ce/papers Proceedings in civil engineering

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ORIGINAL ARTICLE

EUROSTRUCT

Guideline on NDT-supported reliability assessment of existing structures - Current developments in Germany

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Abstract

Information about an existing structure can be collected at certain costs to evaluate the reliability and condition as realistically as necessary. This information can be relevant or irrelevant, true or biased, precise or imprecise. The incorporation of relevant and quality-assessed measured information into reliability reassessment offers the chance to extend remaining lifetimes and support decision making about optimal actions or maintenance strategies. This paper shows recent developments in a national research project that aims to produce a guideline on the NDT-based, structure-specific modification of partial safety factors. The general methodology, results from recalculations according to the Eurocodes and metrologically solvable testing tasks relevant in the recalculation of the concrete bridges are shown and compared with the non-destructive testing methods applicable to concrete bridges. A case study is used to demonstrate that as-built drawings, in this case of the positions of tendons and shear reinforcement, can be verified using the radar method.

Keywords

non-destructive testing, concrete bridges, partial safety factor modification

1 Introduction

Increasing loads and sharply rising traffic flows are encountering a European transport infrastructure that has largely reached or exceeded its originally targeted or expected service life. Use restrictions or even renewals are planned for a noticeable number of structures – especially bridges – although the structures often still have considerable safety reserves. However, these numerical reserves usually cannot be utilized in reassessment, among others since information about the actual state of the structure is not available or questioned in many cases. In addition, there are currently no standardized rules for on-site testing and measurements with subsequent, direct use of the measurement results in reliability analysis. Consequently, structures may experience unnecessary, untimely actions such as use restrictions, repair and strengthening works, coinciding with limited availabilities and wasted resources.

The objective of the national pre-standardization project "ZfPStatik" is to develop a guideline for the assessment of existing structures based on results from non-destructive testing at the structure. The document is intended to contain, on the one hand, rules for the targeted application of non-destructive testing methods on concrete structures and, on the other, a developed procedure for the measuring data-supported and structure-specific modification of partial safety factors, in order to establish a sound basis for the explicit incorporation of NDT results in assessment of existing structures. In this way, the potential of NDT methods for a more reliable, economical, and sustainable reliability assessment will be unlocked. This contribution provides an overview of the methodology and of the latest, intermediate project outputs including a) identified non-destructively measurable parameters, which are relevant in reassessment of concrete bridges, b) NDT methods suitable to solve the relevant testing tasks and c) the comparison of the planned and measured position of tendons and shear reinforcement for one of the investigated bridges.

2 Methodology

2.1 Towards NDT-supported partial safety factor modification

The project aims to combine the advantages of the semi-probabilistic and the probabilistic assessment concepts in such a way that measured information can be included in the reliability analysis of existing structures using the partial safety factor approach. A major advantage of probabilistic computations is the possibility to explicitly consider measurement results in the form of probability distributions. The semi-probabilistic approach, in turn, features the economical application, and the comparability as well

ce/papers 6 (2023), No. 5

https://doi.org/10.1002/cepa.2168

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as verifiability of the results. To bring the advantages of both concepts together, instructions are being developed for combining the targeted application of non-destructive testing (NDT) methods on-site with the subsequent (structure-specific, measurement-based) modification of partial safety factors on the resistance side. Methods for the modification can be, e.g., found in [1-2]. It is intended to publish the project outcomes in the series of publications of the German Committee for Reinforced Concrete (DAfStb).

Key steps of the chosen methodology can be summarized as follows:

1. Definition of the demonstration pilots (see sect. 3.1) and of recalculation principles, e.g., target load level, applied stage acc. to the German recalculation guideline [3, 4], etc. (see section 3.2)
2. Identification of the crucial structure parameters, the variation of which significantly influences reliability – based on the semi-probabilistic recalculation results, on accompanying probabilistic analyses, and expert judgements (see sections 2.2 and 3.3)
3. Elaboration of measurement strategies and testing procedures to solve the previously identified issues relevant in the reassessment (see section 3.4)
4. Collection and analysis of the on-site measuring data including measurement uncertainty calculations to quantify the quality of the measurement results with the objective to provide validated information about the structure [5, 6] (first results in section 3.5)
5. Incorporation of the measurement results into the probabilistic analyses (using probability distributions describing the measurand) and semi-probabilistic recalculations (by modifying partial safety factors and updating the respective characteristic values)
6. Publication of the developed and applied procedures and of the findings from the case studies

2.2 Identification of relevant testing tasks

With the aim of defining the demands for measurements or NDT, respectively, in a targeted and efficient way, the relevance of the information required to perform the structural analyses within the scope of the reassessment is investigated through a) semi-probabilistic reassessment results, b) expert judgements, and c) probabilistic sensitivity analyses. The decision basis is the information available prior to any testing, which can be extracted, e.g., from as-built drawings. This information does not necessarily reflect the actual condition and structure characteristics and may be questioned or not comprehensively available.

