HIERARCHICAL MODELLING OF UNCERTAINTY IN NDT TESTS OF HISTORIC STEEL BRIDGES

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Abstract. *Sustainable development can be supported by extending the service lives of existing road and railway bridges. Preservation and upgrade should be based on improved surveys, monitoring, reliability assessment, and strengthening methods. In the case of metallic materials, hardness methods (NDT) calibrated by a few tensile tests (DT) were shown to be associated with reasonable measurement uncertainty. This contribution discusses the current practice in assessment based on NDT results and introduces the hierarchical modelling of the measurement uncertainty in hardness tests. Preliminary results suggest that the variability of ultimate strength can hardly be estimated on the basis of NDTs only. It seems that the systematic component of measurement uncertainty has a lower coefficient of variation (3%) than the random component (8%); the variability of the latter may thus often exceed the variability of the ultimate strength of a homogeneous material.*

Keywords

Existing bridges, structural assessment, hardness methods, hierarchical modelling, measurement uncertainty.

1. Introduction

The need to address sustainability aspects in construction jointly with significant economic interests resulted in adding the assessment and retrofitting of existing structures into the revision of Eurocodes [1]. Under this highly prioritised work item, new European technical rules for assessment were developed [2] and are intended to become part of the presently revised EN 1990 for the basis of design (prEN 1990-2).

Sustainable development can be significantly supported by using existing lines and crossings, and this leads to the urgent need for extension of service lives of existing bridges [1]. Preserving and upgrading of existing bridges should be based on improved surveys, monitoring, structural assessment, and strengthening methods [3]. In the case of historic steel (metal) bridges, the considerable scatter of mechanical properties and missing design documentation necessitate tests and measurements to obtain sufficient information for structural assessments [4] and [5]. The use of various non- or minor-destructive tests (NDTs) is often preferred to destructive tests (DTs) to reduce the cost of structural survey and damage to the structure.

For metallic materials, hardness methods associated with reasonable measurement uncertainty and may provide a useful basis for structural assessments [6] and [7]. To avoid gross errors in NDT results, structure-specific calibration of NDTs by at least one tensile test, DT, is needed [8].

While the calibration based on a few DTs reduces the systematic component of NDT measurement uncertainty, the random component (aleatory component in the modelling framework adopted in the following analysis) cannot be eliminated. Taking a starting point in the previous studies [6] and [7], this contribution discusses the current practice in NDT assessment, introduces a hierarchical modelling of the measurement uncertainty in hardness tests, and quantifies its systematic and random components.

2. Experimental Database

The database contains 32 pairs of ultimate strength values based on NDTs and DTs, taken from eight historic railway bridges built in the early 20th century. The test methods under investigation are as follows:

- DT results are based on the tensile test according to ISO 6892 for tensile testing of metals under normal temperatures. The test uncertainty is negligible (coefficient of variation, $V < 1\%$) [9].
- NDT: the hardness method according to Leeb (see EN ISO 16859, Parts 1 to 3) considering an empirical relationship to convert hardness values to ultimate strength estimates.

The database contains tests on historic steels (no wrought irons). The materials are assumed to provide a homogeneous sample for the investigation of measurement uncertainty.

3. Current Practice

When material strengths are estimated from NDTs, it is a common practice to calibrate the mean of NDTs by a few DTs and to assume that the standard deviation of NDTs, σ_{NDT}, is a representative (or conservative) estimate of the scatter of the ultimate strength, σ_{DT}. Fig. 1 shows the sample standard deviations [10] obtained from NDT and DT results for each of the eight bridges in the database.

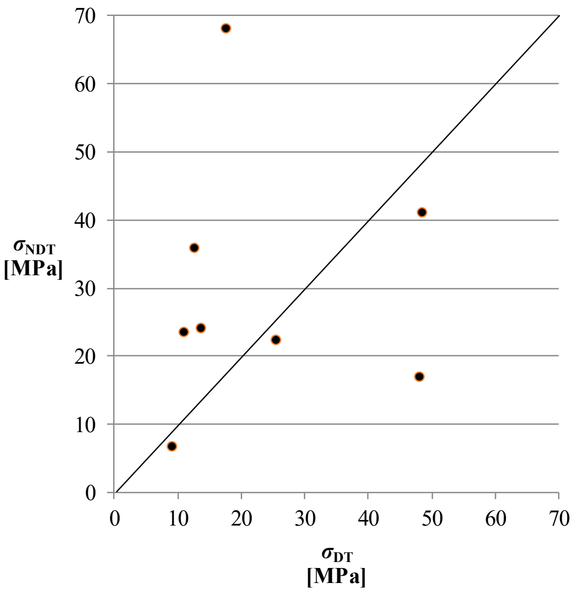

Fig. 1: Sample standard deviations obtained from NDT and DT results for each of the eight bridges in the database.

