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PRACTICAL CONCEPTS FOR THE USE OF PROBABILISTIC METHODS IN THE STRUCTURAL ANALYSIS AND REASSESSMENT OF EXISTING BRIDGES - PRESENTATION OF LATEST RESEARCH AND IMPLEMENTATION

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Abstract. In structural engineering and bridge construction, probabilistic calculations are only performed in a few exceptional cases. The ability to directly use information from the existing structure is an important advantage of probabilistic methods. Geometric data or the position and quantity of the installed reinforcing steel and tendons can be measured. Results from monitoring of the traffic can be used to generate structure-specific load models. Many clients are still very sceptical about the results of probabilistic calculations, even though there are several examples of successful application. The use of probabilistic verification formats is explicitly permitted by the German guideline for the assessment of existing bridges (German: Nachrechnungsrichtlinie). Since a high degree of special knowledge is required for the application of probabilistic calculations, it is difficult to establish the potential of this verification method in practice. It is necessary to enable the practical engineer to utilize the advantages of probabilistic calculations and to include the actual structural conditions into the calculation model, but without the need for all the special knowledge. Structure-specific partial safety factors include measured data and can be used for the well-known and in the codes established semi-probabilistic design concept. The authors present examples for the successful application of probabilistic methods and of data measurement during the reassessment of two existing bridges in Germany. The capabilities of full-probabilistic calculations for the reassessment of existing structures are described and concepts for the calculation of structure-specific partial safety factors are shown.

Keywords: Existing bridges, existing concrete structures, modified partial safety factors, statical recalculation, structural analysis, structural assessment, structural reassessment.

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1. Introduction

In recent years, research activities for the application of probabilistic calculations intensified considerably. However, for the structural analysis of existing bridges the use of probabilistic methods is still limited to few cases. Distinct reasons for this limitation can be identified. In general, the clients are often very sceptical about the results of a probabilistic calculation, either due to the lack of experience or because of regulatory limitations in the past. The results of numerical or probabilistic calculations highly depend on the selected models. Their usage requires a high level of competence and responsibility [1]. Therefore, it is difficult to establish the potential of this verification method in practice.

Compared to the design of a new structure, the construction process of an existing structure is already completed and documented. Typically, the structure has already been used for decades. Relevant information can be detected or measured on site [2–4]. This is a major advantage during the assessment of existing structures. Most codes are primarily focused on new constructions and include reserves for the load bearing capacity, which are mandatory and important for a safe planning process. During the construction process and the service lifetime of a structure, mistakes or variations of parameters or deviations are possible and must be considered in the design and calculation [5]. But the actual parameters are likely to be more beneficial than assumed during the design process for a structure, that operates over a long time without major damage [5]. Existing structures often have more load bearing capacity than currently certifiable, even if they are designed according to historical codes [6]. In most cases, these reserves are not used for the calculations, because information about the actual properties of the structure can hardly be implemented into the semi-probabilistic calculation concept.

2. Capability of full-probabilistic calculations for the structural analysis of existing structures

Full probabilistic methods deliver exact information about the reliability of the examined structure, but they require specialized knowledge. Table 1 gives an overview of possible reliability concepts. It is important to differentiate these levels from the stages of the

	Level	Reliability concept	Reliability measurement tool	
accuracy ↓	0	Deterministic	Global safety factor γ	complexity ↓
	1	Semi-probabilistic	Partial safety factor γ_M, γ_F	
	2	Probabilistic approximation	Reliability index β	
	3	Probabilistic exact	Failure probability P_f	
	4	Economically optimal	Risk (accepted failure probability P_f)	

Table 1. Concepts for the determination of the load bearing capacity of structures [7].

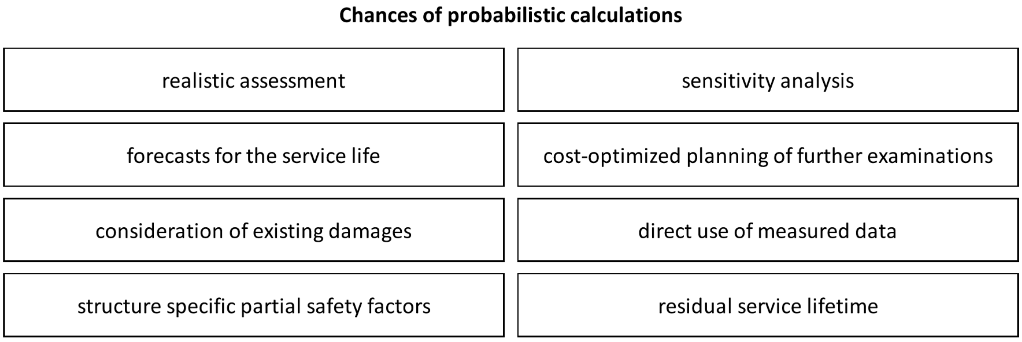

Figure 1. Possibilities of probabilistic calculations in structural engineering.

guideline for the assessment of existing bridges.

The deterministic reliability concept uses a global safety factor γ, to obtain a certain safety level. Before the introduction of the semi-probabilistic concept into most design codes, the global safety factor method was the most often applied concept. Currently, the semi-probabilistic concept is used in most cases and is standardized by European codes [8, 9]. Different partial safety factors for loads and resistances allow for a more efficient design, because the variation of each parameter can be quantified separately. Another reliability concept is the use of the reliability index β, which is an approximation. The calculation of the failure probability is theoretically exact.

