Recent Findings of the Research Project “ZfPStatik” on Inspection-Supported Reliability Assessment of Existing Bridges in Germany

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Abstract

Aging materials, growing traffic demands, changing environmental influences, and constrained budgets influence the evaluation of the load-bearing capacity and foster the need for reserves in the load-bearing capacity of existing structures all around the world. It is imperative to ensure the ongoing operation and maintenance of road infrastructure from both economic and sustainability perspectives. Using data from on-site inspections and measurements can significantly enhance the accuracy of reliability evaluations and structural assessments, leading to more realistic analytical outcomes. As the need for a practical and standardized approach is recognized, a dedicated research project was initiated to develop a systematic methodology for the reliability analysis of existing bridges based on non-destructive testing (NDT) data.

This contribution presents key elements of a national draft recommendation for action regarding inspection-supported reliability analysis in Germany, developed under the German collaborative research project “ZfPStatik”. The proposed guideline integrates the benefits of semi-probabilistic and probabilistic assessment concepts by enabling the use of measured data within the partial factor approach. It covers the entire process, from the purposeful definition of inspection strategies, through the quality assessment of measurement information, to the partial factor-based evaluation incorporating quality-assessed on-site results. A particular focus is placed on broader utilization of NDT methods for verifications in both the ultimate limit state and the serviceability limit state in practical engineering. By linking on-site measurements directly to structural verifications, the guideline aims to enhance transparency, consistency, and the practical usability of reliability assessments, contributing to a maintenance strategy for existing bridge infrastructure. The applicability and advantages of the methodology are demonstrated through several case studies involving typical existing prestressed concrete bridges.

Keywords: reliability analysis; existing concrete bridges; non-destructive testing; NDT; probabilistic; partial factor; ZfPStatik

1 Introduction

Transport infrastructure in Germany and worldwide is suffering from increasing traffic loads and the continuous aging of existing structures. For many structures, especially bridges, the permissible loads must be restricted or, in many cases, replacement of the structures must be planned. However, the existing structures often still have significant safety reserves. Currently, these theoretical reserves cannot usually be utilized in the recalculation of existing structures, as information about the actual condition of the structure is often lacking. Moreover, there are currently no standardized rules for the explicit use of on-site inspection and measurement results in structural analysis. As a result, many structures are subjected to premature usage restrictions or even dismantlement and replacement. The goal of the project “ZfPStatik” is the development of a standard for the assessment of existing structures using non-destructively measured data, based on the commonly used and practically established semi-probabilistic verification method. This involves the development of a harmonized guideline that addresses both measurement techniques and structural analysis, connected via a consistent interface process. The outcomes are intended to be published in the German Committee for Reinforced Concrete (DAfStb) “Green Book” series. By applying the new standard, measured information can be used to reduce uncertainties in the assessment of existing structures without compromising the required reliability level of established codes as the calculation is based on actual measurement data. The approximation of the calculation models to the reality increases. As a result, existing infrastructure can be used for longer periods or even under higher loads. The efficiency and sustainability of the reassessment of existing structures is enhanced by this new methodological approach, which may also result in the creation of a portfolio of new services with high export potential for engineering firms. This paper aims to present key elements of the German collaborative project “ZfPStatik” (translation: ZfP → NDT, Statik → structural assessment) for a recommendation for the reliability analysis of existing bridges using data from non-destructive testing (NDT).

2 Research project “ZfPStatik”

The project started in August 2022 and is scheduled for completion in mid-2025. The project has an interdisciplinary approach for the development of the standardized framework. Given the considerable number of partners with different areas of expertise and locations, efficient project coordination and regular communication are essential. Figure 1 illustrates the collaboration between multiple partners from both academia and industry, engineering firms, and a standardization body. By combining expertise in structural assessment, non-destructive testing, and code development, the project aims to ensure strong practical relevance and broad applicability.

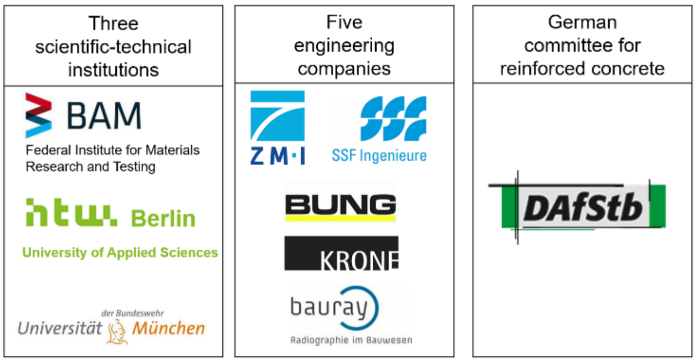


Figure 1: Institutions and associated project partner of “ZfPStatik”

The workflow integrates both semi-probabilistic engineering methods from the design offices and full-probabilistic modeling more frequently used in research to improve the accuracy and for parameter studies, while maintaining compliance with established semi-probabilistic verification procedures. Initially, representative reinforced and prestressed concrete bridges are selected and assessed based on available documentation and conventional calculation methods, see section 3. These assessments are expanded through probabilistic modeling to better account for uncertainties and to establish reference models. Based on these models, critical parameters affecting structural reliability, serviceability, and durability are identified with sensitivity analysis and parameter studies. This creates inspection tasks and leads to the selection of appropriate NDT methods. Subsequent aspects focus on evaluating the technical feasibility and reliability of selected NDT methods. To ensure comparability of results, standardized test instructions are developed. These include guidelines on procedure selection, performance verification, uncertainty quantification, and personnel qualification. The data from the measurements are then incorporated into the statical calculations and structural models, allowing both deterministic and probabilistic analyses to be updated based on the measurement data.

A central aspect of the project is the integration of measured data into the structural verification by modification of partial factors. The measurement or test result must be determined in accordance with test instructions and measurement plans suitable for the intended purpose. The result can either be explicitly incorporated (as a random variable) into a probabilistic calculation or be used within a semi-probabilistic verification through the derivation of characteristic values and the modification of partial safety factors. Since full-probabilistic verification requires expertise in probability theory and, due to a lack of stochastic modeling guidelines, the comparability of the results with target values is often not ensured, such a verification is only carried out in exceptional cases. Instead, verification methods using partial factors are commonly used to demonstrate that none of the relevant limit states is exceeded in any decisive design situation when using the design values for actions or their effects and for resistances. Based on several existing approaches [1 – 4] the modification of the partial factors based on the available information from the NDT testing is shown through different case studies. These modification procedures are based on adjusting one or more of the input parameters to the partial factors. With different parameter studies, the benefits of incorporating measurement data into the reliability assessment process are shown.