Fig. 1 shows that σ_{NDT} underestimates σ_{DT} in half of the cases and provides a rough approximation of σ_{DT} only. It is emphasised that this finding is only preliminary – the database is small, and the σ_{NDT}- and σ_{DT}-values are on average estimated on the basis of merely four measurements.

4. Hierarchical Model of Measurement Uncertainty

4.1. Systematic and Random Components

In accordance with the JCSS Probabilistic Model Code [11], it is assumed that a NDT result equals to the DT outcome affected by Θ_{ran} (component of measurement uncertainty Θ, random for each measurement) and by Θ_{sys} (error systematic for a NDT survey of a particular structure, but random amongst structures).

Measurement uncertainty depends on the combined effect of the imprecision of the technique, device and their application. Based on the authors' experience with hardness tests, the factors influencing measurement uncertainty might be classified as follows:

- Dominantly affecting Θ_{ran}:

- Between structural members - stiffness and mass of the specimen (a NDT should be applied in the stiff and heavy areas, preferably stiffened by stiffeners or close to them; the testing of thin plates far from stiffeners must be avoided).
- Between structural members – partly also the slope of the investigated member (horizontal vs. vertical measurements) – this uncertainty is commonly compensated or eliminated by modern devices.
- Homogeneity of hardness of the material (the outer parts of the plates have higher strength and hardness than the inner parts due to the rolling).

- Affecting both Θ_{sys} and Θ_{ran}:

- Skills and experience of the worker
- Quality of the specimen surface that must be properly grinded to a smooth surface.

This study is focused on the uncertainty in model parameters – probabilistic distribution parameters of Θ. Considerations of some aspects (including the repeatability of a testing device – proper calibration of the device, number of measurements at a particular location, or possible elimination of extreme values from the sample to estimate hardness at a location) are beyond the scope of the presented analysis.

4.2. Model

For bridge i, a probabilistic relationship between NDT measurements ndt_{ij} and DT measurements dt_{ij} taken at the bridge can be established:

$$\theta_{sys,i} \sim \mathrm{LN}(\mu_{sys}, \sigma_{sys}), \quad (1)$$

$$\theta_{rnd,ij} \sim \mathrm{LN}(\mu_{rnd}, \sigma_{rnd}), \quad (2)$$

$$ndt_{ij} = \theta_{sys,i}\, \theta_{rnd,ij}\, dt_{ij} \sim \mathrm{LN}(\theta_{sys,i}\, \mu_{rnd}, \theta_{sys,i}\, \sigma_{rnd})\, dt_{ij} \quad (3)$$

Using capital letters to denote distributions of random variables (also as in Section 4.1) and lower-case letters to denote particular realizations of the distributions in Eq. (1) - (3), the following notation applies:

- Θ_{sys} – the same distribution for all bridges with $\theta_{sys,i}$ as its random realization for bridge i;
- Θ_{ran} – distribution is identical for all NDTs and all bridges with $\theta_{rnd,ij}$ being its random realization;
- LN – two-parameter lognormal distribution with mean μ and standard deviation σ;
- dt_{ij} – random realization of the material property (the true value – measurement uncertainty in DTs is ignored).

Note that measurement uncertainty is often described by a normal distribution [12]. In the case under investigation, the choice between these two types of distributions is of low importance and variability of the measurement uncertainty is low.

In Fig. 2, the DT to NDT ratios are plotted. The short horizontal lines indicate the mean ratio for a particular bridge. In the presented simplified approach, each short line thus represents a realisation $\theta_{sys,i}$ and the scatter of the dots around a respective line is indicative of Θ_{ran}.