Figure 1 shows advantages of probabilistic methods for the reassessment process of existing structures. With the use of probabilistic methods, a realistic assessment of the structure is possible. Usually bridge access technology is used for the inspection of bridges. Information about actual damage and data from in-situ measurements can be implemented directly into the calculation model. For example, the self-weight of the construction can be determined with the actual geometry from measurements instead of using the indications from the as-built documents. Lifting the superstructure is a pragmatic way to verify and measure the construction weight. If the loads are more specified and uncertainties are reduced, a reduction of the partial safety factors does not cause a reduction of the reliability of the structure. Image based damage detection is a current research topic, where image classifiers and damage detectors support the bridge inspector during the evaluation of the on-site documentation [10]. Structure-specific traffic load models are often based on traffic counting. If statistical data about the traffic is already available, e.g., in Germany there is an archived DTV-SV (average daily traffic intensity of the heavy-load traffic), this information can also be used. In general, possible costs and benefits should be estimated before any examination is performed. A sensitivity analysis informs about the contribution of each parameter to the total uncertainty. After the relevant aspects are known, a cost-optimized planning of the examinations is possible. During the reassessment process of existing structures, present defects are identified and calculation models simulate future degradation, e.g., the progress of corrosion or carbonation. The residual service lifetime can be estimated based on the condition and age of the structure, its planned use in the future and potential repair or maintenance actions.

The identification of relevant limit states and parameters is a central aspect of a probabilistic calculation. The available information and measurement data must be preprocessed and classified before it is used in the calculation model. The measurement quality must be high and the data has to be prepared well. With an increasing amount of information and parameters, the susceptibility to errors increases as well. It is vital to validate the calculations with comparative analysis or plausibility checks. Other limiting factors for the application of probabilistic methods are their demand for highly specialized knowledge, the detailed computational programs, the need for a solid data basis and the effort of in-situ measurements. Regulatory standards for the use of full-probabilistic calculations in the analysis of existing structures further reduce the acceptance of probabilistic methods. Although probabilistic verification formats are explicitly permitted by the German guideline for the assessment of existing bridges [11], the approval from the building authority is still required for the application in each case.

3. Structural reassessment of existing bridges in Germany

3.1. Concept of the German guideline for the assessment of existing bridges

About ten years ago, a systematic analysis of the load bearing capacity of German road bridges started. The increased heavy load traffic and the deterioration of existing bridges raised public doubts about the stability and reliability of German bridges. As a result, the federal department for traffic together with specialists from engineering companies, administration and scientists developed and introduced a special national code in 2011 to achieve consistent and standardized calculation methods. The so called *guideline for the assessment of existing bridges* (German: Nachrechnungsrichtlinie) [11] is a national code, which is especially designed for the standardized reassessment of existing structures. The objective of this code is a more realistic assessment of the reliability of existing bridges, with regards to the increased traffic on one hand and to advancements in calculations methods on the other hand. The current condition of the bridge must be considered as well. In this context the term statical recalculation must be explained. Regular inspections are performed every three years in Germany. Damaged structures are analyzed whenever a major defect is detected. The goal of this maintenance is to preserve or recover the "as-built" condition of the structure. However, a statical recalculation focuses on the theoretical reliability of the structure from a modern perspective and with regards to today's requirements. Characteristic aspects of existing structures are also considered. An additional amendment [12] including further improvements was released in April 2015. The reliability of a few thousand existing bridges was examined according to the regulations of this guideline during the past ten years. Many positive experiences about this special assessment of existing bridges are reported [6]. Currently, the BEM-ING Part 2 [13] is in preparation for technical approval. This new guideline will extend the regulations of the guideline for the assessment of existing bridges.

The guideline provides a standardized procedure with four stages. Figure 2 shows the principal process of a statical recalculation based on [11]. With each step the effort for the calculation and the on-site examinations increases.

In the first stage (stage 1), the calculations are performed based on the current regulations of the Eurocodes. Depending on the intensity of heavy traffic on the bridge, it is also possible to apply the regulations of the former German technical reports (German: *DIN-Fachbericht*). These national codes were introduced during the preparation of the Eurocodes and created especially for bridge design. The technical report 101 (German: *DIN-Fachbericht 101*) [15] specifies loads and actions on bridges. The reports 102 to 104 [16–18] provide rules for the calculation and design of concrete, steel and composite bridges. The intent of the national codes was to facilitate the transition to the Europe-wide harmonized codes. Most of the now assessed bridges were designed without the use of numerical calculations. Present-day calculation models and computer-based methods, e.g., finite element method, can mobilize considerable load bearing reserves compared to the manual calculations of the past. On the other hand, the increased design loads of newer code generations can repeal those profits.

In the second stage (stage 2), specific regulations and additional methods can be used. The guideline for the assessment of existing bridges adapts design equations and input variables like loads, resistances and coefficients. For example, predefined and general modifications of the partial safety factors are allowed. A reduction of the factors for the variation of post tensioning forces is possible. A common aspect during the structural analysis of existing concrete bridges is their shear capacity. Especially in old concrete bridges, the shear stirrups are designed according to former standards. The number, form and design of the stirrup reinforcement bars is appropriate to modern code standards. Adaptions to the verification process of the shear force resistance are necessary to obtain sufficient load bearing capacity and based on new knowledge since the construction of the existing bridges. The guideline defines certain requirements for stirrup forms of the reinforcement. Based on a better understanding of the material behavior a variation of the shear compression angle is allowed. A verification of the load bearing capacity based on the principal stress criteria is also possible during the reassessment process. One example for the mobilization of reserves in the load bearing capacity is the so called cutting of the shear force coverage, where local deficits in the shear reinforcement are permitted. This means that the amount of existing shear reinforcement is allowed to be smaller than theoretically required, if there is more shear reinforcement than required in the immediate surrounding area. This gives another small additional reserve, that can be relevant for a decision about the future use of the structure, if the existing reinforcement is otherwise slightly surcharged.

