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Towards NDT-supported decisions on the reliability of existing bridges

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ABSTRACT: A major advantage in the reassessment of existing structures is the possibility of including measured data that describe the actual properties and the current condition of the structure to be reassessed. Currently, the incorporation of such measured information is mostly unregulated. However, the use of measurement results is vitally important, since a measured data-based improvement of the computation models level of approximation can lead at least to more meaningful results, possibly to extended remaining life times of the structure and in the best case to a saving of resources. Conversely, not appreciating well measurable and relevant information can be equated with a waste of resources. In this paper, a concept for the comparable use of non-destructively measured data as basic variables in probabilistic reliability assessments is outlined and examined using a typical prestressed concrete road bridge as a case-study. An essential requirement is the calculation of measurement uncertainties in order to evaluate the quality of the measurement results comparably. In conclusion, the example of ultrasonic and radar measurement data is used to demonstrate the effects that the incorporation of the measured information has on the reliability of the structure.

KEYWORDS: Measurement uncertainty, Reliability, Assessment, Existing structures, Concrete Bridge, Non-Destructive Testing (NDT).

1 INTRODUCTION

The validity of computation results depends to a large extend on the trueness, on the precision and on the relevance of the underlying information. The decisive difference between the reassessment of an existing structure and the design of a new is the possibility and the necessity to include additional information about the current condition and actual structure parameters. The incorporation of measured information can lead to a reduction of both the bias of considered models and the uncertainty in the reassessment as well as to an increasement of the robustness of the computation results. On the one hand, measurements can be used to determine the current state of a structure and to represent it mathematically. On the other, errors that have occurred over the life cycle of the structure and that can have serious consequences can be obtained. Since measurements are considered particularly beneficial when necessary information is missing, doubts have arisen about the available information, and since traffic loads are continuously increasing, extensive destructive interventions into the structure should be avoided.

This paper outlines an approach for the use of non-destructively obtained measurement results as basic variables in the probabilistic reassessment of existing structures and discusses the advantages of applying that approach by means of a case study. The aim is the NDT-based stochastic modelling of sensitive basic variables to be incorporated in the reassessment explicitly. The reliability analyses are performed in two limit states in order to proof the bending and shear force resistance of a bridge using the First Order Reliability Method (FORM). For this purpose, two geometrical parameters were measured on site at the structure by applying both an ultrasound and a ground penetration radar measurement procedure.

An essential part of the chosen approach is the calculation of measurement uncertainties (cf. sect. 3.3). A useful model of a basic variable covers the uncertainty associated with both the acquisition and processing of information. The measurement uncertainty analyses ensure the comparability of the measurement results. Furthermore, the quality (i.e. accuracy and precision) of the measurement results is known. The effects of the incorporation of the NDT-based basic variables are conclusively shown in relation to the reference values calculated without appreciating the measured information.

2 CONCEPT

The concept for the reassessment using measured data is summarized in Figure 1.

The preliminary investigations (first step) serves the purposeful definition of the measurand (quantity to be measured) and specification of the requirements on the measurement derived from the analysis of the structural reliability without appreciating measured data (e.g. a maximum permissible uncertainty). For this purpose, sensitivity coefficients, elasticities and parameter studies are analyzed (see sect. 3.2). The prerequisite is the definition of the limit state function (cf. sect. 3.1) and the modelling of the initial basic variables (without consideration of measured data).

In the second step, the measurements on site at the structure are planned, conducted and the observations are analyzed. This leads to a measurement result consisting of a best estimate and the measurement uncertainty attributed to this value and expressed in accordance to internationally harmonized and accepted rules (cf. section 3.3). The measurand is composed by a multitude of input quantities.

The third step comprises the derivation of the NDT-supported models from the measurement results (see section 3.4). These measured data-based basic variables replace the respective initial basic variables in the reliability analysis using the measured data in the fourth step (cf. sect. 3.5). This reliability analysis can in turn be the starting point for the definition of new measurands.

The reliability analyses are based on the FORM proposed in (Hasofer & Lind, 1974) and enhanced i. a. by (Rackwitz & Fiessler, 1978) as well as (Hohenbichler & Rackwitz, 1981). The reliability index is computed according to (Hasofer & Lind, 1974). The proofs are performed time-invariant and at cross-sectional level. The reference period results implicitly from the modelled traffic loads and is $T = 50\ \mathrm{a}$. The measurement uncertainty calculations are based on the rules of the Guide to the Expression of Uncertainty in Measurement (Joint Committee for Guides in Metrology, 2008).