The sensitivities can be analysed using the First Order Reliability Method (FORM) [7-9]. An example can be found in [5]. Basically, an assessment basis should be selected in which the measurable quantities are included (e.g., geometrical variables such as the shear stirrup spacing; see sect. 3.5). The sensitivity factors (α-values) provide information about the stochastic significance of a basic variable. The collection of new information (through testing) is particularly useful when a measurable basic variable is sensitive (high α-value), since the uncertainty regarding this quantity and the influence on reliability are significant. A more detailed interpretation can be made by including the elasticities, because the benefit of a measurement can be described in terms of any distribution parameter. Since both the elasticities and the sensitivities are the result of a local analysis, i.e., they apply to small changes in the distribution parameters, additional parameter studies are performed. These consist of multiple probabilistic calculations for the individual variation steps of the distribution parameter(s) defined in a certain interval. The reliability index can then be plotted over the varied parameter. In this way, the effects of larger changes in the models can be analysed. It should be noted that the distribution parameters are usually interdependent. For normally distributed quantities, it is however possible to derive the effects of i) larger deviations between the measured ("actual") structure characteristics and the properties according to available documents and drawings and ii) a larger uncertainty reduction based on testing on-site. This combined approach allows for a) the evaluation of the impact of the variation of individual distribution parameters on reliability and b) more global conclusions than sensitivity analyses solely based on the alpha-values.

3 Insights into NDT-supported reassessment

3.1 Investigated structures

In cooperation with the involved engineering companies, a total number of seven existing concrete bridges were selected. Those bridges are typical for the majority of the road bridge stock in Germany. Preferably a variety of parameters like different spans, cross-section or longitudinal systems were intended. Figure 1 shows the location of the structures on the map.

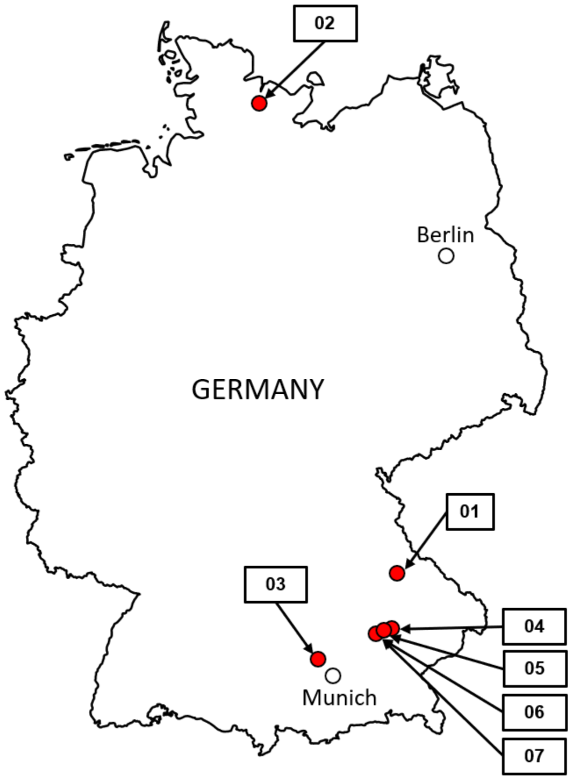

Figure 1 Location of the selected bridges in Germany

All investigated structures are existing concrete bridges built between 1965 and 1986. Their current age thus ranges from 58 to 37 years. Two of them are rather long with a length of 113 m and 96 m, three bridges have a medium length of 15 m to 39 m and two bridges have a rather short length of 5 resp. 8 meters. Considering the statical system in longitudinal direction, four bridges are constructed with differential superstructures: one four-span (02), one three-span (01) and two singles-span superstructures (03, 04). Three bridges are designed as integral frames (05, 06, 07). Table 1 compares the key parameters of the selected structures.