A practical guideline is currently prepared for publication in accordance with standardization requirements. It is intended for publication in the DAfStb “Green Book” series, forming the foundation for future regulations in the field of NDT-supported reliability assessments of existing structures.

3 Recommendation for action document

3.1 General structure and content

The guideline describes a methodology for the utilization of results from non-destructive testing (NDT) in the structural reassessment with a focus on existing prestressed and reinforced concrete bridges. Verified and quality-assured measurement data is integrated into structural calculations through the structure-specific modification of partial factors and characteristic values derived from the measurements. With this approach, the actual condition of the structure can be more accurately represented in the assessment process. The primary objectives are to (a) provide an efficient method for the NDT-supported reassessment, (b) highlight the potential of NDT in addressing key questions relevant to the reassessment of existing structures, and (c) demonstrate the added value of NDT in structural evaluations. A core focus is on the development of a shared interdisciplinary understanding: On the one hand to introduce NDT as a practical tool to structural engineers and on the other hand to present the field of structural reassessment as a key application area to NDT professionals. Additionally, this publication serves as a source of inspiration for the continued development of infrastructure preservation strategies. The document addresses common non-destructive testing (NDT) tasks for concrete bridges in Germany. A key focus is on the detection and localization of reinforcement and prestressing steel, which is particularly valuable when existing documentation is incomplete or missing. The detection of damage and continuous monitoring are not examined in detail. The guideline concentrates on the resistance side of structural verification. A possible modification of the actions would need to be considered separately. The document is structured with main sections on the general methodology, specific guidance on the application and capabilities of non-destructive testing (NDT) in structural reassessment and six case study bridges. The process for a structure-specific modification of partial factors based on non-destructive testing results is described for a general use and the six consistently structured case studies illustrate the practical application and benefits of the NDT-supported structural reassessment. Figure 2 shows the table of content of the document. The frequent testing tasks addressed in the guideline are, e.g. the determination of the internal and external geometry of structural components, the detection and localization of reinforcement and tendons as well as the estimation of concrete compression and tensile strengths.

Figure 2: Preview of the table of contents of the planned guideline

In the first step, the input parameters relevant to the structural verification are identified. Their relevance may be indicated by missing as-built drawings, by insights from previous assessments, or by additional sensitivity analyses. In the second step, it is examined whether these key parameters can be measured in a physically, technically, and economically feasible way. For each parameter intended to be measured on-site, a corresponding inspection task must be defined. This includes specifying the target quantity, personnel, testing location, timing, inspection interval, and equipment to ensure the inspection process is reproducible. In the third step, the quality of the measurement or testing results is assessed before they are finally incorporated into the structural reassessment.

3.2 Identification of relevant and measurable parameters and definition of measurement tasks

Starting point for the NDT-supported reassessment is often an unsuccessful verification according to the German national Guideline for the reassessment of existing bridges [5, 6] in levels 1 and 2. Furthermore, questionable, inconsistent, or missing structural information from the documentation can be the initial situation for the need of measurements. In such cases, a key question is which information is relevant for the structural analysis. If it is unclear which variable is relevant, sensitivity analyses can be used to gain case-specific insights. The following scenarios can provide indications of when the measurement of a variable is relevant, e.g. required information for the reassessment is missing, available documentation contains inconsistencies, or some variable is known from experience to be important.

Following the identification of the relevant variables, the next step is the selection of the testing method by which a relevant variable can be measured. Relevant criteria that must be taken into account are according to [7]:

- Physical suitability of a measurement principle to solve a testing task (e.g., physical properties of the construction materials that allow the propagation of a certain form of energy),
- Technical suitability of a measurement method to solve a specific testing task on the specific component (e.g., accessibility of the measurement area, surface characteristics, availability of suitable sensors and evaluation methods, reliability of the test result),
- Economic feasibility (e.g., size of the measurement area in relation to the measurement grid, time required for measurement and evaluation, impact on traffic flow).

In the context of concrete structures, the following measurement quantities may be relevant: component thickness (external dimensions of the structural element), lateral position of the reinforcement bars, diameter of the reinforcement bars, detectability of the reinforcement bars and material strength. Remarks for common testing tasks are included in the guideline, e.g. the determination of the internal and external geometry of structural components, the detection and localization of reinforcement and tendons as well as the estimation of concrete compression and tensile strengths.

To obtain a reliable test result, an appropriate testing strategy is essential. The strategy is either specified by standards and regulations or should be defined in scenario-specific inspection procedures. The specific measured variables and measurement locations are determined first, based on the variables, that are both of interest and can be measured, and of the critical cross-sections to be assessed. Depending on the temporal variability of the measured variable as well as the boundary conditions of the structure, the timing and intervals between on-site inspections must also be carefully selected.

The effort expended on creating and following an inspection procedure is justified by the added value of a *quality-assured* acquisition of the actually *desired* information. This is particularly important for service providers operating with divided responsibilities (e.g., separate personnel for execution, evaluation, and documentation), as complete information not only enables reproducibility but also minimizes missing data and uncertainties during assessment. In this way, reliable test results can be substantiated and verified. While the inspection procedure is intended to contain all information necessary for the testing personnel to perform and evaluate the test, measurement plans serve as communication tool between all parties involved in the NDT-supported reassessment. Measurement plans, which are execution plans for the actual testing activities, represent a central outcome of the strategy development phase. Here, a responsible person must be designated and both structural and measurement-related aspects are compiled (e.g., the respective inspection procedure should be linked). Depending on the structure and the scope of measurements, existing documents should be supplemented at least with information on the testing task, the measurement method, the location and extent of the measurement, access paths and required access technology, traffic safety measures as well as responsibilities and scheduled dates.