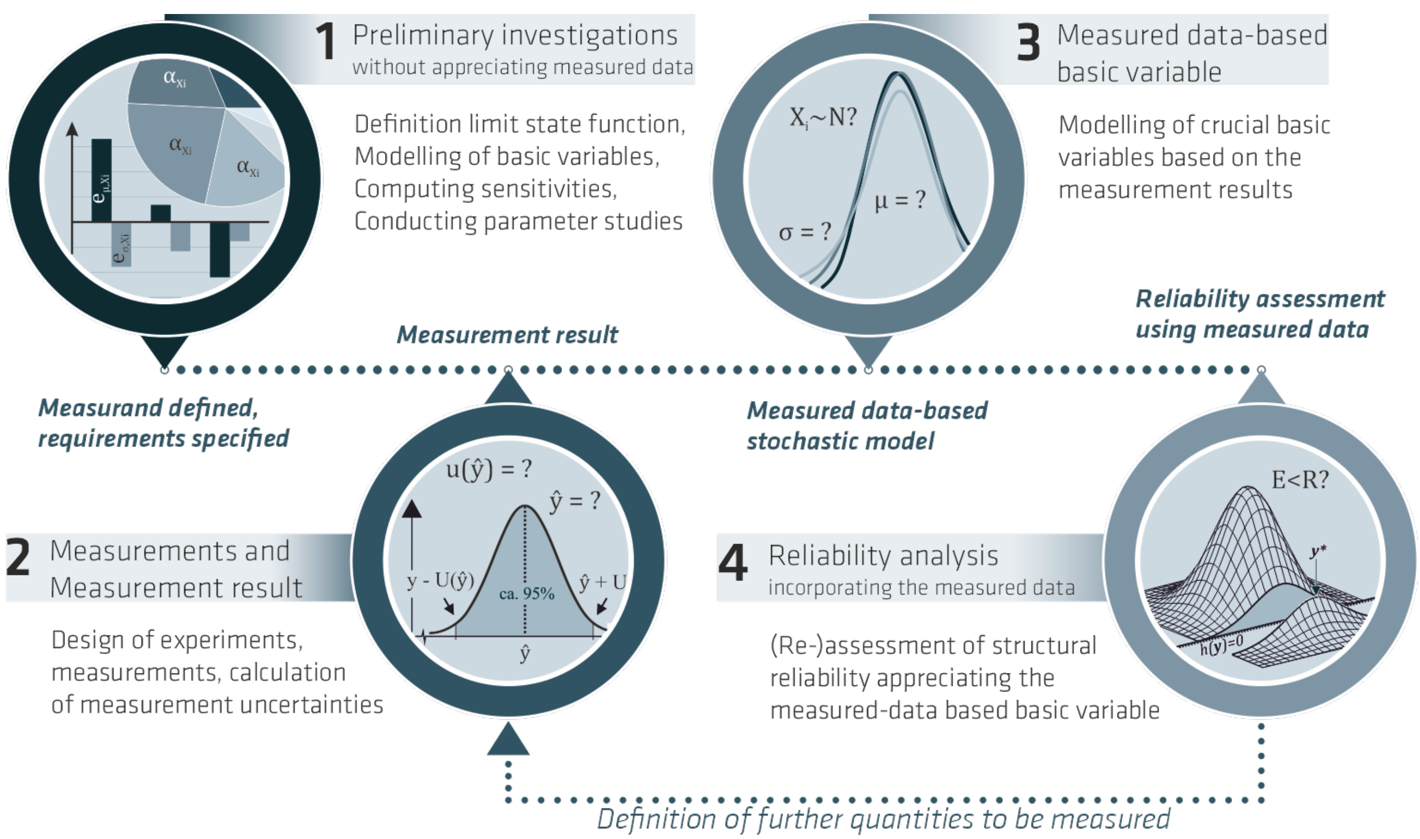

Figure 1. Procedure for the targeted definition of quantities to be measured (measurands), the measured data-based modeling of basic variables and the reliability reassessment of existing structures appreciating measured information

Figure 2. The investigated prestressed concrete bridge.

3 CASE-STUDY

3.1 *The structure and definition of limit states*

The structure investigated in the present case-study is a prestressed concrete bridge (cf. Figure 2) that has been dismantled recently. The three-span bridge was approx. 133 meters long, carried a two-lane federal highway over a river and had a single-cell hollow box girder cross-section (cf. Figures 3 and 4). It was built in 1965. The as-built plans show 44 to 46 longitudinal tendons in the center of the bridge (center among axis 20 and 30). Shear force reinforcement was mounted in the area around the bridge pillars. The bridge is described further in (Küttenbaum *et al.*, 2019).

The bridge is to be reassessed in two ultimate limit states (ULS). The proof of the bending load-bearing capacity in longitudinal direction and the proof of the tension strut, which is considered decisive for the evaluation of the shear force load-bearing capacity, is chosen. The bending proof is performed in the center of the bridge. The shear force proof is conducted at a distance of two meters (corresponds to the effective depth of the cross-section d) from the axis 20 in the center field.

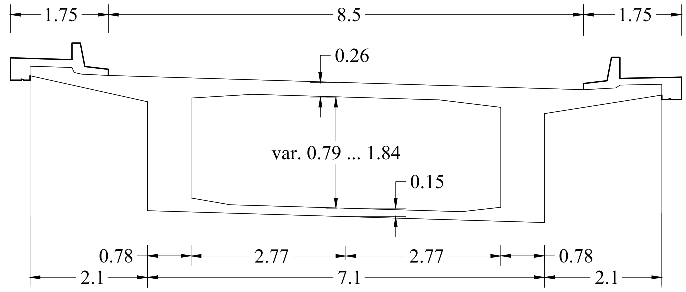

Figure 3. Standard cross-section; dimension unit is m (Küttenbaum *et al.*, 2019).