Table 1 Characteristic parameters of the selected bridges

ID	Year of construction	Length [m] (Spans [m])	Cross-section	Material
01	1965	113 (39 - 55 – 39)	Box beam	Prestressed concrete
02	1980	96 (20,4 - 27,5 - 27,5 - 20,4)	T-Beam	Prestressed concrete
03	1971	38,5	T-Beam	Prestressed concrete
04	1978	18,2	T-Beam	Prestressed concrete
05	1985	5,2	Slab	Reinforced concrete
06	1986	14,6 (7,3 – 7,3)	Slab	Reinforced concrete
07	1978	8,0	Slab	Reinforced concrete

Concrete is the material of choice for all investigated structures. Three structures are constructed with reinforced concrete and four structures with prestressed concrete. The bridges also differ regarding their cross-section types – with one box girder, three T-Beams and three slabs. The cross section of the 113 m long three-span bridge is a single cell hollow box girder with variable hight. Additionally, two T-beams with two webs and one T-beam with six webs will be investigated. Fig. 2 shows the simplified cross sections and Figure 3 a picture of each investigated bridge.

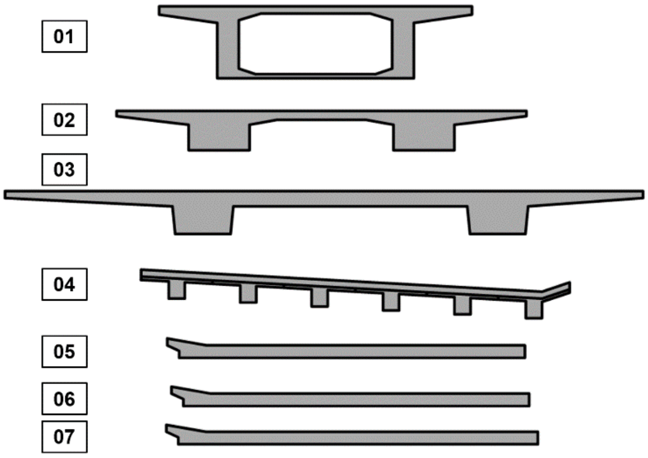

Figure 2 Cross sections of the investigated bridges

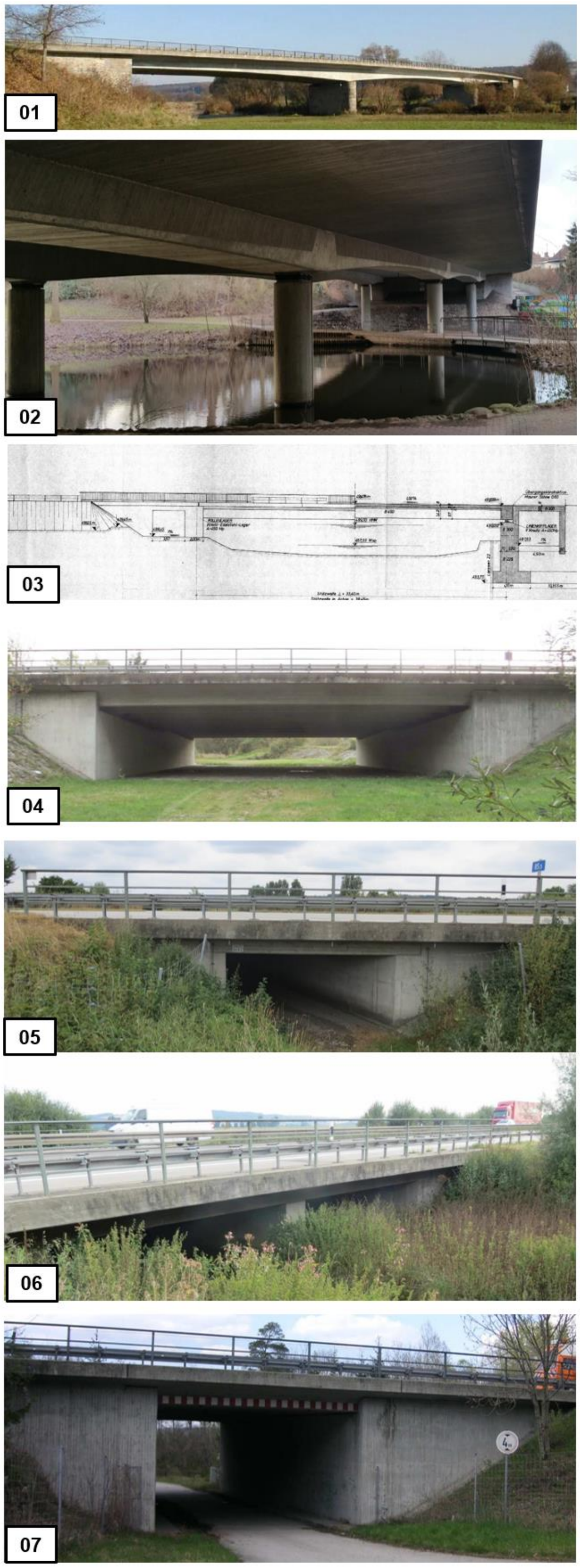

Figure 3 Overview of the selected bridges

3.2 Limit states and calculation principles

Most existing bridges were designed and constructed according to former guidelines. The appreciated knowledge is partly out-dated, design formats have changed, and load models have increased over the years. The German guideline for the recalculation of existing bridges (Nachrechnungsrichtlinie) [3, 4] already provides a standardized procedure consisting of four stages for the reassessment. In the first stage (stage 1), the calculations are performed solely based on the current regulations of the Eurocodes or of the German technical reports for bridges (German: DIN-Fachbericht). Further specific regulations and additional methods can be used during a stage 2 assessment. While the regulations of stage 3 do allow further options for the reassessment process, like the use of monitoring data, there is no standardized process for the extent of the performance and for the use of in-situ measurements in the statical calculation so far. Therefore, the objective of the national pre-standardization-project "ZfPStatik" is the development of a guideline for the assessment of existing structures based on results from non-destructive testing at the structure. While the serviceability limit state or fatigue are important aspects during the assessment process of existing structures, the load bearing capacity has a superior importance. Therefore, the project focus is on the ultimate limit state calculations, especially regarding bending moments, shear forces and torsional forces.