3.3 Use of the measurement results for the reassessment and modification of partial factors

For the assessment of existing structures, the coefficient of variation of a basic variable based on on-site inspections can be determined through measurement uncertainty considerations. If this value deviates from the value assumed in the safety concept of the applicable design standard, there is the possibility of the modification of the partial factor while still maintaining the required reliability level. In general, a lower coefficient of variation results in a lower value of the partial factor. On the other hand, if measurements on the structure reveal that the actual variability is greater than that assumed in the standard, this indicates the need to adjust the partial safety factors to less favorable (i.e., higher) values than those specified in the codes. In such individual cases, this may also create the need for more in-depth investigations of the structure. Depending on the selected probability distribution of a basic variable, the modification of the partial safety factors for resistances can be carried out for example by using equations Eq. (1) or (2) with the mean value m and coefficient of variation V determined from the measurement results. Eq. (1) can be used for normal distributed variables and Eq. (2) for log. normal distributed variables. While other distribution functions are possible, N and LN distributions are the ones most encountered for resisting quantities in structural engineering. In principle, the value of a partial factor depends on the target reliability index β, the type of distribution of the respective basic variable X_i, the quantile value of the characteristic value (represented by the factor k), the coefficient of variation v_x of the basic variable, and the sensitivity factor α_i of the variable.

$$\gamma = \frac{1 + k \cdot V_x}{1 - \alpha_i \cdot \beta \cdot V_x} \tag{1}$$

$$\gamma = \frac{m_x \cdot \exp(-k \cdot V_x - 0{,}5 \cdot V_x^2)}{m_x \cdot \exp(-\alpha_i \cdot \beta \cdot V_x - 0{,}5 \cdot V_x^2} \tag{2}$$

Documents like the Bulletin 80 [1], Model Code 2020 [2], DBV-booklet 24 [3] and prEN 1992-1-1:2023 [4] provide procedures for these modifications based on this conceptual framework. The modification of the partial factors is based on a modification of one or more or the aforementioned input parameters. Fib bulletin 80 and fib model code 2010 define the partial factor γ_M for materials as the product $\gamma_M = \gamma_{Rd1} \cdot \gamma_{Rd2} \cdot \gamma_m$. For the partial factor of the reinforcement material, the values of $\gamma_{Rd1} = 1{,}025$ for the model uncertainties and $\gamma_{Rd2} = 1{,}05$ for the uncertainty of the reinforcement position are given. For the calculation of a 5%-quantile value of a normal distributed variable the factor k of -1,645 is to be used. The fib bulletin 80 assumes $V_x = 0{,}05$ for the reinforcement in a new structure, which leads (with $\alpha_R = 0{,}8$ and $\beta = 3{,}8$) to $\gamma_m = (1 - 1{,}645 \cdot V_x) / (1 - \alpha_R \cdot \beta \cdot V_x) = 1{,}08$ accounting for the variability of the material and statistical uncertainties. With these input parameters, the partial factor for the reinforcement results in the value of $\gamma_M = 1{,}025 \cdot 1{,}05 \cdot 1{,}08 \approx 1{,}15$.

The prEN 1992-1-1:2023 [4] contains an approach, where one single coefficient of variation for the resistance V_{Rs} is used for the partial factor modification and additional factors μ_d and $\mu_{\theta s}$ cover systematic deviations. A beneficial feature of this code regulation is the consistent specification of the variation parameters for an effective depth of 200 mm and that the values need to be adjusted for other geometries. This represents a theoretically consistent regulation, since the standard deviation of the rebar position is studied in most datasets and for different mean values of the effective depth a constant standard deviation would result in a varying coefficient of variation (CoV). Figure 3 shows an example for the value of a modified partial factor γ_s of the steel reinforcement for different variation in the vertical position of the rebars (defined via the effective depth).

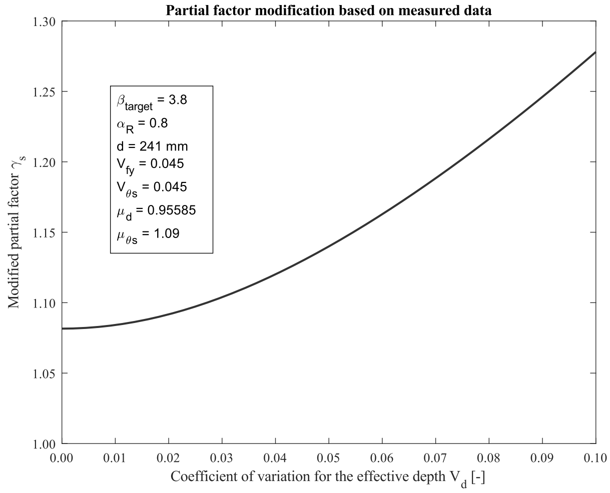


Figure 3: Example for the modification of the partial factor over the coefficient of variation for the effective depth V_d of a concrete slab (updated from [8])

The verification methods with partial factors are commonly used to demonstrate that none of the relevant limit states is exceeded in any decisive design situation when using the design values for actions or their effects and for resistances. The adjustment of the partial factors directly affects the verifications and, as a result, has an immediate impact on the usability and structural safety of the structure. Depending on the modification based on the measurement, this may lead to restrictions, continued use without intervention, or the need for structural strengthening measures. It should be highlighted that, in addition to the change in partial factors, the modified characteristic value has a comparably significant influence on the assessment outcome. For example, the vertical position of a tendon or reinforcement affects the effective depth of a structural component. An increased effective depth has a beneficial effect on structural verification. In contrast, a reduced effective depth results in a smaller load-bearing capacity.

4 Included case study bridges

4.1 Overview

Six case studies are used as representative examples for existing concrete bridges in Germany. These bridges were selected at the start of the project and are used to demonstrate the method on actual structures. The selected road bridges have one to four spans and total lengths of 5 to 133 m. The cross-sections are slabs, T-beams, and a hollow box girder. Figure 4 shows pictures of the bridges used in the "ZfPStatik" project and the following sections provide more details.