By this time, a reassessment according to the stages 1 and 2 is a common task for specialized engineering companies and for federal administrations. If the performed analysis cannot provide the necessary reliability level, and the methods of the stages 3 or 4 seem unlikely to achieve the necessary reliability, usage restrictions and compensatory measures are necessary. Possible actions are weight or speed limits for the traffic, changes to the lane markings like closed or

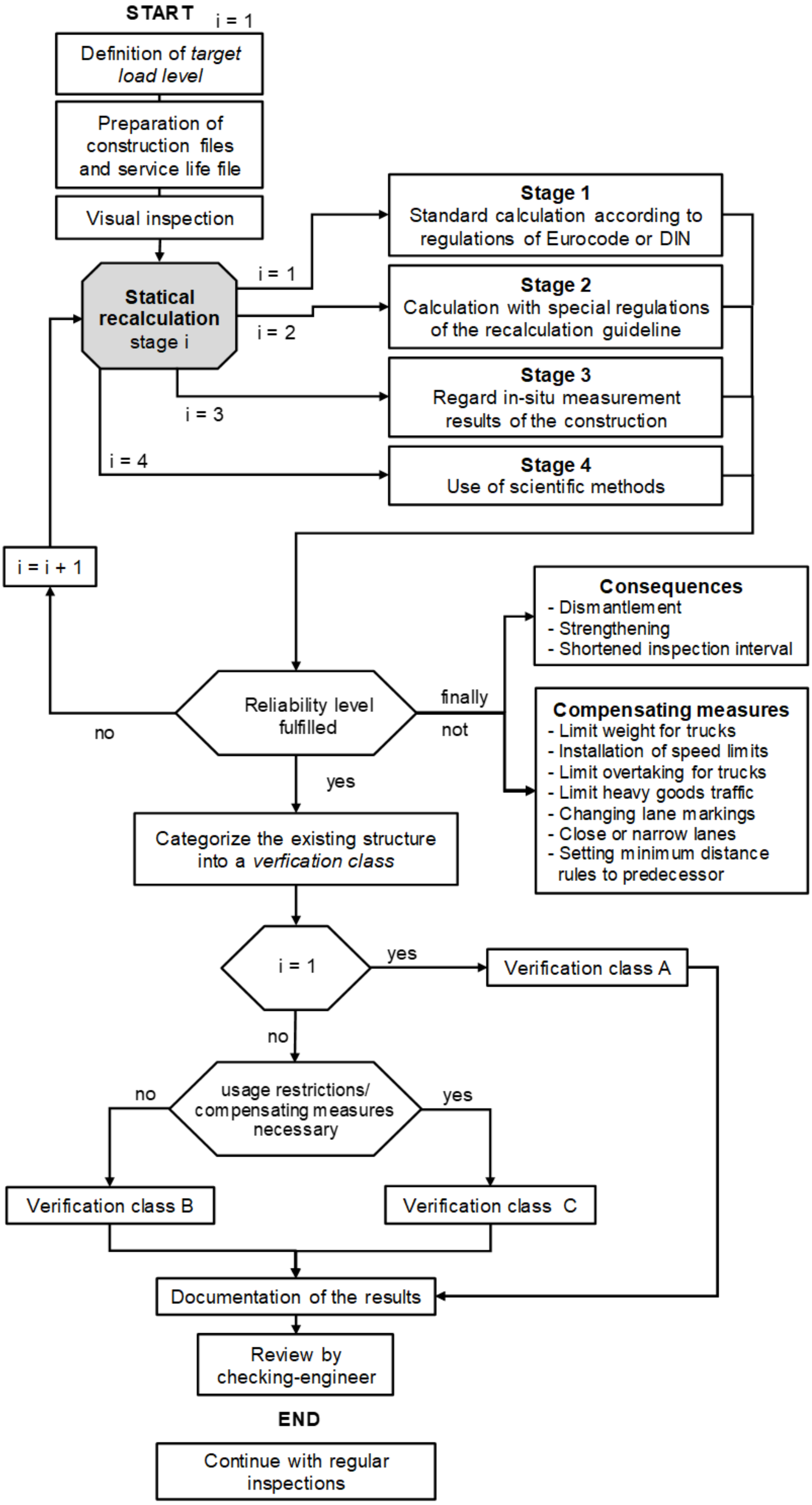

Figure 2. Flow chart for the process of a statical recalculation.

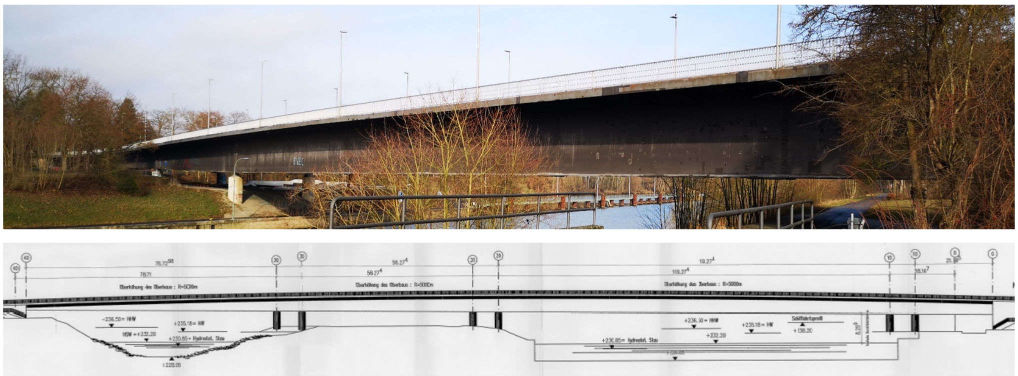

Figure 3. Longitudinal section and view of the Heinrich's bridge [14].