At first, the regulations of stage 1 and 2 of the guideline for the assessment of existing bridges are used for the statical calculations of the selected bridges. At this point, no on-site data from measurements is considered in the analyses. The calculations are based on information extracted from construction plans or other available documents and the semi-probabilistic safety concept is applied. The traffic load models are defined according to the recalculation guideline. Depending on the daily traffic intensity of the heavy-load traffic, the necessary load model is predefined, e.g., the current LM1 according to Eurocodes or the previous German technical reports, or in minor scenarios the former bridge classes according to DIN 1072.

Based on the results from the finite element models, full-probabilistic calculations are performed. In the semi-probabilistic safety concept the design equations are:

$$E_d < R_d \tag{1}$$

$$E_d = E\{\gamma_{F,i} \cdot F_{rep,i}; a_d\} i \geq 1 \tag{2}$$

$$R_d = \frac{1}{\gamma_{Rd}} \cdot R\left\{\eta_i \cdot \frac{X_{k,i}}{\gamma_{m,i}}; a_d\right\} i \geq 1 \tag{3}$$

While the semi-probabilistic concept is grounded on characteristic values in combination with partial safety factors, probabilistic methods can provide a more realistic assessment of the structure and in-situ measurement results can be implemented directly into the computation model. The failure probability P_f of the structure is a decisive parameter and can generally be defined as the integral of the probability density functions f(x) over the failure area V_x. Since this integral can only be solved in rare practically relevant cases, different approximation methods and numerical simulations can be useful approaches in practice.

$$P_f = \int_{V_x} f_x(\boldsymbol{x}) d\boldsymbol{x} \tag{4}$$

The failure area V_x is given through the limit state function, where R is the resistance of the considered system and E the effects of actions, e.g., stresses, bending moments or shear forces. The limit state functions are defined based on the relevant design equations of the semi-probabilistic safety concept and the critical assessment results.

$$g(x) = R - E = 0 \tag{5}$$

The limit state functions are formulated to include as many measurable data as possible. While a number of limit state functions for current design equations are available in literature [10-12], the former design equations of the codes from the time of construction and from previous codes still need to be formulated as limit state equations for full-probabilistic calculations. The loads and reactions from the finite element models are converted from characteristic values to mean values and a fully probabilistic calculation is performed based on the transformed results from the finite element models and with accepted distribution parameters from literature, e.g., provided by the Joint Committee on Structural Safety. The initial probabilistic calculations, performed to analyze sensitivities, do not include data from on-site measurements.