Figure 4: Investigated bridge structures within "ZfPStatik"-project, updated from [9]
case study #1: Single span, prestressed concrete bridge with precast T-girders (section 4.2);
case study #2 and 3: Smaller reinforced concrete frame bridges with one or two spans (section 4.3);
case study #4: Prestressed concrete bridge over four spans with T-beam and two main girders (section 4.4);
case study #5: Prestressed concrete bridge with a hollow box girder cross section over three spans (sec. 4.5);
case study #6: Single span, prestressed concrete bridge with T-beam and two main girders (section 4.6)

4.2 Case study #1: Single span, prestressed concrete bridge with a cross-section of precast T-girders

This existing concrete bridge was constructed in 1978. Its superstructure consists of six precast T-girders connected by a 25 cm thick cast-in-place concrete layer. During the statical reassessment, deficiencies were identified in both the ultimate limit state (ULS) and the serviceability limit state (SLS). The verification of decompression was achieved by considering the tensile strength of concrete during assessment stage 1, ensuring that the compressive stress remained within the range $0 < \sigma_c < f_{ctk,0.05}$. Figure 5 shows the cross-section of the superstructure.

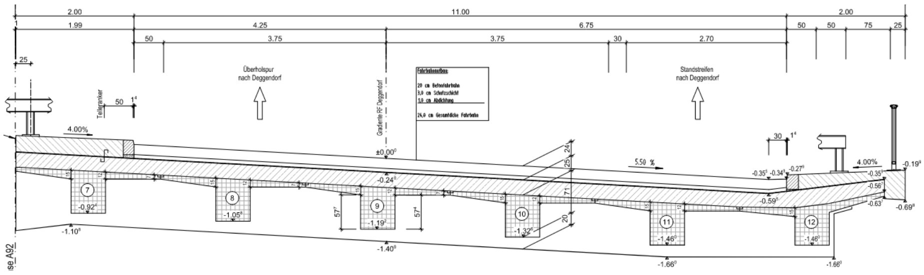


Figure 5: Cross-section of the case study bridge #1

Each precast element contains three tendons, and their exact horizontal and vertical positions were modeled in the finite element analysis, see right side in Figure 6. Measurements support the structural analysis and are used for confirmation of key assumptions. Given the high level of utilization in the decompression proof, the exact positions of the tendons were defined as on-site measurement task. Furthermore, the stirrup spacing and the locations where stirrup density changes along the longitudinal direction of the bridge were measurement tasks for the verification of shear forces. In addition, the concrete strength is relevant for estimating the tensile strength of the concrete and was assessed during the project. Figure 6 shows the used 3D finite element model of the bridge on the left side.

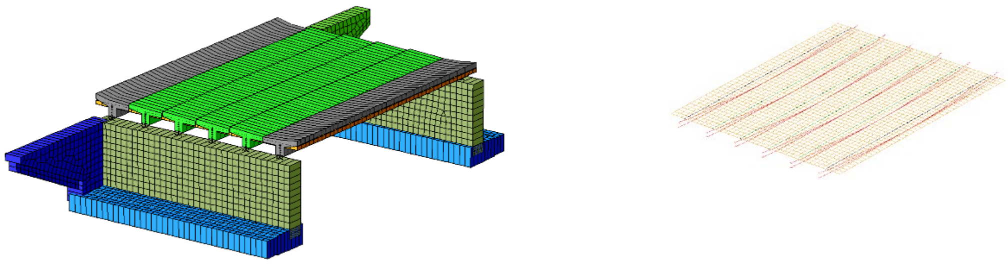


Figure 6: Finite element model (left) and implemented tendons (right) for the case study bridge #1

Simultaneously a full-probabilistic analysis is conducted. The limit state functions g(x) generally include the basic variables, which are predominantly modeled stochastically and represent resistance variables R and actions E. The limit state functions can be derived based on the mechanical relationships provided in the Eurocodes for various limit states and describe potential failure modes. A detailed description of the stochastic models used for this case study is given in [10,11]. The steep gradients of the reliability index β in relation to potential changes in the mean values $\Delta\mu_{dsp}$ shows that the mean value has a significantly greater individual influence on the reliability index β than changes in the corresponding variation parameter. A higher position of the tendons, which equals an increase in the distance of the tendon to the bottom side of the beam d_{sp} and a reduced structural height, has a negative effect on the structural reliability as the reliability index β decreases (visible in the left side of Figure 7). In this specific case, a change in the variation parameter of the tendon position Δv_{dsp} has almost no impact on the reliability index β (see Figure 7 right). This indicates for this structure, that the actual position of the tendons, which means the correctness of the measurement, is more important than the measurement accuracy. The horizontal line in Figure 7 indicates the required target reliability index of $\beta_{target} = 3{,}80$.

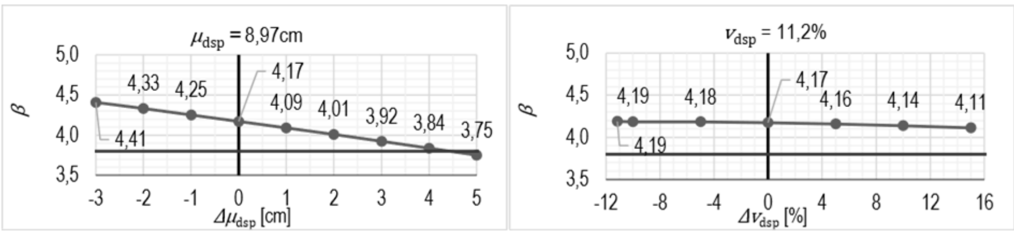


Figure 7: Parameter study for the influence of changes in the tendon position on the reliability index β (left: mean value $\Delta\mu_{dsp}$, right: coefficient of variation Δv_{dsp}), extracted from [11]

The planned on-site inspections were performed during the project and measurement results are available for three girders (no. 9, 10, and 12). Generally, there is good agreement between the position of the tendons from the plan documents and from measurement, see Figure 8. The deviations between the planned and measured tendon position range from 0 to 40 mm, with a tendency of the tendons being located slightly lower than assumed based on the as-built drawings. The results of the measurements are incorporated into the structural analysis, which has a favorable effect on the structural verification, as the effective height of the beam increases. In midspan location, the tendons are positioned lower than indicated in the as-built documentation with a mean deviation of $\Delta\mu_{dsp}$ = - 2 cm, which increases the reliability index β from 4,17 to approximately 4,33.