The limit state function in ULS bending for structures with compressive reinforcement can be found in (Braml, 2010) and can after limiting the compression height be written as:

$$g(M_{\mathrm{R}}) = U_{\mathrm{R,M}} \cdot \Big(A_{\mathrm{sp}} \cdot f_{\mathrm{p}} \cdot \big(h - d_{\mathrm{Sp}} - d_2\big) + a_{\mathrm{R}} \cdot b \cdot \xi \cdot \big(h - d_{\mathrm{Sp}}\big) \cdot 0{,}85 \cdot f_{\mathrm{c}} \cdot \big(d_2 - k_{\mathrm{a}} \cdot \xi \cdot (h - d_{\mathrm{Sp}})\big)\Big) - U_{\mathrm{E}} \cdot \big(M_{\mathrm{G}} + M_{\mathrm{Q}} + M_{\mathrm{VP}}\big). \quad (1)$$

The statically determined bending moment is appreciated via the cross-sectional area A_{sp} and the tensile strength f_{p} of the prestressing steel as well as the distance between the lower edge of the web and the longitudinal tendons d_{Sp}.

The limit state function for assessing the load-bearing capacity of the tension strut (ULS shear) is:

$$g(V_{\mathrm{R,s}}) = U_{\mathrm{R,s}} \cdot \left(\frac{A_{\mathrm{sw}}}{s_{\mathrm{w}}} \cdot f_{\mathrm{y}} \cdot \big(0{,}9 \cdot (h_{\mathrm{S}} - d_1)\big) \cdot (\cot\theta + \cot\alpha) \cdot \sin\alpha\right) - U_{\mathrm{E}} \cdot \big(V_{\mathrm{G}} + V_{\mathrm{Q}} + V_{\mathrm{P}}\big). \quad (2)$$

Equation (2) is based on the formula published in (Braml, 2010) and the truss model standardized in Eurocode; cf. (CEN, 2005). The descriptions of the variables in equations (1) and (2) as well as the models of the basic variables are given in section 3.4 and in excerpts in Figures 5 and 6.

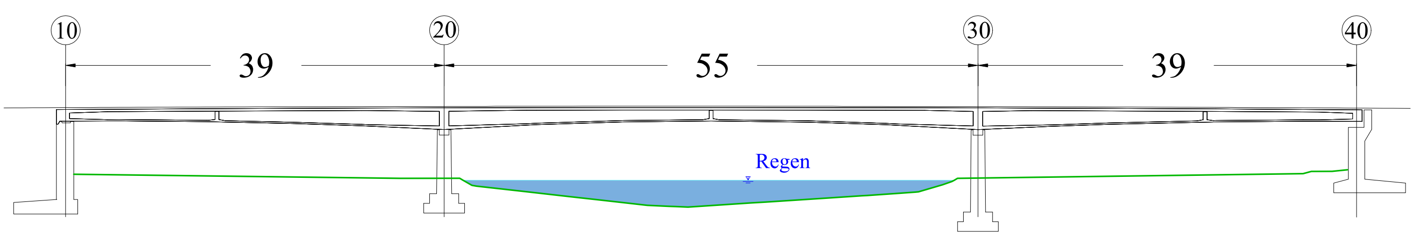

Figure 4. Longitudinal view of the investigated prestressed concrete bridge; span lengths specified in m (Küttenbaum *et al.*, 2019).

32 *Results of the preliminary investigations*

The results of the reliability analyses in limit states ULS shear and ULS bending are plotted in Figure 5. The calculations are based on equations (1) and (2) and on the initial stochastic models in Table 1. Thus, the measured information is disregarded. A further discussion can be found in (Küttenbaum *et al.*, 2021).

The value of the reliability index in ULS shear is $\beta_{\mathrm{HL}} = 1{,}08$ (SORM: $\beta_{\mathrm{HL}} = 1{,}05$) and $\beta_{\mathrm{HL}} \approx 6{,}3$ in ULS bending (FORM & SORM). The load-bearing capacity regarding bending in the bridge center is significantly higher than common target values as $\beta_{\mathrm{req}} = 3{,}8$ (CEN, 2002) require. One reason for the small numerical shear force bearing capacity is that the truss model according to Eurocode 2 can produce rather conservative, in the sense of "too safe", results.

The computed values of the sensitivity factors indicate that the greatest stochastic impact can be attributed to the model uncertainties in both limit states. The spacing of the stirrups s_{w} accounts for 12 % and the vertical position of the longitudinal tendons d_{Sp} for 5 % of the respective pie charts.

It can be deduced from the elasticities of the mean values, that even a theoretical increase in the distance among the shear reinforcement by one centimeter results in a loss of numerical reliability of about −32 %. The influence of a change in the vertical position of the longitudinal tendons is less noticeable in this specific case. The results of the parameter studies shown as functions of the reliability index against the mean values of both normally distributed basic variables at the bottom are consistent with these observations. The basic variables s_{w} and d_{Sp} are discussed in more detail below and defined as measurands in this paper.