A sensitivity analysis, cf. sect. 2.2, indicates the influence of each parameter on structural reliability. Based on this analysis (and based on the general experience of the engineering partners), the relevant testing tasks are determined. The measurability of the relevant parameters is discussed in chapter 3.4. After the results of the measurements are available, the calculations are performed again with implemented data from NDT on-site.

3.3 Reassessment results

Since existing bridges were often designed in compliance with former standards, concepts and load models, certain numerical deficits during the reassessment process acc. to current regulations can be expected. The most frequent deficits are related to the shear force load bearing capacity. About half of existing concrete bridges do have calculational problems in this regard [13]. In general, typical deficits of existing concrete bridges are

- Bending (moment) bearing capacity in longitudinal and/or transversal bridge direction
- Torsional longitudinal reinforcement
- Web/slab connections
- Shear force capacity and stirrup design
- Fatigue
- Decompression for prestressed concrete elements

Currently the reassessment processes of all seven selected bridges are performed. The individual reassessment of bridge 04 showed deficits for the bending moment load bearing capacity in cross direction concerning the amount of reinforcement steel in the upper layer of the cast-in-place slab, which was added on top of the precast T-beams. The results also indicate deficits for the web/slab connection and for the torsional longitudinal reinforcement. The shear reinforcement stirrups have a very high utilization ratio and deficits of about 10% resulted from the semi-probabilistic calculations. While, theoretically, there is no limit of tolerance designated, the practical daily routines often do accept a minor exceedance. Therefore, this structure is well fitted for a more detailed analysis with measurement data to see, if the small numerical deficit can be eliminated with the results of on-site measurements of the diameter of the bars and their spacing. While the individual reassessment of the prestressed concrete bridge 01 revealed, that there is no deficit in the bending moment bearing capacity in longitudinal and/or cross direction, there are major deficits in its shear force capacity. The condition $V_{Ed} \leq V_{Rd,sy}$ is used to determine the necessary shear reinforcement amount and shows deficits up to 450 %, which means the ratio of the required amount of reinforcement to the existing amount of reinforcement is about 5,50. This problem is mainly due to the fact that the initial design from the construction period did not take into account the same requirements that are imposed on shear reinforcement design today.

Based on the recalculation results of each bridge, the relevant limit states, parameters, and measuring areas for the on-site measurements will be suggested.

3.4 Measurability of the relevant parameters

In contrast to the design of new structures, the basis for a refined assessment of existing structures can be the determination of relevant parameters using testing or NDT-methods, respectively, to appreciate the individual as-built characteristics. The identification of relevant information enables the demand-oriented formulation of testing tasks. Based on such a defined testing task, a testing or measurement method can be purposefully selected, and a suitable measurement strategy defined. The first step is to analyze whether and, if so, which testing method(s) is physically capable for solving the task (see Table 2). For example, it is not yet possible to determine the diameter of reinforcement bars using the ultrasonic method, while determining the geometrical position of the rebars can be considered state of the art. Furthermore, it must be taken into account whether the measurement on the structure is reasonable with regard to the technical and economic boundary conditions. A common testing task is the estimation of the concrete compressive strength. Here, the sampling of cores can be combined with the application of the rebound hammer and with ultrasonic investigations. This approach allows the extrapolation of the local information from the destructive tests of the cores to areas decisive for the proof, where the structure should not be disproportionately weakened by (destructive) inspections. In concrete bridge assessment, for example, this concerns the highly loaded compression zones in bearing proximity.

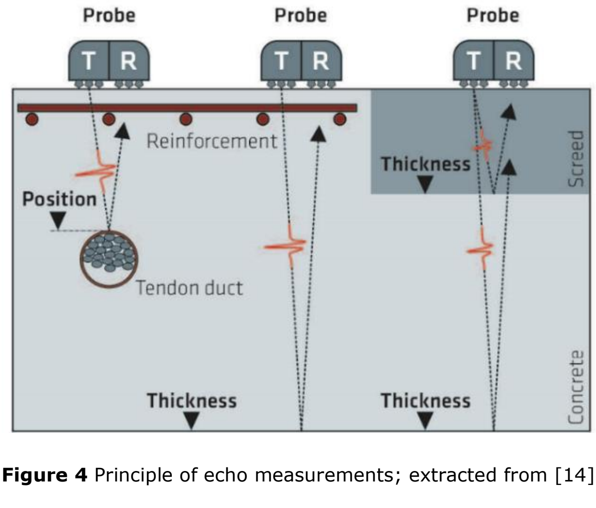

Figure 4 Principle of echo measurements; extracted from [14]