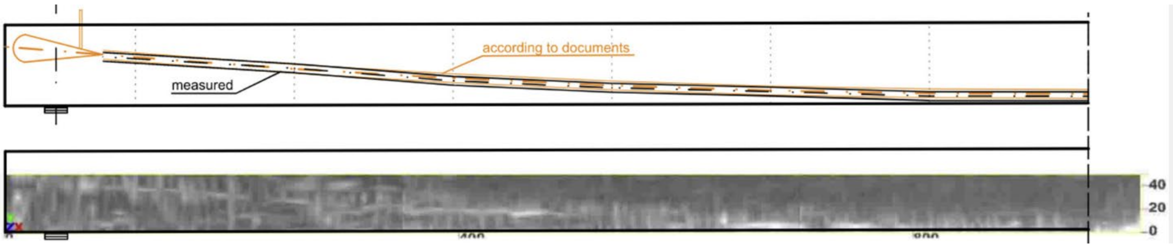


Figure 8: Comparison of the tendon position according to plan and NDT (top) and imaging of the centre tendon (bottom), extracted from [12]

4.3 Case study #2 and #3: Smaller reinforced concrete frame bridges with one or two spans

These two case-study bridges are located along a highway in southern Germany and represent typical existing frame bridges with smaller spans. The reinforced concrete bridges were constructed in 1985 and 1986, respectively. They are designed for traffic loads corresponding to Bridge Class 60, as defined in DIN 1072:1967-11 [13]. The first is a single span reinforced concrete bridge, see Figure 9 left. The thickness of the reinforced concrete slab increases to 0,45 m towards the centre of the span. The load from the abutments, which have a thickness of 0,60 m, is transferred into the subsoil via a 0,75 m thick base plate. The second case study, Figure 9 right, is a two-span reinforced concrete bridge as a closed frame with rigid connections to the abutment walls. The superstructure has a skewness angle of 80 degrees. Each span has a length of 7,43 m resulting in a total length of 14,86 meters. Both structures are modelled with a three-dimensional finite element surface model using *INFOGRAPH* Software, see Figure 9. While most of the large bridges have specific names in Germany, many of the smaller bridges are just identified by specific numbers, e.g. continuously within a given section of the road. The two present case study bridges (German: "Bauwerk", short: "BW") are called BW81/2 and BW79/1.

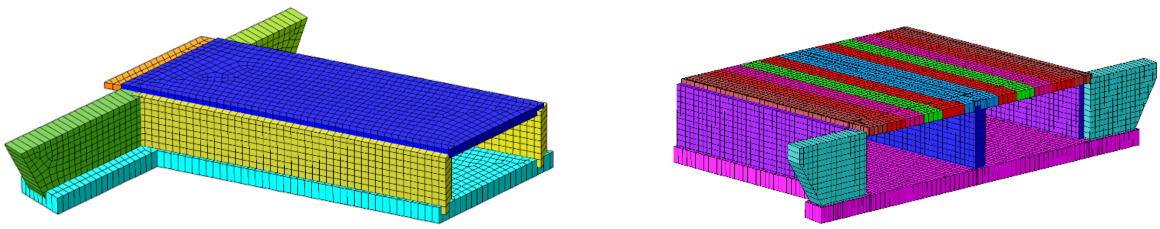
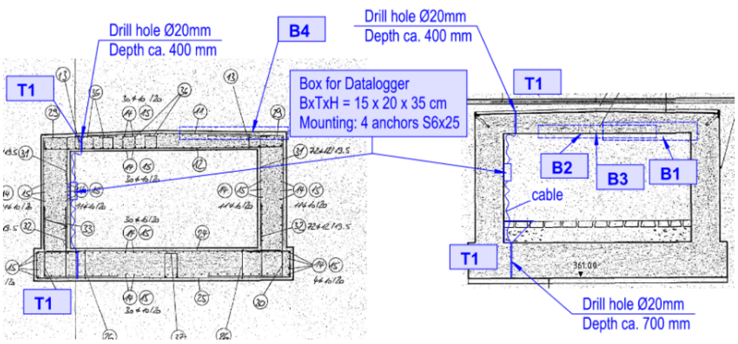


Figure 9: Finite element models of the two case study bridges (left: bridge "81/2"; right: bridge "79/1")

For the full probabilistic assessment, the First Order Reliability Method (FORM) and the commercial software *STRUREL* are used. A detailed description of the modelling and calculation is included in [14]. Based on the results from the semi-probabilistic and full-probabilistic calculations, a measurement campaign on the existing structure was planned and conducted. Measurement plans are important tools for the measurement and are created collaboratively by all involved project partners (engineering company, measurement specialists and probabilistic assessment personnel). Figure 10 shows excerpts of the measurement plan.



ID	Testing task	Object	Method
B1	Localization of reinforcement	Shear reinforcement	Radar
B2	Localization of reinforcement	Longitudinal reinforcement midspan bottom	Radar
B3	Localization of reinforcement	transversal reinforcement midspan bottom	Radar
B4	Localization of reinforcement	Longitudinal reinforcement frame corner upside	Ultrasonic
T1	Temperature measurement	Superstructure + Abutments	Temperature sensor

Figure 10: Example for a measurement plan for the case study #2

While long-term monitoring of actions is not typically within the scope of NDT, it is highly relevant in this case as the constraining forces highly influence the reliability index of this frame bridge. The measurement is described in more detail in [15]. As another testing task, the detection of the reinforcement (geometry and position) with GPR from the bottom side of the superstructure is carried out by the project partner Bundesanstalt für Materialforschung und -prüfung (BAM). Exemplary measurement results are displayed in Figure 11.