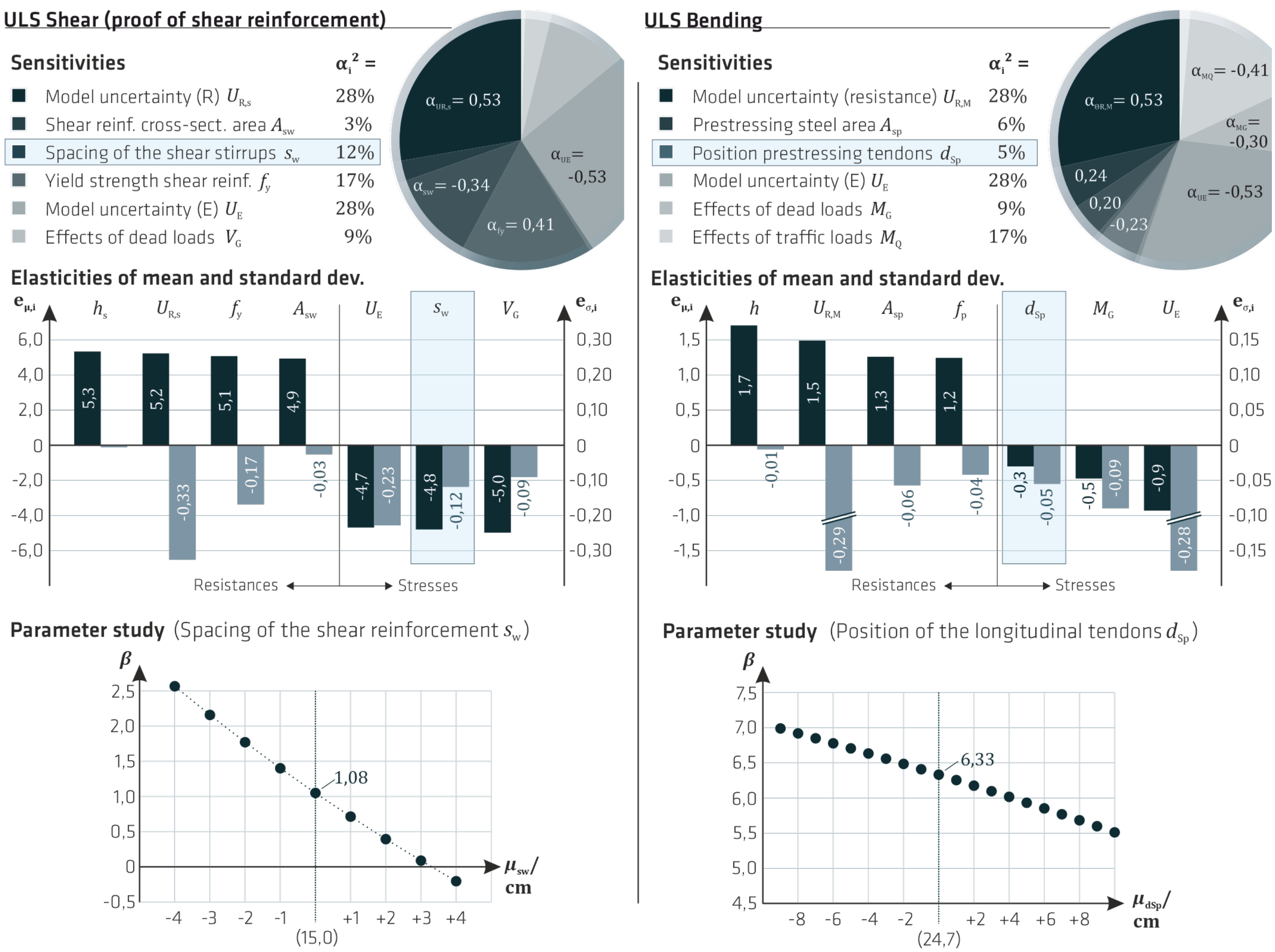

Figure 5. Results of the sensitivity analyses, elasticity analyses and parameter studies without appreciating measured information; extracted from (Küttenbaum *et al.*, 2021), translated

3.3 *Measurement uncertainty calculation*

The measurement uncertainty neither describes a mistake nor can it be eliminated by arbitrarily careful measurements. The aim of a measurement is to obtain the value of a quantity to be measured (measurand) and thus to generate knowledge. The true value of a measurand remains generally hidden. Consequently, measurement uncertainties must be specified in order to evaluate the quality of a measured information on the one hand. On the other hand, the calculation of measurement uncertainties ensures the comparability of the measurement results and creates confidence in measurements. A stochastic model to be incorporated as a basic variable in reliability reassessment is then considered useful, if the uncertainty associated with the acquisition and processing of information, i.e. the measurement uncertainty, is appreciated. In a broader sense, a measured value to which no measurement uncertainty has been attributed is useless. For this reason, its specification is an essential requirement for the use of measured information in reassessment of existing structures.

Internationally harmonized and approved rules for measurement uncertainty considerations are provided within the Guide to the Expression of Uncertainty in Measurement (GUM)-framework. The subsequent discussion is based on the main document *JCGM 100:2008* (Joint Committee for Guides in Metrology, 2008). Basically, a model of the measurement is to be formed, which consists of multiple input quantities X_i known to be involved in a measurement, cf. *VIM* (Joint Committee for Guides in Metrology, 2012). The mathematical relation among these quantities serves to determine the output quantity (measurand) and can be expressed as an explicit model equation:

$$Y = f(X_i). \tag{3}$$

The identified and individually relevant input variables are to be quantified, i.e. for each variable a (mostly stochastic) model is to be found. The analysis of independent, identically distributed observations by means of statistical methods (Type A evaluation) as well as the incorporation of knowledge generated otherwise (Type B) are equally appropriate for this purpose. Regarding Type A, the sample mean $\bar{x}$ is the best estimate of a directly measurable input quantity in many cases, provided that the systematic errors are corrected. The standard measurement uncertainty is to be attributed to this best estimate. This uncertainty is expressed as the standard deviation of the mean:

$$u(\hat{x}) = \sqrt{\frac{s^2}{n}} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(x_i - \bar{x})^2}. \tag{4}$$

