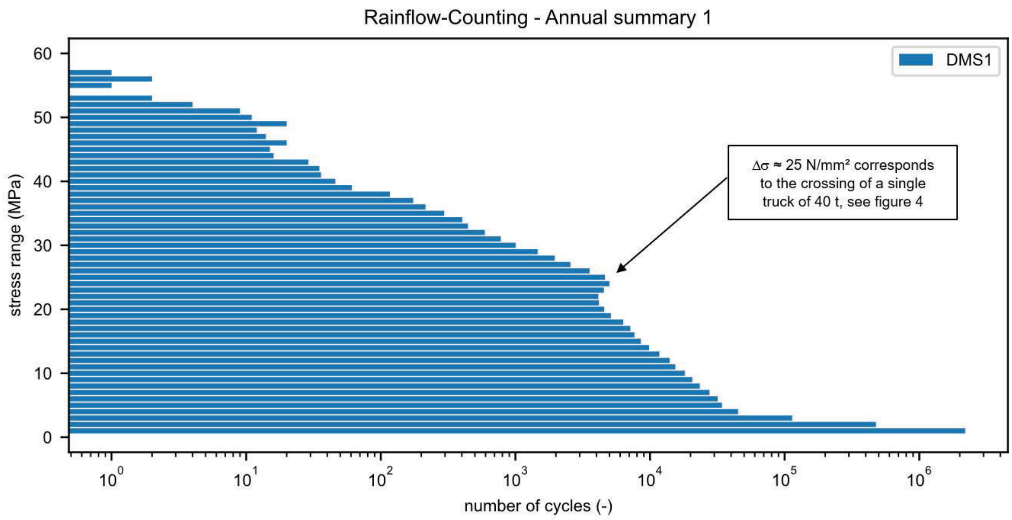

Figure 6: Results of rainflow-counting für “DMS 01”

4 Evaluations Concerning Traffic Loads in ULS

4.1 General Approach

For the assessment of structural safety under ultimate limit state (ULS) conditions, the extreme effects of traffic loads are of primary interest. The derivation of these effects, along with temperature-related components in the recorded data, has been previously explained. To derive characteristic load values from the one-year measurement period, extensive data preparation and statistical evaluation are required. The approach followed corresponds to the procedure outlined in [2].

This process begins with analyzing the distribution of weekly extreme values (52 in total), which is described using a Gumbel distribution (Type I). From this, reference distributions can be derived, such as the distribution of annual extreme values. To safely assess the most extreme traffic load expected during the remaining service life, the corresponding quantile values from the annual extreme value distribution must be determined.

For new bridge constructions, a theoretical service life of 100 years is required. The definition of the normative load model LM1 is based on a return period of once in 1,000 years for the characteristic load (DIN EN 1991-2, Section 2.2). Accordingly, the characteristic traffic load for new structures is determined by the 99.9 % quantile value of the annual extreme value distribution. Normative load models must account for sufficient reserves to cover future traffic developments over a service life of 100 years. However, for existing structures, a shorter reference period is generally appropriate [2, 3]. This is because traffic conditions are better known through traffic counts or systematic monitoring, and the remaining service life is typically shorter.

For the “Donau-Wald-Brücke” at Winzer, an approximately 50-year-old structure (constructed in 1974), a remaining service life of 50 years is to be evaluated. In line with [2, 3], the characteristic traffic load effect can be derived from a 50-year return period of extreme values. To cover future traffic developments, a systematic annual traffic increase of 1 % is considered, enhancing the safety margin.

The reference to the normative load model LM1 can be established based on this data evaluation. First, the normative charac¬teristic load value is determined for all strain gauges using the calibrated structural model. A comparison of these values with the measured values allows the calculation of an adjustment factor ($\alpha_{total-OS}$). This factor can then be used in future recalculations based on [1] to account for object-specific (and future-proof) load models.

4.2 Results of “DMS 01”

This approach is exemplified using the results from strain gauge "DMS 01." Initial comparisons of the stress collective revealed that the negative stresses (compression) represented the relevant extreme values. From the weekly data analysis, 52 minimum values were extracted.

Using the results of the short-term measurement, it was determined that a single truck weighing 39 tons generated a stress level of approximately -11 N/mm² (Figure 4). The stress levels of the extreme values were significantly higher, caused by events such as traffic jams, oncoming traffic, trucks driving closely together, or special vehicles crossing the main span. These extreme events were identified and evaluated during detailed data analysis.

Figure 7 illustrates the data extrapolation process. The 52 discrete extreme values are shown as gray bars, described by a Gumbel distribution (blue line). The distribution was then extrapolated to a 50-year return period (orange line), with further consideration of a 1 % annual traffic increase (green line). This resulted in a characteristic traffic load value of -51.2 N/mm² at “DMS 01”.

Two recorded values of -17 N/mm² and -18 N/mm², corresponding to the Christmas holiday period in weeks 52 (2023) and 01 (2024), are also shown in Figure 7. These values reflect the significantly reduced heavy traffic crossing the bridge during that time.

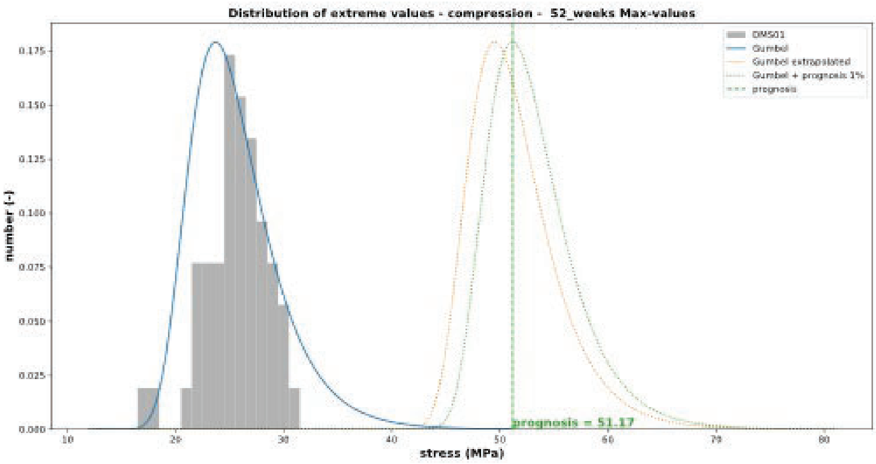

Figure 7: Extrapolation of the discrete weekly extreme value distribution at “DMS 01”

To establish a reference to the normative load model LM1, calculations were performed for the related TS and UDL loads in the roadway area using the calibrated structural model. A stress value of 140.1 N/mm² at "DMS 01" was determined. The ratio between the extrapolated value from the monitoring data and the normative characteristic value resulted in an adjustment factor of $\alpha_{total-01}$ = 0.37 for "DMS 01."

The adjustment factors were similarly determined for all strain gauges. The maximum value in the main structure was found to be $\alpha_{total-OS}$ = 0.38. For the crossbeam girders, whose load is predominantly influenced by vehicle weight and axle loads, significantly higher values of up to 0.71 were derived. These factors allow the global reduction of the normative load model LM1 according to DIN EN 1991-2, enabling a safe and object-specific approach to future-proof traffic loads without compromising safety in ULS verification.

At the time of publication, the data evaluation was not yet fully completed. However, based on the results available from the first recalculation, it can already be reasonably assumed that the required volume of repair and reinforcement measures can be significantly reduced as a result of the structural monitoring campaign.

5 References

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