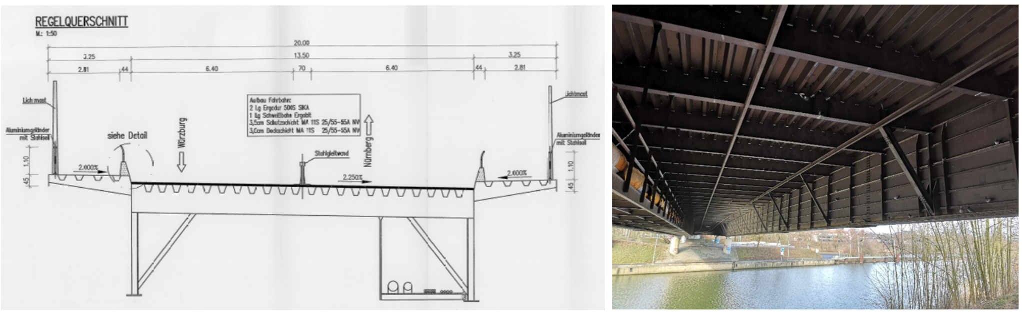

Figure 4. Cross section of the Heinrich's bridge (left: extract from plan, right: photo under the bridge) [14].

narrowed lanes or other additional rules for heavy traffic.

The regulations of stage 3 deliver further options for the reassessment process, like the use of monitoring or proof load tests. Measured data, e.g., material properties and deformations of the construction, can be used for the structural analysis [2]. A more precise knowledge about the actual traffic on the bridge or material properties reduces uncertainty and enables more economic calculation results. The results of in-situ measurements can also be used to validate the results of the finite element calculation model. A practical example for the successful use of data measurement during the structural analysis of an existing bridge is presented in the next section.

In the last stage (Stage 4) of the structural analysis, the use of scientific methods is authorized. These methods are usually not included in the design codes and the calculations exceed the regular level of detail and knowledge. Possible methods are analytical models, physical non-linear calculations, non-linear finite element models or non-linear crack simulations. Probabilistic methods are explicitly allowed during this stage of the examination. Pressure arch models for the shear resistance or a modified compression field theory are further options.

At the end of the reassessment process, each bridge is classified with a verification class (German: *Nachweisklasse*). The three verification classes inform about the depth of the examination and if there are any future restrictions necessary (class C). They provide information, if modifications to the calculation were necessary to reach the target load level (class B) or not (class A).

3.2. Data measurement during the reassessment process on the example of Heinrich's bridge in Bamberg

The Heinrich's bridge (German: *Heinrichsbrücke*) is a 270 m long road bridge located in Bamberg, Germany. It crosses the Rhine-Main-Danube Canal as well as a street and the right arm of Regnitz river. Therefore, the four spans have rather unusual proportions with measures of 18 m - 119 m - 56 m - 79 m. Figure 3 illustrates the urban conditions and shows the longitudinal section and a picture of the bridge.

This bridge from 1974 is constructed with an orthotropic steel deck. The single superstructure carries two traffic lanes in each direction and bike lanes on both sides, see Figure 4. In 2016 a structural analysis with investigations according to the regulations of the guideline for the assessment of existing bridges [11] started. A finite-element model was used during the first and second stage of the reassessment process. The serviceability limit state (SLS) as well as the ultimate limit state (ULS) and the fatigue limit state showed insufficient load bearing capacity.

An examination according to stage 3 of the guideline for the assessment of existing bridges [11] was then used to meet the requirements in the critical limit states. On-site measurements and a calibration of the finite element model were performed during

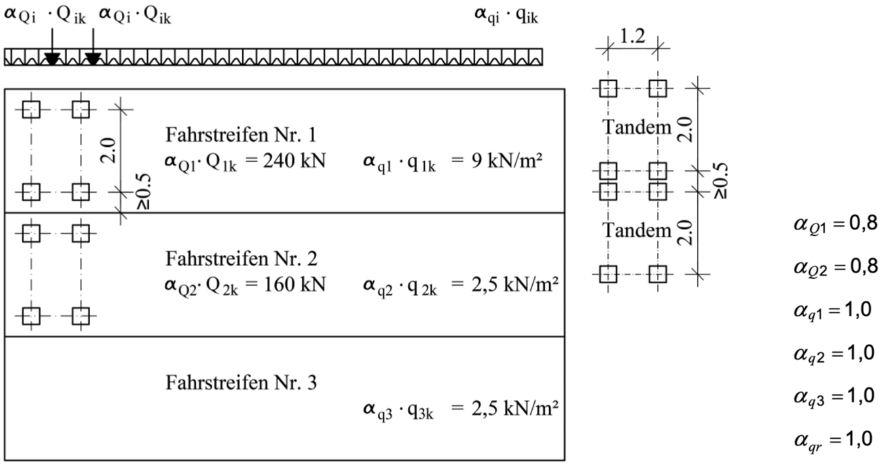

Figure 5. Load model LM1 and *adjustment factors* α according to DIN-Fachbericht 101 [15].