Accordingly, when the Type A evaluation is conducted, the standard uncertainty results from parameters of a probability distribution defined on the basis of measured information. Uncertainties determined by Type B evaluation are derived from distributions assumed e.g. in accordance with previous measurement uncertainty considerations, experience, etc. If adequate probabilistic models have been found for all identified, relevant input quantities, the measurand can be calculated. For this purpose, the best estimates $\hat{x}_i$ of the input quantities are inserted into the model equation (3) in order to derive the best estimate

$$\hat{y} = f(\hat{x}_i). \tag{5}$$

This measured value $\hat{y}$ needs to be corrected for systematic measurement errors that have not yet been appreciated.

An appropriate measure for the uncertainty associated with the measurand Y is the combined standard measurement uncertainty derived by the propagation of the standard uncertainties $u(\hat{x}_i)$ attributed to the input quantities:

$$u(\hat{y}) = \sqrt{\sum_{i=1}^{n} c_i^2 u^2(\hat{x}_i) + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n} c_i c_j u(\hat{x}_i, \hat{x}_j)}. \tag{6}$$

The coefficients c_i are also called sensitivity factors (of the input quantities). They are the result of the partial derivation of the model equation according to the input quantities X_i at the expected values corresponding to the best estimates $\hat{x}_i$. The values of c_i provide information on how sensitive the result $u(\hat{y})$ is to (small) changes in the models of the X_i. They thus serve to differentiate between relevant and negligible input quantities and to purposefully define future metrological research demands.

The term on the right in equation (6) indicates that correlations should be appreciated, provided that sufficient information about the statistical interaction is available. In the present case-study, correlations between measured input quantities (Type A) are estimated via empirical covariance.

With regard to the choice of a distribution type to define the function of the measurand, reference is made to the central limit theorem and to the GUM. The choice of the normal distribution for modelling the measurands discussed in the present case-study was validated by means of simulation computations.

Subsequently, a model for the determination of the lateral position of a reflector (related to the measuring surface) is used as an example to briefly illustrate how a model of the measurement can be designed. The explanations are limited to the application of a specific ground penetration radar (GPR) procedure.

The results may serve as a starting point for future measurement uncertainty calculations. Inadmissible generalizations are to be refrained from. A model of the measurement is basically valid for the individual case considered. The following discussion is based on chosen results provided in (Küttenbaum, 2020).

The measurand is the lateral position of a reflector in a specified small area around a sampling point to be formulated. The model equation can be written as

$$X_{\mathrm{S}} = X_{\mathrm{A}} - X_{\mathrm{VZ}} - X_{\mathrm{L}} - X_{\mathrm{BSC},x} - X_{\mathrm{BSC},v}\ , \quad (7)$$

where

X_{S} :	lateral position of a sampling point
X_{A} :	measurement series (coordinates)
X_{VZ} :	measurement data logging delay
X_{L} :	limited resolution of the scale
$X_{\mathrm{BSC},x}$:	shifted mounting of the scanner
$X_{\mathrm{BSC},v}$:	twisted mounting of the scanner

The designations of the listed input quantities indicate that automated measurement systems were used to locate (in this case) the shear reinforcement. These scanners may have been mounted displaced from the intended and geodetically measured position of the measuring area on the surface of the structure.

This model of the measurement was developed in (Küttenbaum, 2020). Without further explanations in the present paper it will be shown in the following, how an input quantity can be quantified according to the GUM using the example of the logging delay X_{VZ}. The reason for evaluating this input quantity is that delays in measurement data recording have been observed in the past, especially at a higher motion speed of the GPR-antenna mounted on the structure scanner (Trela *et al.*, 2012). This would cause the position of a recorded time signal on the measuring line to shift at least systematically with respect to the actual measurement position. For the NDT-system used in this particular case, this observation could not be confirmed. Nevertheless, an uncertainty component with an equivalent effect could be measured in the laboratory. Variations included the motion speed of the antenna, the measurement line length, which partly did not correspond to any multiple of the measuring point distance, and the measurement direction (positive, negative).

As a result, it was found that the recorded time signals in a measurement line shift by two to three times the measurement point spacing in the measurement direction compared to the actual antenna positions, provided that the measurement direction is negative. The cause may lie in the data acquisition software. This would mean, that X_{VZ} is an NDT-system-specific uncertainty component. Since the systematic measurement error by two to three times the measuring point distance cannot be precisely quantified on the basis of the available information, a random measurement error must be added to this systematic measurement deviation. The interpretation of the observed shift as limit values leads referring to the principle of maximum entropy to $X_{\mathrm{VZ}} \sim \mathrm{U}$. Provided the measuring point distance is 4 mm, it follows for the expected value that $E(X_{\mathrm{VZ}}) = \hat{x}_{\mathrm{VZ}} = 10\ \mathrm{mm}$. Given the choice of the uniform distribution, the attributed standard uncertainty is $u(\hat{x}_{\mathrm{VZ}}) = 4\ \mathrm{mm}/2\sqrt{3} = 1{,}2\ \mathrm{mm}$.