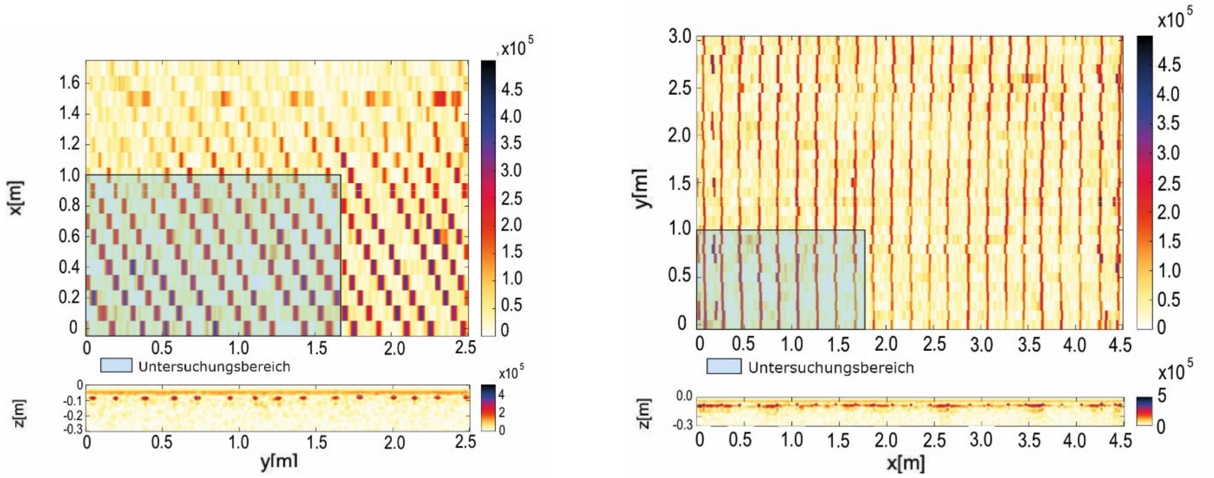


Figure 11: Examples for the detection of the bottom reinforcement in the superstructure of the case study bridges; detected by radar, visualized and measured by the Bundesanstalt für Materialprüfung und -forschung (BAM)

Based on the results, a modification of the partial factors for the reinforcement is carried out. The variation of the effective depths varies between 1,3% and 2,1% (depending on the verification point under consideration), which leads to modified partial factor of $\gamma_s = 1{,}07\ldots1{,}13$ instead of $\gamma_s = 1{,}15$.

4.4 Case study #4: Prestressed concrete bridge over four spans with a cross-section of a T-beam with two main girders

This case study bridge was constructed in 1981 and carries a federal road over a lake in northern Germany. It represents a large prestressed concrete road bridge constructed with cast-in-place technology and complex geometry. The as-built documentation includes structural safety verification and execution drawings from the time of construction. The bridge was designed for traffic loads of bridge class 60 in accordance with DIN 1072 [13]. The four-span, skewed, and horizontally curved bridge structure features a prestressed concrete superstructure with longitudinal and transverse post-tensioning. The individual span lengths are 21,53 m – 28,28 m – 27,75 m – 20,39 m for the northern main girder and 19,96 m – 27,07 m – 27,31 m – 20,41 m for the southern main girder. The deck slab was constructed with linear varying thickness depending on the span width (31 to 40 cm in the mid-span area and 45 to 55 cm at the connections to the main girders). The span width between the slab edge and the main girders varies from 14,00 m at the western end to 8,25 m at the eastern end of the bridge. Figure 12 shows the cross section with the tendons (left) and the top view of the bridge (right). The verification location investigated in lateral direction is highlighted with the red circle.

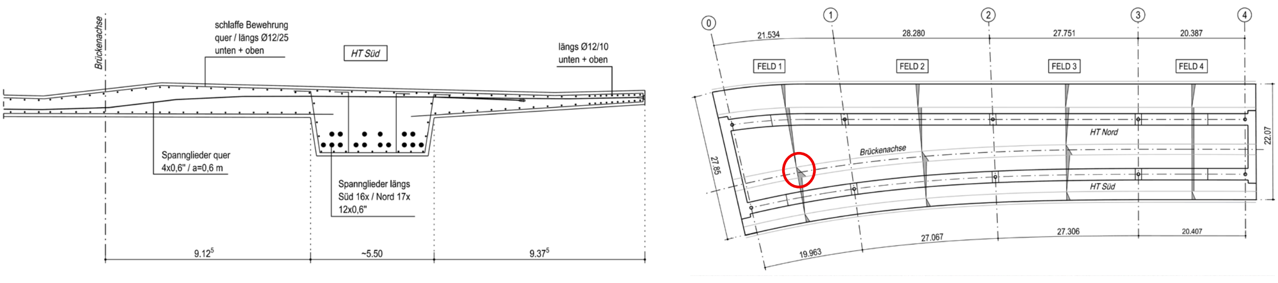


Figure 12: Cross section with tendons (left) and top view (right) of the case study bridge #4 (unit of all lengths: [m])

The bridge was built using concrete grade B 45 with $f_{ck} = 35$ N/mm², reinforcing steel BSt 420/500 with $f_{yk} = 420$ N/mm² and prestressing steel St 1570/1770 with $f_{pk} = 1770$ N/mm². The reassessment is carried out in accordance with the German guideline for the reassessment of existing bridges [5, 6], including verifications in the ULS (ultimate limit state, excluding fatigue) and the SLS (serviceability limit state). For comparison purposes, the structural analysis is performed for both the target load level LM1 according to DIN FB 101 [16] and DIN FB 102 [17], as well as for the target load level LMM in accordance with DIN EN 1991-2 [18] and DIN EN 1992-2 [19]. As a result, deficiencies were identified, among others, in Span 1 of the deck slab in the verifications of bending and axial force, decompression, and concrete compressive stresses. Figure 13 shows the utilization ratio $m_{Ed,y} / m_{Rd,y}$ for a reassessment of the deck slab in Stage 1 for a target load level LMM according to DIN EN 1991-2 and DIN EN 1992-2 verification of bending and axial force in the relevant location of span 1.

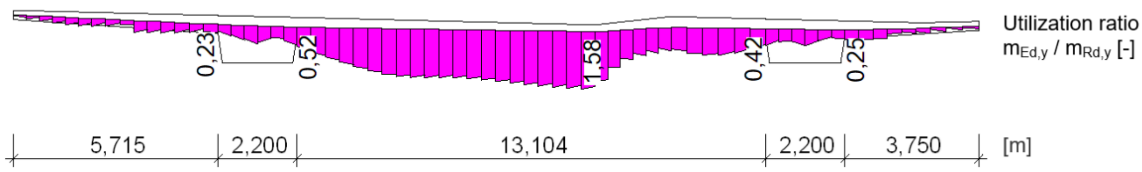


Figure 13: Utilization ratio $m_{Ed,y}$ / $m_{Rd,y}$ for the reassessment of the deck slab; verification of bending and axial force (highlighted location of span 1; reassessment Stage 1; target load level LMM according to DIN EN 1991-2; verification according to DIN EN 1992-2)

An additional full-probabilistic analysis and parameter studies are performed. The position of the tendons is one of the most important parameters for this case study. Figure 14 shows the parameter study for the mean value and standard deviation of the distance of the tendon to the bottom of the slab. In the middle of the span, a lower position of the tendons, which equals an increased structural height and a smaller value of the distance of the tendon to the bottom of the slab d_{sp}, has a positive effect on the structural reliability as the reliability index β increases, see Figure 14. In this specific case, a change in the standard deviation of the tendon position $\Delta\sigma_{dsp}$ also has noteworthy impact on the reliability index β. This indicates that the measurement accuracy and correctness are both important for this rather slender part of the structure. After the measurement of the actual tendon position, a reliability index based on the actual geometric situation can be calculated.