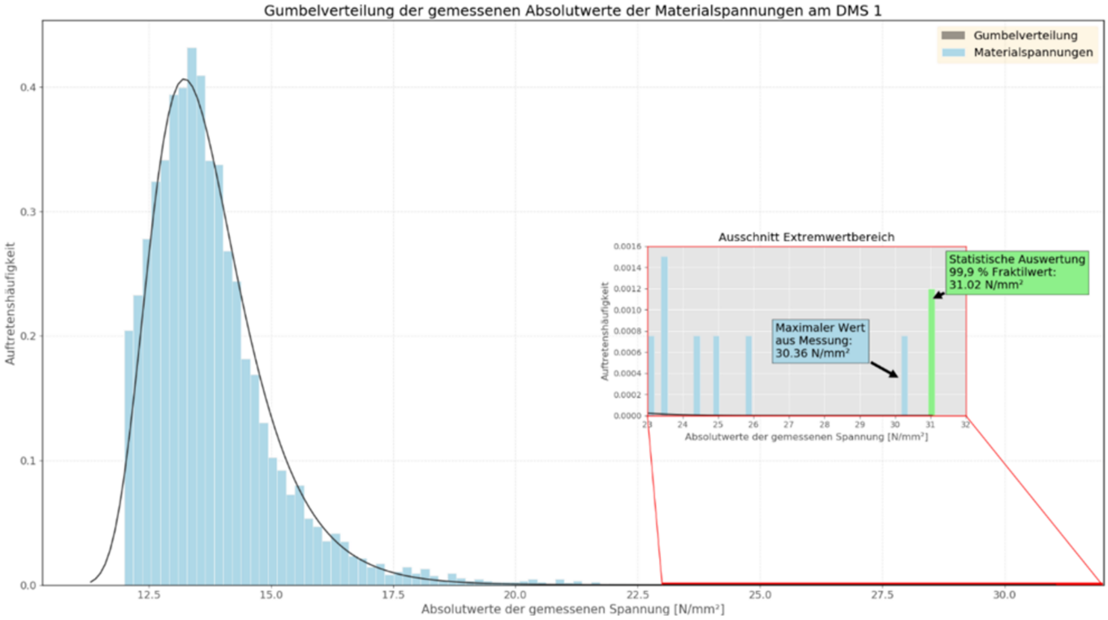

Figure 6. Gumbel distribution of the measured stresses over the whole measurement period [14].

the reassessment. The analysis of the bridge is part of a research project and the final report [14] was compiled last year. Generally, a distinction is made between structural monitoring over a certain time to evaluate statistical data, and structural health monitoring (SHM). The Heinrich's bridge was equipped with measurement instruments (13 strain gauges, 2 accelerometers and 3 temperature sensors) over a period of 15 months.

To calibrate the results of the finite element model with the measurement data from the strain gauges, a typical truck had to drive on the bridge in predefined schemes. The bridge was closed for other public traffic during this night. It is essential to select a vehicle, where all the relevant data (axle weights, geometric measurements or driving speed) is exactly known [14]. The driving schemes for the calibration include a variation of driving speeds from 5 to 70 km/h and predefined lanes to drive in. The tension stresses are calculated from the measured strains by using Hooke's law of elasticity. The load model for the single truck is applied to the finite element model and the measurement data is then compared to the results of the FE-calculation.

Based on the measurement data from November 2019 to January 2021, a structure-specific traffic load model is developed [14]. The *adjustment factors* α of the vertical traffic load model LM1 make reference between the normative values of the codes and the actual traffic intensity on the bridge. The load model LM1 of the technical report 101 (German: DIN-Fachbericht 101) [15] with its regular *adjustment factors* α is shown in Figure 5. The load model LM1 of the technical report 101 is similar to the LM1 of the Eurocode, but the tandem loads are smaller and only applied in two traffic lanes.

The strain gauge DMS1 is located on the bottom of a longitudinal girder in the middle of the main

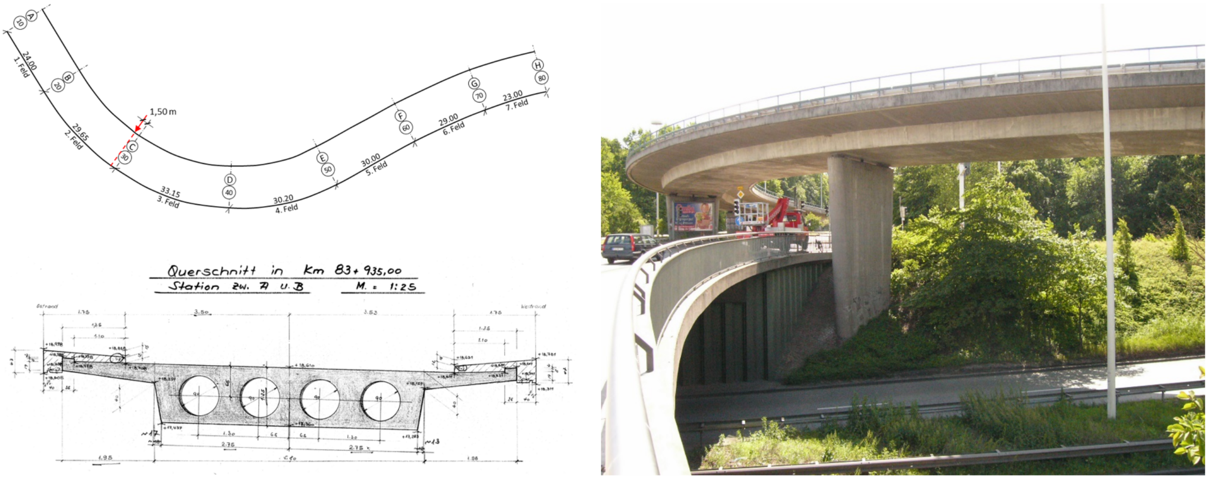

Figure 7. Layout, cross-section and view of the Bw 046.1 across the Barkauer crossing in Kiel, Germany [19].

span. Figure 6 shows the distribution of the measured stresses from DMS1 due to heavy traffic. The stresses on the horizontal axis do not start at zero, because just the distribution of the heavy traffic is relevant for the load-model. The beginning of heavy traffic was defined at a measured stress of 12 N/mm^2. As seen in Figure 6, a Gumbel distribution is very well suited to describe the traffic on the bridge [14].