According to the boundary conditions, all other relevant individually identified input quantities are quantified and the sampling points X_{S} are calculated, each describing the (in this case lateral) position of a shear reinforcement stirrup related to the longitudinal bridge axis. The sampling points scatter in the direction of this axis. The uncertainty attributed to the lateral position with respect to this x-axis is $u(\hat{x}_{\mathrm{S}}) < 3\ \mathrm{mm}$ for all calculated points within a measured volume.

In total, 64 sampling points were calculated from 448 observed positions of $i = 16$ stirrups on $j = 4$ horizontal lines imposed in the longitudinal bridge direction and upon the other in a range around the investigated cross-section of $\pm 1{,}30\ \mathrm{m}$. By combining these points $X_{\mathrm{S},i,j}$ (appreciating the combined standard measurement uncertainties of the considered $X_{\mathrm{S},i,j}$), the averaged spacing of the shear reinforcement bars has been calculated. The entire model, the measured data and the related discussions can be found in (Küttenbaum, 2020). The result can be expressed as follows: $S_w \sim N$ with $\hat{s}_w = 14{,}827\ \mathrm{cm}$ and $u(\hat{s}_w) = 0{,}012\ \mathrm{cm}$.

The procedure for determining the measurand d_{Sp} is methodologically equivalent. The corresponding model of the measurement is given in (Küttenbaum, 2020) as well. It should be noted that the combination of many sampling points can sometimes (and as here) result in exceptionally small values of measurement uncertainties compared to usual NDT-measurement results. This is reasonable in that the displacement of many or all reflectors, such as the geometrical center of a bundle of tendons, is less likely than a shift of a single reflector. This is valid especially if – as in this case – measured data is available providing sufficient evidence about that at least the displacement of some reflectors can be precluded. Nevertheless, absolute positions of reflectors obviously cannot be measured by means of ultrasonics or radar with measurement uncertainties comparable to the values calculated for the measurands composed of a multitude of sampling points in the present case. However, the approach is consistent to the conclusion in (Thoft-Christensen & Baker, 1982), that the definition of the distribution of a basic variable by means of analyzing empirical data then results in convenient models, if the distribution is synthesized incorporating all available information about *components* of uncertainty.

3.4 *Stochastic models of the basic variables*

A concept for the transformation of non-destructively obtained measurement results expressed according to the GUM into FORM input quantities will shortly be published in (Küttenbaum, 2020). The imaging of the measured data and the calculation of the measurands d_{Sp} and s_{w} dealt with in this paper are described further in (Küttenbaum *et al.*, 2019), (Küttenbaum *et al.*, 2021). The individual specifications in modelling the geometrical basic variables considered in the present case-study are summarized below:

The NDT-based basic variables d''_{Sp} and s''_{w} equal the related measurands. The statically indeterminate part of the prestressing M''_{VP} has been updated based on the measured curves of the tendons. This will not be discussed further here. The FORM is not merged with the measurement uncertainty calculation, since the operating points differ in linearization, in order to maintain comparability of measurement results, and because both methods serve different purposes. The combined measurement uncertainty (cf. equation (6)) is taken as standard deviation of the best estimate of the measurand and is consequently a suitable measure to describe the scattering of the characteristics to be modelled by the basic variables (here: d''_{Sp} and s''_{w}).

The tail sensitivity problem (c.f. (Diamantidis, 2001), (Benjamin & Cornell, 1970), (Ditlevsen, 1994), etc.) plays a minor role in the present case, since the modelling recommendations given e. g. in (JCSS, 2001/2002), as well as the initial basic variables and the measurands follow normal distributions, respectively. In other cases, the inclusion of conjugate priors via Bayes' theorem might become necessary. Additional uncertainties need not to be covered here, since the statistical uncertainties are negligible due to large numbers of observations (an advantage of conducting NDT), and because competing models from which one would have to be chosen arbitrarily based on the information available are delimited here. Any prior knowledge about the vertical positions of the tendons that have not been reliably detected was already incorporated in the measurand calculation.

Table 1. Initial stochastic models of the basic variables, extracted from (Küttenbaum *et al.*, 2021).

Basic variable (initial)	Distribution type and parameters: Type	Mean	CoV
Concrete strength f_{c}	Normal	35 MN/m²	8,6 % [1)]
Prestr. steel. str. f_{p}	Normal	1536 MN/m²	2,6 % [2)]
Yield strength f_{y}	Normal	400 MN/m²	7,5 % [3)]
Height midspan h_{F}	Normal	1,40 m	0,7 % [3)]
Height (axis 20) h_{S}	Normal	2,25 m	0,4 % [3)]
Width cross-sect. b	Normal	1,56 m	0,6 % [3)]
Tendon position d_{Sp}	Normal	0,247 m	12 %
Pos. reinforcem. d_1	Normal	0,18 m	5,6 % [3)]
Pos. reinforcem. d_2	Normal	0,13 m	7,7 % [3)]
Coefficient α_{R}	const.	0,8	
Coefficient k_{a}	const.	0,4	
Height compr.zone ξ	const.	0,29	
Concr. strut angle θ	const.	31,07°	
Angle stirrups α	const.	90°	
Area prestr. steel A_{sp}	Normal	$5{,}47 \cdot 10^{-2}$ m²	3,0 % [4)]
Area stirrups A_{sw}	Normal	$6{,}93 \cdot 10^{-4}$ m²	3,0 % [5)]
Spacing stirrups s_{w}	Normal	0,15 m	6,7 % [3)]
Model uncert. $U_{\mathrm{R,M}}$	Log.-N.	1,025	7,0 % [6)]
Model uncert. $U_{\mathrm{R,s}}$	Log.-N.	1,1	10 % [7)]
$-\parallel-$ (bending) U_{E}	Log.-N.	1,0	7,0 %
$-\parallel-$ (shear) U_{E}	Log.-N.	1,0	10 % [3)]
Dead loads M_{G}	Normal	18,933 MNm	10 % [4)]
Prestr. ($M_{\mathrm{cp,ind}}$) M_{VP}	Normal	13,279 MNm	5,0 %
Traffic loads M_{Q}	Gumbel	7,589 MNm	15 % [8)]
Dead loads V_{G}	Normal	5,339 MN	5,6 %
Prestressing V_{P}	Normal	−1,455 MN	5,0 %
Traffic loads V_{Q}	Gumbel	1,276 MN	15 % [8)]