In addition to the characterization of material properties, it is frequently necessary to supplement existing plans or, if these are not available, to reconstruct them completely. The related testing tasks range from the determination, whether structural elements such as reinforcement bars were mounted as planned, to the geometrically precise reconstruction of tendon courses. A number of NDT methods exist for solving such testing tasks, e.g., the ultrasound and ground penetrating radar methods, which are based on the time of flight (TOF) measurement principle, and the radiography, which can be utilized depending on the individual boundary conditions found at the structure. Figure 4 shows the principle of a TOF measurement in echo arrangement of the probes. A pulse is transmitted into the component to measure the time it takes the pulse to travel a certain path through the component. The geometrical positions of the reflectors (e.g., tendon ducts, rebars) can then be reconstructed by consideration of the propagation velocity of the pulse within the component and the physical characteristics of the building material.

Table 2 Comparison of chosen testing tasks relevant in reliability or condition assessment and selected physically suitable NDT techniques, see also [15-18]

Testing task	NDT techniques
Material strengths, e.g., concrete compressive strength	Rebound hammer
Component thickness	Impact-echo, ultrasonic, radar
Detection of reinforcement	Radar, radiography, eddy current
Concrete cover	Eddy current, radar, radiography
Diameter of steel bars	Radiography, eddy current
Localisation of rebars, tendons, etc.	Radar, ultrasonic, thermo-, radiography
Detection of broken steel strands	Magnetic leakage flux measurement
Grouting condition of tendons	Radiography, ultrasonic
Areas subjected to active corrosion	Potential field mapping
Moisture content / distribution	Direct and indirect methods / radar
Chloride, sulphate contents (chemical material composition in general)	Laser induced breakdown spectroscopy (LIBS)

An important prerequisite for the use of measured data in the reassessment of structures is the specification of the quality of the measurement. A suitable measure for this purpose is the measurement uncertainty, which can be calculated based on the Guide to the Expression of Uncertainty in Measurement; GUM [19]. By specifying the measurement uncertainty, the requirements on the measurement and the precision achieved can be compared (e.g., in verification or validation). On the other hand, measurement uncertainties determined under comparable boundary conditions in previous measurements can be used to compare expected strengths and weaknesses of different test methods and to select a suitable method for solving a specific task while considering the precision requirements.

3.5 Exemplary results of on-site GPR inspections

The ground penetrating radar (GPR) method has been applied to the single span prestressed concrete bridge shown in Figure 5 (ID 04 in sect. 3.1) with the objective to verify the reassessment assumptions and information extracted from the drawings with regard to the amount and position of various steel bars and tendons. This section refers to the localisation of the longitudinal tendons and shear stirrups inside the web.

Figure 5 The investigated prestressed concrete bridge with embedded GPR scan indicating the shear stirrups; extracted from [20]

Vertical positions of the longitudinal tendons

When locating the longitudinal tendons, the aim was to determine their vertical position at the low points and near the supports, and, at which point in longitudinal bridge direction they are raised how steeply. The respective positions for one of the webs according to the plans and to the measured data are compared in Table 3. Axis 7 indicates the centre of the span. The reference axis in longitudinal bridge direction (x) is the front of a bearing, the reference in vertical (y) direction the lower surface of the web. The values refer to the tendon duct axis. The GPR measurements were carried out in a grid with a 10 cm measuring line distance using a 2 GHz antenna. The accuracy of the values can be estimated by approx. ±1 cm without comprehensive measurement uncertainty calculations, as the lateral and not the depth positions were to be determined.