This distribution function can only be implemented in a full-probabilistic calculation, but in the third stage of the structural analysis the semi-probabilistic reliability concept has to be used. However, the structure-specific definition of the characteristic value can be based on the measurement data. According to DIN EN 1991-2 [9] the recurring interval of the characteristic traffic load values is 1,000 years. This approximates a probability of 0.1% for the characteristic value of the traffic load to be smaller than the weight of the heaviest truck of one year. As a result, the structure-specific traffic load model is defined with a characteristic value equal to the 99.9% quantile of the Gumbel distribution. Over a period of 15 months, the maximum measured stress was 30.36 N/mm^2, see Figure 6. The characteristic value from statistical evaluation is 31.02 N/mm^2. Because the assessment represents only the traffic intensity in 2020 and the heavy traffic increased considerably over the last decades, an additional factor of 1.20 for possible future growth of traffic is implemented [14]. Additionally, a model uncertainty factor of $\gamma_{sd} = 1.20$ hedges simplifications and inaccuracy in the calculation models. The characteristic values should be multiplied with these two factors. The structure-specific *adjustment factors* α are calculated by comparison of the characteristic stresses from the measured data with the stresses of the finite element model, which implements the ULS loading according to the code [15]. The *adjustment factors* α are different for each location of the strain gauges. In general, the *adjustment factors* α for the Heinrich's bridge had a high conformity and numbered in a range from 0.19 to 0.39. The choice of $\alpha = 0.5$ represents an engineer-like and pragmatic approach, which allows a more cost-efficient maintenance work compared to the value of $\alpha = 0.8$ from [15]. On the other hand, there are additional reserves for bigger traffic loads, in case the results of the measurement data are not exactly representative due to a generally reduced traffic during the Covid-19 pandemic [14].

The *damage equivalence factors* λ for fatigue stresses can also be reduced based on the measurement results. The measured stress ranges are classified by their occurrence probability with the rainflow method. The contribution of each stress range category to the damage is determined with the Palmgren-Miner rule. The stress range spectrum is then represented by the *damage equivalent stress range related to* 2×10^6 *cycles* $\Delta\sigma_{E,2}$. The damage equivalence factor λ is calculated with division of $\Delta\sigma_{E,2}$ from the measurements with $\Delta\sigma_{E,2}$ from the finite element model, which implements the load model LM3 according to the codes. The additional factors for future growth of traffic and for model uncertainties are applied in the same way as mentioned before [14].

The measured data of this bridge is currently used for further research about intelligent data processing and machine learning techniques [21, 22].

3.3. Use of full-probabilistic methods for the analysis of the Barkauer crossing in Kiel

The bridge *Bw 046.1 across the Barkauer crossing* in Kiel, Germany, is an example for the successful application of stage 4 methods from the guideline for the assessment of existing bridges [11]. The 198 m long concrete bridge has a heavily curved horizontal alignment and a hollow-core superstructure. The seven spans are up to 33 meters long. The superstructure is prestressed in longitudinal and lateral direction. The bridge was constructed in 1970/71 and originally designed for *bridge class 60* according to the regula-

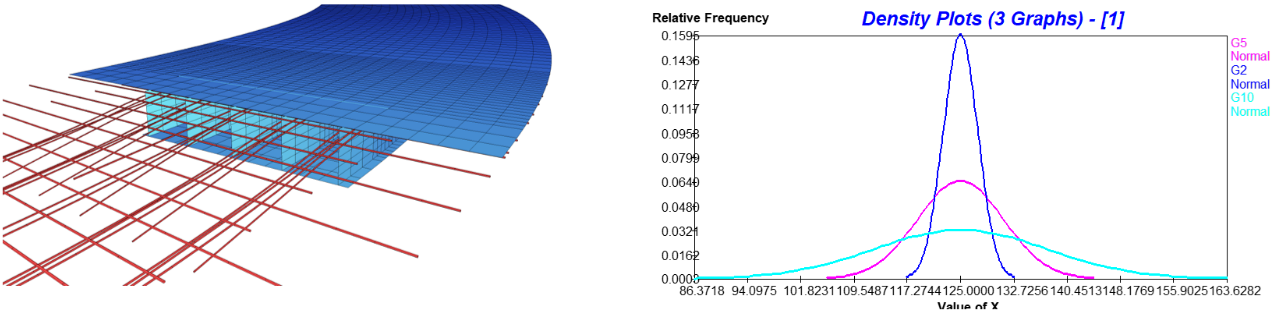

Figure 8. Finite element model including the reinforcement (left) and possible probability distributions for the height of the cross-section (right) [20].

tions of DIN 1072:1967-11 [23]. The concrete strength B450 of that time equals the contemporary C30/37. The reinforcement steel of type St III b has a yield stress $f_y = 420$ MPa. Figure 7 shows part of the construction plans and a photo of the bridge. Further descriptions and material properties can be found in [19].

In 2013, a reassessment process according to the German guideline for the assessment of existing bridges [11] started. The methodology of the stages one and two delivered satisfying results for almost every aspect of the bridge. However, substantial local shortcomings in the stirrup reinforcement and the torsional longitudinal reinforcement showed. The critical web, where the existing stirrup reinforcement is maximally stretched, is located 1.50 m before axis C and marked red in Figure 7. It was necessary to reduce the torsional moments for the superstructure with the installation of a single-lane traffic restriction together with a weight limit of 30 tons for traffic.

All construction documents were completely archived and available for the structural reassessment, which is a key requirement for a possible analysis. Because the reinforcement was only insufficient in some local areas, the methods according to stage four of the guideline for the assessment of existing bridges [11, 12] can be used to proof sufficient reliability of the structure.

A three-dimensional FEM shell model with a linear-elastic material behavior was created. Figure 8 shows a part of the model on the left side. This model implements the reinforcement as well as the tendons in longitudinal and lateral direction. Compared to a two-dimensional model, this mobilizes considerable reserves in the load bearing capacity of the torsional longitudinal reinforcement.

The amount of necessary stirrup reinforcement remained nearly the same as calculated during the analysis in the second stage of the process [19]. The first amendment to the guideline for the assessment of existing bridges [12] gives the option to proof the shear load bearing capacity based on the main stress criteria and not based on the existing amount of reinforcement. The condition for the use of this method is, that the concrete is not cracked [12]. To analyze the concrete for cracks, an additional non-linear finite element model uses the *layer method* for the superstructure. The cross-section profile is thereby modeled with multiple, consecutive superimposed layers that include assignments of the reinforcement, material behavior and bond properties. The shell-elements have non-linear material behavior assigned. The redistribution of internal forces as well as cracking and tension-stiffening are implemented. The commercial *SOFiSTiK*-Software was used for the physical non-linear calculations. The mean values of the material parameters are used as input values. The model indicated cracks with widths of 0.2 to 0.3 mm [19].