[1)] (Spaethe, 2013), (Rüsch *et al.*, 1969), (Mirza *et al.*, 1979)
[2)] (JCSS, 2001/2002), (Jacinto *et al.*, 2012)
[3)] (JCSS, 2001/2002) [4)] (Braml & Wurzer, 2012)
[5)] (JCSS, 2001/2002), (Braml & Wurzer, 2012)
[6)] (Bach, 1992) [7)] (Braml *et al.*, 2009) [8)] (Braml, 2010)

Table 2. NDT-based stochastic models, extracted from (Küttenbaum *et al.*, 2021).

Basic variable (NDT-based)	Distribution type and parameters		
	Type	Mean	CoV
Tendon position d''_{Sp}	Normal	0,223 m	0,6 %
Spacing stirrups s''_w	Normal	0,148 m	0,1 %
Prestr. ($M_{cp,ind}$) M_{VP}	Normal	13,763 MNm	5,0 %

This reflects an advantage of the GUM-concept: All information can be processed. The modelling results can be found in table 2. With respect to the relatively small uncertainty covered in s''_w, it should be noted, that only the relative distances of the reflectors to each other in the measurement coordinate systems are of interest. The number of observations is large and the precise absolute position of the stirrups irrelevant.

3.5 *NDT-supported reliability analyses*

The NDT-supported reliability analyses are based on equations 1 and 2 and on the stochastic models given in tables 1 and 2, with the NDT-based basic variables listed in table 2 substituting the corresponding initial models given in table 1. The results are plotted in Fig. 6, analogous to the initial results in Figure 5.

The values of the reliability index increase by $\Delta\beta = +0{,}14$ (+ 13 %) in ULS shear and slightly by $\Delta\beta = +0{,}27$ (+ 4 %) in ULS bending. The values of the sensitivity factors of the NDT-based quantities tend to zero, because the uncertainties covered lead to the quantities d_{Sp} and s_w being stochastically insignificant after incorporating the information measured onsite. The elasticities of the standard deviations are correspondingly small.