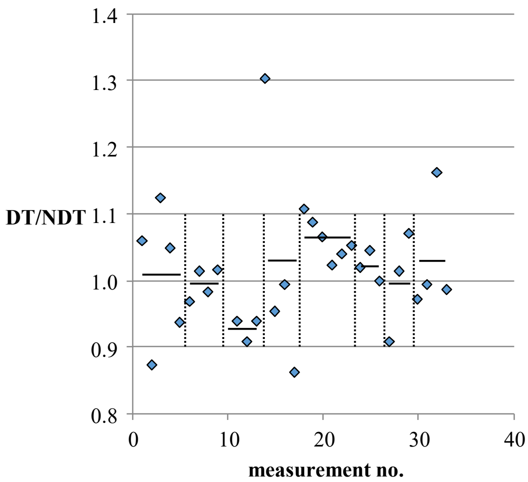

Fig. 2: DT to NDT ratios – illustration of systematic and random components of the measurement uncertainty (the dotted lines separate the measurements for different bridges).

The eight observations of Θ_{sys} lead to the estimate of the mean $\mu_{\Theta sys} \approx 1.03$ and of a low coefficient of variation $V_{\Theta sys} \approx 2.7\%$. Analysis of all 32 observations reveals that the random component is unbiased and has a comparatively higher coefficient of variation, $V_{\Theta ran} \approx 7.8\%$. This finding is consistent with that made in Section 3 – while the bias in NDTs can be corrected by calibration considering DTs, the random component of measurement uncertainty is quite significant and exceeds the variability of the ultimate strength of a homogeneous material in common cases.

More refined analysis of measurement uncertainty, based on the desired extension of the database, may provide background information for investigation of the efficiency of calibration by DTs. Related uncertainties can then be quantified and considered in the framework of the partial factor method.

5. Discussion

Based on a limited database and using a simplified approach, this contribution provides only the first insight into the hierarchical modelling of measurement uncertainty in hardness tests. Further investigations should be focused on the effect of within-structure non-homogeneity on measurement uncertainty. It is widely recognized that different strengths are commonly observed for rolled sections and plates as a result of the production process. The first analysis suggests that a slightly higher coefficient of variation is obtained for plates.

Regarding practical applications, it is emphasised that measurement uncertainty can be considerably reduced, mainly:

- Measurements should be conducted by an experienced worker.
- Specimen surface must be adequately treated.
- Measurements should be taken at stiff (and possibly heavy) areas, preferably stiffened by stiffeners or close to them; the testing of thin plates far from stiffeners, at edges of plates or at locations where vibrations and resonance may occur must be avoided.

Besides the desired extension of the database, future research should provide answers to the following questions:

- Can different hardness test methods (static or dynamic) be described by the same model for measurement uncertainty? First results seem to suggest so [6] and [7].
- Is the multiplicative format for Θ—see Eq. (1) and (2)—appropriate, or should the additive format or their combination be preferred?
- Can the random and systematic components of measurement uncertainty be described by the same distributions for various structures?
- What is the statistical uncertainty in Θ_{sys} and Θ_{ran} using the frequentist or Bayesian approach?
- Is the hierarchical modelling needed for practical applications or would it be sufficient to describe measurement uncertainty by a single random variable as was considered e.g. in [6] and [7]?

It might well appear that the random component of measurement uncertainty is dominating and it may be sufficient in practical applications to describe the measurement uncertainty ignoring the systematic component.

6. Conclusion

The limited database providing the basis for this study makes it possible to provide only preliminary concluding remarks about measurement uncertainty in hardness methods for historic steels:

- Variability of ultimate strength can hardly be estimated on the basis of NDTs only.
- Systematic component of measurement uncertainty is found to have a significantly lower coefficient of variation (3%) than the random component (8%).
- The variability of the latter may thus often exceed the variability of the ultimate strength of a homogeneous material and the efficiency of calibration by DTs can be doubtful. A more reasonable approach seems to be to verify homogeneity of the material by NDTs and establish the model for ultimate strength from DTs.
- The topics of further research include investigations into the effect of within-structure non-homogeneity on measurement uncertainty, uncertainties in various NDT methods, and appropriate approaches to hierarchical modelling and to statistical inference.

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