The stirrup reinforcement is further analyzed with probabilistic methods. The *first order reliability method (FORM)* calculations are performed with the program STRUREL [24]. A detailed on-site investigation of the structure gives precise knowledge about the material properties, i.e., concrete density, and geometry [19]. The limit state equation g is:

$$g(R, E) = N_r - N_e = 0 \tag{1}$$

The resistance of the stirrup reinforcement N_r is determined by the area of reinforcement A_s and the yield strength f_y. The force acting on the stirrups N_e is based on the results of the linear-elastic finite element model. It contains the combined effects of permanent load N_G, prestressing N_V, creepage N_C, settlement of supports N_S, temperature N_T, tandem system of traffic loads N_{SLW} and uniformly distributed traffic load N_{UDL}. The section width b is included in both sides of the equation. The factors U_R (N_V, $\mu = 1.00$, $v_x = 0.05$) and U_S (N_V, $\mu = 1.00$, $v_x = 0.07$) regard model uncertainties. Substitution of these variables gives the equation of the limit state for the stirrup reinforcement. As a result, the failure probability of the superstructure is calculated to $p_f = 1.94 \times 10^{-4}$ [19].

$$\begin{gathered} g(R,\, E) = U_R \cdot (A_s \cdot b \cdot f_y) - \\ U_s \cdot (N_G - N_V + N_C + N_S + N_T + N_{SLW} + N_{UDL}) \cdot b \end{gathered} \tag{2}$$

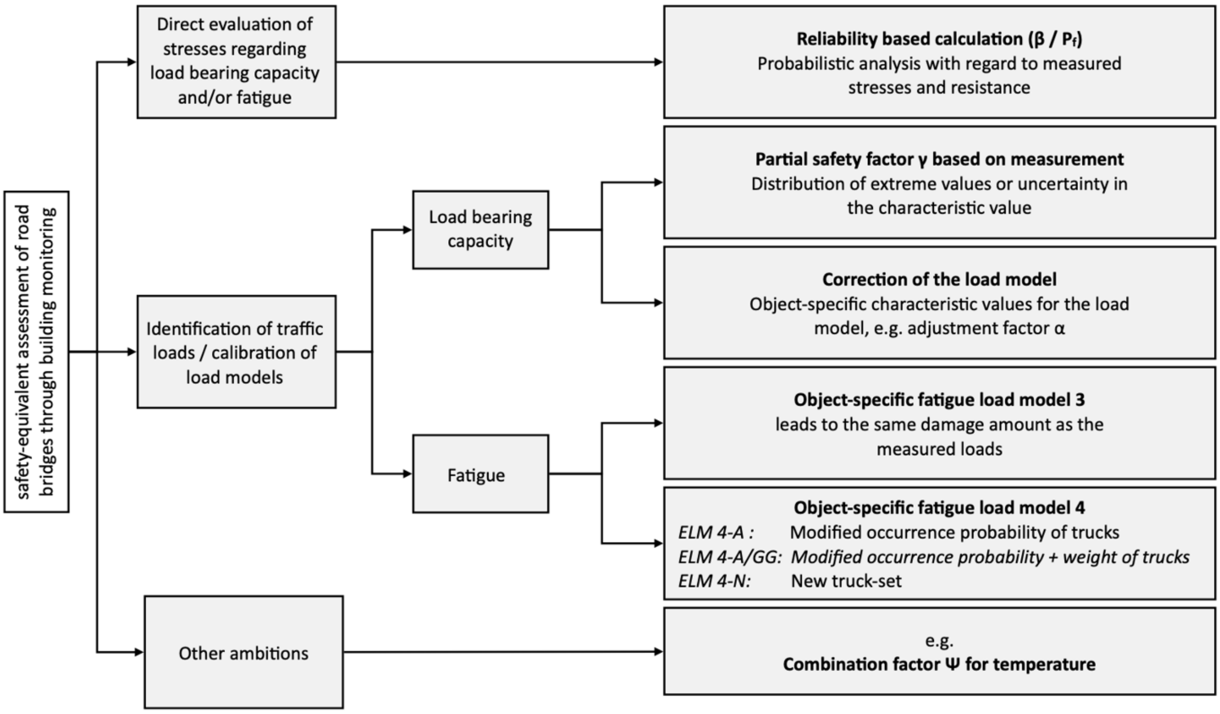

Figure 9. Possibilities of the safety-equivalent assessment of road bridges through monitoring (translated and reformatted) [25].

Additional rehabilitation work improved the durability of the structure. Due to the successful proof of the load bearing capacity with the methods of the guideline for the assessment of existing bridges [11], a continued use of this existing bridge is possible.

4. STRUCTURE-SPECIFIC PARTIAL SAFETY FACTORS FOR THE ASSESSMENT OF EXISTING BRIDGES

Compared to the planning of a new building, existing structures require adapted methods for an economic, sustainable and reliable reassessment. Structural monitoring is used in an increasing number of cases. A considerable amount of research has been conducted in this field. Most of the current code regulations focus primarily on the design of new structures. Only few regulations explicitly focus on existing structures. Examples for national regulations in Germany are the guideline for the assessment of existing bridges [11, 12], the RIL805 [26] for railway bridges or the DBV-booklet [5] for buildings. International publications are, for example, ISO 13822:2010 [27] and the fib bulletin 80 [28].