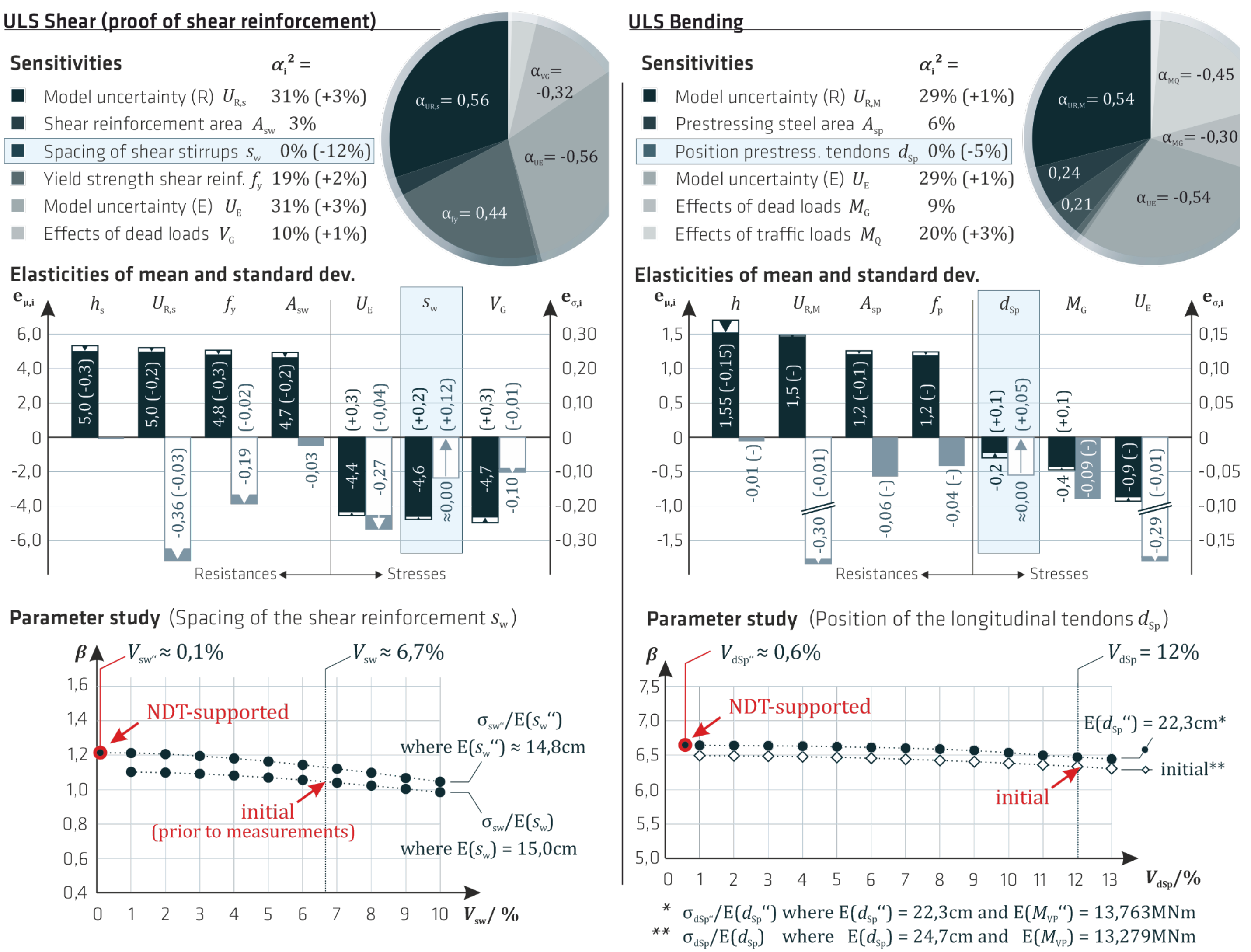

Figure 6. Results of the sensitivity analyses, elasticity analyses and parameter studies incorporating the measured information; stated changes refer to the initial results given in Figure 5; extracted from (Küttenbaum *et al.*, 2021), translated

The elasticities of the means further indicate that a change in stirrups spacing $\Delta\mu_{\mathrm{sw}}$ would continue to have a significant effect on the structural reliability in ULS shear. In contrast, a shift of the vertical position of the tendons in ULS bending has less effects on the reliability in this specific case. The value of $e_{\mu,dsp}$ is comparatively small, since the elasticities are defined by a one percent change in a parameter and the mean value of d_{sp} is small. Nevertheless, the inner lever arm z has a significant influence on reliability, as can be seen i. a. from $e_{\mu,h} = 1{,}55$.

The functions of the reliability index against the scattering characteristics of the NDT-based basic variables plotted in Figure 6 illustrate on the one hand the effects of the incorporation of the measured data on the reliability. On the other hand, the flat function curves in the area around the NDT-based uncertainty provide information about a certain robustness of the measured data-based stochastic models.

Overall, the measurement of s_{w} is precise, simple and fast, the quantity sensitive and a bias regarding previously available information significant. The measurement of d_{sp} turns out to be difficult in the present case because not all tendons could be located reliably. The increase in reliability after including the measured tendon positions is small in this specific case. In comparison to the initial models, the effects of the larger inner lever arm and of the higher value of the (destabilizing) bending moment due to the statically indeterminate effect of the prestressing largely equalize.

4 CONCLUSION AND OUTLOOK

If information on a system is the essential basis for decisions regarding the reliability of structures, then the utility of all eligible sources of relevant, quality-evaluated information in reassessment should be analyzed. This paper emphasizes how measurement results generated demand-oriented, onsite and non-destructively can be used explicitly as basic variables in the probabilistic reassessment of the bending and shear load-bearing capacity of a prestressed concrete bridge and what effects the implementation of the non-destructively measured information can have. This can be seen as a first step towards considering NDT as an additional component in and an expansion of the number of reliable sources of information for reliability assessments of existing bridges. Regarding the case-study, the radar measurement of the stirrup spacing particularly proved to be simple and useful. The effect of incorporating the measured position of the tendons is individually small and the solution of the testing task complex, among others because a large number of tendons should be detected whose distances correspond approximately to the tendon duct diameters.

The state of knowledge about the investigated bridge was sufficient prior to the measurements. Plans, reports of structural analyses, etc. were available. The measurement-supported reliability assessment as shown in this paper is particularly useful if information required for the reassessment is missing or doubts about relevant information have arisen. Not only the uncertainty but also the bias in the stochastic models can be reduced. In addition, the application of the harmonized rules of the GUM-framework, whose main objective is to ensure the comparability of measurement results, can also increase the comparability and, as the circumstances require, the robustness of individual reliability analyses. In any case, the level of approximation of the computation model used for the reassessment can be increased.

The results presented are part of an ongoing research project. An intermediate objective is to simplify the concept outlined in this contribution to a semi-probabilistic approach. Characteristic values and individual, structure-specific partial safety factors are to be derived on the basis of data individually measured onsite non-destructively. A further goal is to quantify the utility and the value of non-destructively measured information in the reassessment process. One metrological goal is to methodically combine approaches for deriving the detection capability of NDT-systems, such as POD-analyses, with measurement uncertainty considerations. Based on this, the measurement uncertainty of combined measurands such as the center of a tendon bundle could be plotted against the number of objectively and reliably detected components of such measurands. Additionally, the comparable specification of strengths, weaknesses and limitations of non-destructive measurement procedures as well as the designation of uncertainties that can reasonably be expected under certain boundary conditions allows a purposeful planning and commissioning of tests to be performed at a structure. For this purpose, systematic investigations of the input quantities under typical boundary conditions are conducted and the effects of changes in the conditions on the measurement results are analyzed.

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