Table 3 Comparison of the vertical tendon duct positions indicated in the drawings and measured using GPR on-site / cm; axis numbering acc. to drawings with x_1 = 70 cm from bearing and $\Delta x_{2\ldots7}$ = 140 cm

Tendon		Axis 1	Axis 2	Axis 3	Axis 4	Axis 5	Axis 6	Axis 7
#1	Plan	16,55	13,95	11,75	10,15	8,95	8,15	8,05
	NDT	16,10	13,90	10,50	6,30	6,50	6,50	6,00
#2	Plan	42,45	31,85	23,25	16,55	11,75	8,95	8,05
	NDT	41,10	32,40	21,00	14,50	-	-	-
#3	Plan	-	-	33,55	24,45	15,25	9,75	8,05
	NDT	-	-	37,80	24,50	15,50	6,50	6,00

The measurements were performed from both web sides. The tendon #2 could, however, not reliably be detected in the axes 5 to 7 as it is shadowed by the tendons #1 and #3, between which it courses centrally through the web in the transverse bridge direction. This missing information can be collected by measurements from the underside of the web. Overall, there are three noticeable differences between plan and measurement: tendon #1 is actually about four centimeters lower in axis 4 than assumed, tendon #3 in axis 3 about four centimeters higher and in axis 6 about three centimeters lower, although the measuring objects are prefabricated elements. Apart from this, the assumptions in reassessment can be mostly confirmed.

Spacing of the shear reinforcement:

When locating the shear reinforcement, the focus was on measuring the spacing and inclinations of the bars. In addition, but not solvable with the help of the radar method, the bar diameters are of interest as well as the information whether the stirrups were mounted closed, making a difference in the torsion proof. Table 4 indicates the measured positions of the "last" bar within the area with a smaller and the "first" bar within the area with a larger spacing referring to one end of the beam in longitudinal bridge direction. The information was generated from the same data set used for tendon location.

Table 4 Comparison of length positions, at which the shear stirrup spacing varies, acc. to the drawings and measured using GPR on-site

	Start in length direction	End in length direction	Spacing
Area I	0 cm (plan)	150 cm (plan)	5 cm (plan)
	0 cm (NDT)	146 cm (NDT)	5 cm (NDT)
Area II	150 cm (plan)	350 cm (plan)	10 cm (plan)
	154 cm (NDT)	372 cm (NDT)	10 cm (NDT)
Area III	350 cm (plan)	-	17,5 cm (plan)
	387 cm (NDT)		15,0 cm (NDT)

Overall, the longitudinal positions where the bar spacing changes can be approximately confirmed. Nevertheless, there is one noticeable deviation: the shear stirrup spacing in area III (from a distance of 3.5 m according to the plan or measured 3.8 m) is actually 15 cm instead of planned 17.5 cm. To deduce the amount of steel mounted, the bar diameters would have to be measured additionally. Either partial destructive uncovering or the eddy current method is physically suitable for this purpose. It can be concluded, as in many other practical measurement scenarios, that a combination of different methods can have a significant informative added value. However, such "incomplete" measurement results can be combined with prior information to refine the recalculation models successively.

4 Conclusion and outlook

This paper summarizes the ambitions of a national pre-standardization project for the development of a guideline on NDT-supported reliability assessments of existing structures and the NDT-based, structure-specific partial safety factor modification. The interim results from the first months of the project were shown including the defined prestressed and reinforced concrete bridges to be investigated during the project, chosen initial recalculation results and identified crucial structure parameters, as well as first measurement results, which were compared with the respective information available prior to any testing.

The procedure ranging from the identification of relevant structural parameters via the development of purposeful measurement strategies, the calculation of measurement uncertainties for the preparation of stochastic models as input quantities for probabilistic recalculations to the subsequent modification of partial safety factors will be shown using seven bridges as demonstration pilots. Additional round robin tests will serve to provide more in-depth knowledge about the measurement accuracies as well as the human factor. In addition, it is intended to develop an uncertainty database to assign expected accuracies to NDT methods and procedures that are physically suitable to solve specific testing tasks under individual boundary conditions. In this way, the capability of one or more methods to meet certain, individual requirements can be compared and evaluated more efficiently.

Acknowledgement

The authors gratefully acknowledge the financial support of the German Federal Ministry for Economic Affairs and Climate Action under grant number 03TN0042.

References

[1] International Federation for Structural Concrete (2016) *Partial factor methods for existing concrete structures – Recommendation*. Bulletin 80. Lausanne, Swizerland: Fédération internationale du betón.

[2] Fischer, A. M. et al. (2014) *DBV-Heft 24: Begründung eines reduzierten Zuverlässigkeitsindexes und modifizierter Teilsicherheitsbeiwerte für Stahlbetontragwerke im Bestand*. Berlin: Eigenverlag [German].