Probabilistic methods give the possibility to use data from on-site measurement, because the data can be implemented directly into the calculation. However, their infrequent application in the past and their effort restrict a broad commercial use. The large number of necessary reassessments of the ageing infrastructure in the next decades can only be handled with the contribution of the majority of bridge engineers. The implementation of on-site data is essential for a more realistic reassessment and for the mobilization of load bearing reserves. Many existing bridges can have a continued use under traffic with the mobilization of these reserves during the structural analysis process. Structure-specific partial safety factors combine an individual reassessment of existing bridges, the use of the familiar and efficient semi-probabilistic reliability concept and the implementation of measurement data. Results from on-site analysis provide additional information about defects and material properties. A more detailed knowledge about the existing structure reduces uncertainties and justifies the reduction of partial safety factors. Because of their simple application, the structure-specific partial safety factors are more suitable for practical engineers than full-probabilistic methods. The calculations are comparable to past assessments, because in most cases the semi-probabilistic concept was used there.

With a focus on the measurement of actions and loads, possible methods for the safety-equivalent assessment based on data were presented in [25, 31, 32]. Figure 9 shows possible applications for the use of monitoring data in the reassessment process. As mentioned earlier, a reliability based probabilistic analysis can implement the measurement data. The adaption of standard load models or combination factors to the actual traffic on the bridge uses the monitoring results with a semi-probabilistic reliability concept. The load models from the code are either corrected with factors or individual load models are generated [32]. Structure-specific partial safety factors are deduced from the results of a full-probabilistic calculation.

With focus on the investigation of the structure,

Figure 10. Application and results of ultrasonic measurements of a prestressed concrete bridge [29].

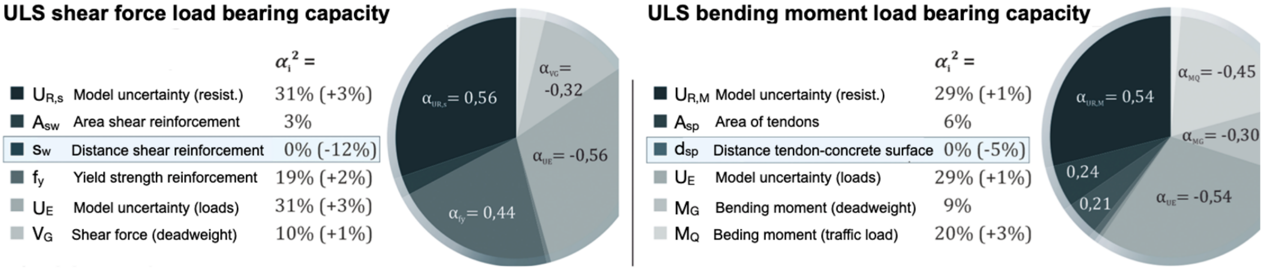

Figure 11. Results of a sensitivity analysis for the shear (left) and bending moment load bearing capacity (right) during the reassessment of an existing prestressed bridge by Küttenbaum et al. (translated) [30].

practical examples for the use of data in the reassessment process were published in [2, 29, 30]. Structural inspection processes are, e.g., the localization of rebars and tendons, the determination of the cross-sectional thickness, the estimation of concrete strengths, the detection of corrosion or the investigation of the injection status and of the applied forces to the tendons. Figure 10 shows the use of bridge access technology and the application of scanning equipment on a bridge. The red lines in Figure 10 display the longitudinal tendons in the web over a length of about 12 meters. The measurement technique and an approach for the validation of their results were presented in detail by Küttenbaum in [33].

Methods to quantify uncertainties during the measurement are crucial for the calculated reliability of the structure. Parameter studies and sensitivity analysis inform about the influence of each sensitivity factor. Figure 11 displays the results of a sensitivity analysis of the load bearing capacity for shear and bending moment of an existing bridge based on measured data. The numbers in brackets display the change compared to the results of the sensitivity analysis without the implementation of the measurement data, see [30]. As seen on the left side, the sensitivity of the distance of shear reinforcement changes significantly with the implementation of the on-site results.

The limit state functions should be formulated to include as many data from the measurement as possible. A sensitivity analysis is able to show the influence of the results of the non-destructive testing on the reliability index of the structure. How to quantify the complete inability to measure a certain parameter during the probabilistic calculation is still a key question in this context. Possible aspects of the decision-making process are shown in [34]. Whether the data from individual measurements can have an equivalent significance as the well-known normative load models is another aspect which must be addressed more detailed. Requirements to the equipment or the qualification of the personal can ensure accurate data. However, a standardized framework for the calculation of structure-specific partial safety factors is needed and will be topic of future research. The goal is to propose a guideline aimed at practical engineers, that can be used for a more realistic reassessment of existing bridges based on measured data, but without the need for a full-probabilistic calculation.

5. Conclusions

This paper presents the German concept for the reassessment of existing bridges and the practical implementation of the latest research during the reassessment process. Many existing structures have reserves in their load bearing capacity. The guideline for the assessment of existing bridges includes four stages to evaluate the reliability of a bridge. With each step the effort increases and modifications in the calculation methods are added. Probabilistic calculations have potential and advantages, but they are only used for some special cases because of their complexity. The successful use of probabilistic methods is shown on the example of the Barkauer crossing in Kiel. The example of Heinrich's bridge in Bamberg presents the implementation of data from on-site measurements to calibrate a structure-specific load model. The costs for maintenance work are reduced with the use of a structure-specific load model.

Structure-specific partial safety factors combine an individual reassessment of existing bridges, the use of the familiar and efficient semi-probabilistic reliability concept and the implementation of measurement data. Even though a general modification of partial safety factors is allowed by existing regulations, there is no normative standard to obtain structure-specific partial safety factors. A standardized process is important for the practical use and for the comparability of the results. The structure-specific partial safety factors can be used by practical engineers to perform a reassessment of existing bridges based on the semi-probabilistic reliability concept and including additional information from on-site measurement and testing. With this approach, a more realistic analysis is possible and the service lifetime of existing bridges can be extended after the assessment. Proposals for a standardized guideline regulating the data-based reassessment process with structure-specific partial safety factors are therefore aspired for an increased efficiency during the reassessment process and for a better sustainability due to the preservation of the existing infrastructure.

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