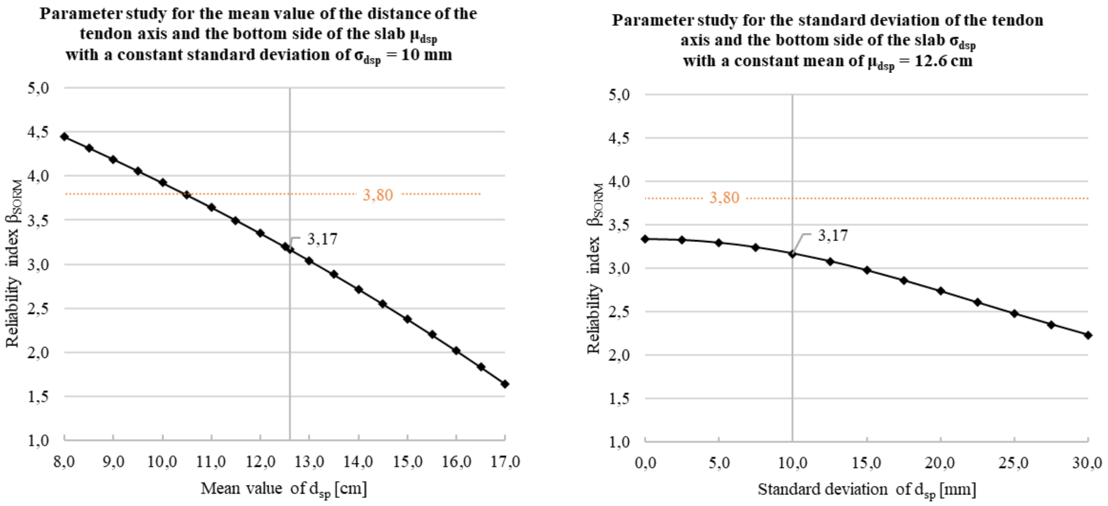


Figure 14: Parameter study for the influence of the distance of the tendons from the bottom on the reliability index β in transverse bridge direction located at span 1

4.5 Case study #5: Prestressed concrete bridge with a hollow box girder cross section over three spans

This case study represents an older, large hollow-box girder bridge from 1965 and carries a Federal Highway over a river in southern Germany. The superstructure is a vouted, three-span prestressed single-cell box girder. The span lengths are 39,0 m – 55,0 m – 39,0 m, see Figure 15. The height of the box-girder is 1,21 m at the ends of bridge, 1,40 m at the center of the middle span and 2,25 m above the piers. The bridge has longitudinal prestressing in the webs and transverse prestressing in the deck and bottom slab. The structure was designed for a traffic load model of bridge class 60 according to the former standard DIN 1072:1952-06 [20] and for military load class 100/50. The concrete grade is B450, which is classified as a strength class of C30/37. For further information on the bridge see references [21 - 24].

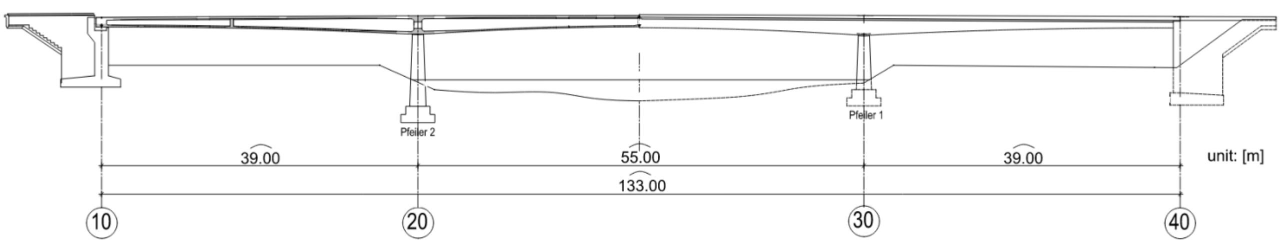


Figure 15: Longitudinal section of the case study bridge #5

The bridge is reassessed according to [5, 6] for load model LM 1 of the DIN Technical Report 101 [16]. In both ULS and SLS limit states, the verification revealed deficits especially in the shear force verifications in support areas. Structural safety could not be proven in the critical areas around the bearings and piers as the utilization rates are significantly greater than 1. Therefore, further analysis based on the main tensile stress criterion was performed. The basis for the formulation of the limit state function is the proposed semi-probabilistic verification format in [25] for the first amendment to the guideline for the reassessment of existing bridges [5]. In the sensitivity analysis, figure 16, the contribution of each parameter is examined and the relevance of their value and variation is shown. The influence of the concrete tensile strength f_{ctm} is predominant, which is expected in this case. Based on this result further testing of the concrete tensile strength was indicated. For the use of the measurement results and the verification of the bridge with the main tensile criterion refer to [24].

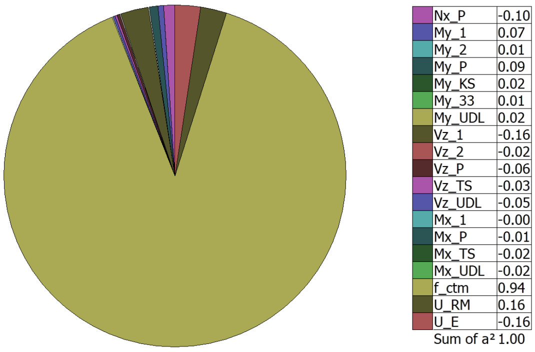


Figure 16: Sensitivity analysis based on alpha-values for the limit state of the main tensile stress criterion, extracted from [24]

However, the probabilistic assessment is primarily used for the determination of relevant parameters instead of the actual reliability assessment in this case study. This case study also highlights the limitations of a measurement data based assessment. Certain boundary conditions of code standards could not be fulfilled, and therefore a verification could not be successfully completed. Furthermore, significant exceedance due to a substantially increased traffic load cannot generally be offset with measurements on the resistance side, e.g. material parameters and geometry. Current verification approaches, that are different compared to the standards at the time of the construction of existing bridges, can also not be met by the measurement of data alone.