[3] Bundesministerium für Verkehr, Bau und Stadtentwicklung (05/2011) *Richtlinie zur Nachrechnung von Straßenbrücken im Bestand (Recalculation guideline) [German]*.

[4] Bundesministerium für Verkehr und digitale Infrastruktur (04/2015) *Richtlinie zur Nachrechnung von Straßenbrücken im Bestand (Recalulation guideline)*. 1. Supplement [German].

[5] Küttenbaum, S. et al. (2021) *Reliability assessment of existing structures using results of nondestructive testing* in: Structural Concrete 22, H. 5, S. 2895–2915. https://doi.org/10.1002/suco.202100226

[6] Küttenbaum, S. et al. (2022) *On the treatment of measurement uncertainty in stochastic modeling of basic variables* in: Acta Polytech CTU Proc. 36, S. 109–118. https://doi.org/10.14311/APP.2022.36.0109

[7] Hasofer, A. M.; Lind, N. C. (1974) *Exact and Invariant Second-Moment Code Format* in: Journal of the Engineering Mechanics Division 1974, H. 100, S. 111–121.

[8] Rackwitz, R.; Fiessler, B. (1978) *Structural reliability under combined random load sequences* in: Computers & Structures 9, H. 5, S. 489–494. https://doi.org/10.1016/0045-7949(78)90046-9

[9] Hohenbichler, M.; Rackwitz, R. (1981) *Non-Normal Dependent Vectors in Structural Safety* in: Journal of the Engineering Mechanics Division 107, EM6, S. 1227–1238.

[10] Braml, T. (2010) Zur Beurteilung der Zuverlässigkeit von Massivbrücken auf der Grundlage der Ergebnisse von Überprüfungen am Bauwerk. Düsseldorf: VDI-Verlag [German].

[11] Fischer, A. (2010) Bestimmung modifizierter Teilsicherheitsbeiwerte zur semiprobabilisti-schen Bemessung von Stahlbetonkonstruktionen im Bestand. Kaiserslautern: Dissertation [German].

[12] Küttenbaum, S.; Maack, S.; Braml, T.; Taffe, A.; Strübing, T. (2021) *Bewertung von Bestandsbauwerken mit gemessenen Daten, Teil 2. Berechnung der Tragwerkszuverlässigkeit unter Einbeziehung der ZfP-Messergebnisse*. Beton- und Stahlbetonbau 116, H. 3, S. 183–199. doi.org/10.1002/best.202000087

[13] Fischer, O.; Müller, A.; Lechner, T.; Wild, M.; Kessner, K. (2014) *Ergebnisse und Erkenntnisse zu durchgeführten Nachrechnungen von Betonbrücken in Deutschland*. Beton- und Stahlbetonbau 109, H. 2, S. 107–127. https://doi.org/10.1002/best.201300084

[14] Maack, S. et al. (2021) *Die Ultraschall-Echomethode – von der Messung zur bautechnischen Kenngröße* in: Beton- und Stahlbetonbau 116, H. 3, S. 200–211. https://doi.org/10.1002/best.202000091

[15] Bergmeister, K. and Rostan, S. (2003) *Monitoring and safety evaluation of existing concrete structures: fib Bulletin 22*. state-of-the-art report. Lausanne: fib.

[16] Beushausen, H. and Fernandez Luco, L. (eds.) (2015) Per*formance-Based Specifications and Control of Concrete Durability: State-of-the-Art Report* RILEM TC 230-PSC, 1st edn, Springer, Dordrecht.

[17] IAEA (2002) *Guidebook on non-destructive testing of concrete structures*, TRAINING COURSE SERIES No. 17, 17th edn, Vienna.

[18] Forde, M.C. (2013) *Report on nondestructive test methods for evaluation of concrete in structures*: Reported by ACI Committee 228, ACI 228.2R-13, American Concrete Institute, Farmington Hills, Mich.

[19] JCGM (2008) JCGM 100:2008. *Evaluation of measurement data — Guide to the expression of uncertainty in measurement*.

[20] Küttenbaum, S. et al. (2023) *Ways to unlock the potential of non-destructive concrete testing for the reliability assessment of our built environment*, 8th International Workshop on Reliability of NDT/NDE, Los Angeles.