4.6 Case study #6: Single span, prestressed concrete bridge with a cross-section of a T-beam with two main girders

The last case study focuses on a prestressed, single-span concrete bridge constructed in the 1970s. The superstructure spans 38,45 m and carries a two-lane federal road across a river. Routine inspections have not revealed any significant damage that would compromise structural safety. The bridge features a T-beam cross-section composed of two main girders, cantilever extensions on either side, and a haunched deck slab. Figure 17 shows the cross section of the bridge. Prestressing is applied in both longitudinal and transverse directions. Due to the slender proportions and cantilevered geometry, the reassessment primarily focused on the transversely prestressed slab. Generally, deviations in the position of reinforcing and prestressing steel have a greater impact on reliability in reassessment of thinner components.

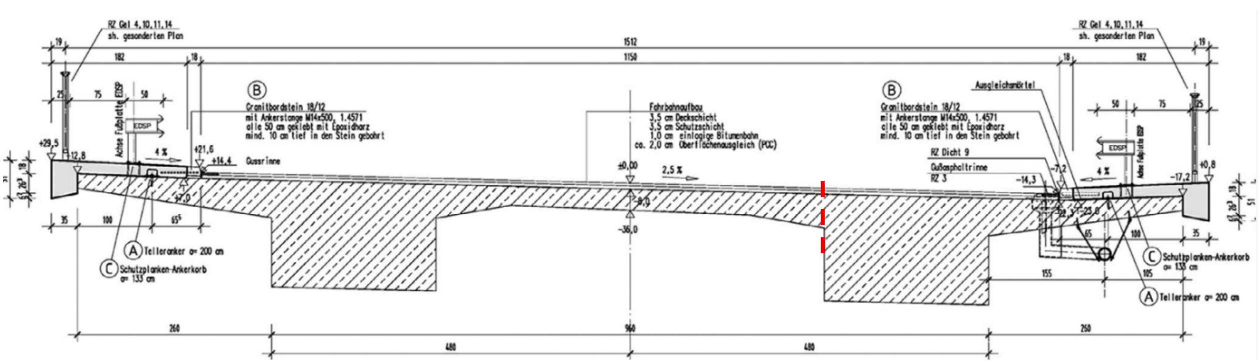


Figure 17: Cross section of the case study bridge #6 with highlighted position of the measurement, updated from [8]

The load-bearing capacity is verified as a first step with a semi-probabilistic assessment. This analysis shows sufficient load-bearing capacity for the decisive sections in the transverse direction. The maximum capacity utilization has been obtained for the slab in the middle of the span (positive bending moment). However, the results at the junction with the main girder (negative bending moment, see red mark in Figure 17) are intended to be assessed as part of the research project. The distance of the tendons from the bottom of the slab is documented by a value of d_{sp} = 24,5 cm in the as-built drawings at the junction cut with the main girder. An increase in d_{sp} equals a higher vertical position of the tendons in this section. A higher vertical position is more favorable for the bending moment bearing capacity against negative moments, because the internal lever arm increases. On-site testing was performed, and the inspection enables a slight reduction in uncertainty to be considered in the reliability analysis. Figure 18 displays the different measurement equipment used on the bridge during the testing.

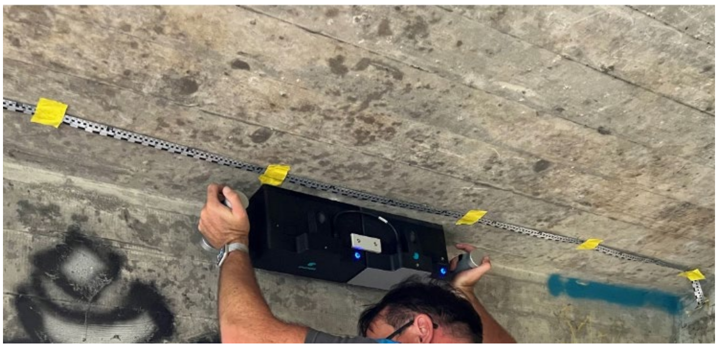


Figure 18: Performance of the measurements with measuring devices based on ultrasonic echo (left) and radar (right)

Generally, the measurement largely confirmed the available information from the documents. The result is a mean value that aligns well with the information available prior to testing. In this case, the position of the tendons d_{sp} is updated based on a measured mean value of μ_{dsp} = 24,1 cm. The standard deviation results in σ_{dsp} = 7,5 mm. Due to the high level of agreement between the as-built documentation (24,5 cm) and the inspection results (24,1 cm), the revised reliability indices and the modified partial factors closely match those used in the initial assessment. A detailed description of the analysis and measurement can be found in [8]. Although the impact on the verification utilization is minor in this case study, this procedure is an important step for verifying design documents and is especially relevant in cases where no as-built documentation is available.

5 Conclusion and Outlook

ZfPStatik is a method for a more realistic assessment of existing bridges. By incorporating non-destructive testing data into the reliability analysis, the calculation results are based on actual structural properties and therefore reflect the real condition of the structure more accurately. This can lead to more favorable outcomes if the actual structure and material characteristics are “better” than originally assumed. Conversely, it may also result in less favorable outcomes and further steps when the on-site conditions are more unfavorable than expected. Given the increasing risk posed by aging infrastructure, it is strongly recommended to evaluate the actual structural situation if possible.

While for a long time the primary focus was on increasing the utilization of existing structures, the priorities within society are shifting towards greater safety demands due to recent accidents. Therefore, this method will increasingly serve to validate the assessment of existing bridges in the future, as it helps to reduce discrepancies between the actual structural conditions and the information provided in the as-built documentation.

With the upcoming finalization and publication of the guideline document, engineering offices and infrastructure owners will be provided with specific guidance for the purposeful application and utilization of NDT methods in structural analysis. The inclusion of practical examples is intended to promote a broad applicability in engineering practice and to contribute to a safer infrastructure.

6 Acknowledgments

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