UNCERTAINTIES IN CHARACTERISTIC STRENGTHS OF HISTORIC STEELS USING NON-DESTRUCTIVE TECHNIQUES

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Abstract. *The use of various non- or minor-destructive tests (NDTs) is often preferred to reduce the cost of structural surveys of historic structures made of cast and wrought irons or old carbon steels. This contribution thus explores the measurement errors associated with common NDT techniques and quantifies uncertainties in characteristic strength estimates based on NDTs only. It appears that a unity mean and coefficient of variation of 12% might be adopted for the measurement uncertainty of the methods under study (Brinell, Leeb, Poldi, Vickers, Rockwell). On average, the true characteristic ultimate strength is by ~15% larger than that based on many NDTs. This represents the expected gain when the characteristic value is estimated from five DTs instead of a large number of NDTs. In practice detailed reliability assessments should always be based on results of DTs or at least on NDTs properly calibrated by DTs.*

Keywords

Historic steel, characteristic strength, iron, measurement error, non-destructive test, uncertainty.

1. Introduction

The mechanical properties of historic metal materials such as cast and wrought irons or old carbon steels exhibit a considerable scatter dependent on periods of construction and the region of a producer, resulting in differences in the production procedure, its quality and alloy composition [1] and [2]. Commonly, the design documentation for historic structures is missing and there is no clear relationship between material strengths and year of execution for historic steel bridges in the Czech Republic [3]. This is why the information for their assessments needs to be based on measurements and tests only [4] and [5]. The use of various non- or minor-destructive tests (NDTs) is often preferred over to destructive tests (DTs) to reduce the cost of structural survey and damage to the structure.

However, limited attention has been paid to the investigation of uncertainties in characteristic strength estimates based on NDTs only. This is why the submitted contribution explores the measurement errors associated with common NDT hardness techniques and quantifies uncertainties in characteristic strength estimates. The measurement uncertainty is assessed considering the database of pairs of NDTs and DTs taken from historic structures from the 19th century.

2. Experimental Database

The database contains 119 pairs of NDT and DT results obtained from mostly railway bridges and some buildings from the second half of the 19th century. Most of the test results were published in previous scientific contributions [6], [7], [8], [9] and [10]. The tests of tensile strength were conducted by the following methods:

1. DT results are based on tensile tests according to ISO 6892 for tensile testing of metallic materials under normal temperatures. The test uncertainty is negligible (coefficient of variation, “CoV”, $V < 1\%$) [11].
2. The following NDT methods were used to determine ultimate strength of historic steels on the basis of empirical relationships with hardness of the material:

- static (Brinell, Rockwell, Vickers),
- dynamic (Poldi hammer, Leeb).

The materials under investigation include wrought irons and historic steels.

3. Measurement Uncertainty

In line with common practice, the measurements taken at a structure are assumed to be independent observations. The database contains no obvious outliers; for instance, measurements beyond the limits of calibration curves or very small/ high NDT strengths in pairs with moderate DT strengths that could explained as measurements at local non-homogeneities.

The measurement uncertainty ε is treated here as a random variable. A widely adopted multiplicative format for measurement uncertainty is taken into account:

$$f_{DT} = \varepsilon\, f_{NDT}, \qquad (1)$$

where f denotes strength of the material.

Following the observations related to model uncertainty [12], the multiplicative format is more appropriate when the difference between measurements and true values – DT strengths here – is proportional to the latter. When the difference is independent of the magnitude of a true value, the additive format becomes more appropriate.

The multiplicative format is assumed hereafter to be representative for NDT measurements. Outliers are detected by the significance test (Grubb's test [13]) and excluded from further analyses (one NDT result for Brinell, Vickers, and Leeb tests). The measurement uncertainty characteristics – mean μ_ε and CoV V_ε – are given in Tab. 1. NDT results are compared with respective DTs for a) Brinell, b) Leeb, and c) all hardness methods in Fig. 1.

Considering broadly different sample sizes for the NDT methods, the measurement uncertainty characteristics in Tab. 1 indicate that the same mean and CoV might be adopted for the methods under study in a first approximation, $\mu_\varepsilon \approx 1$ and $V_\varepsilon \approx 12\%$. This assumption is also supported by:

- the same principle of the methods, based on the relationship of hardness and material strength,
- similar factors influencing the measurement uncertainty and thus by the similar expected magnitude of associated uncertainty.

Tab.1: Measurement uncertainty characteristics for various NDT methods.

Method	Sample size n	Mean μ_ε	CoV V_ε
Brinell	35	0.98	12 %
Leeb	51	1.01	12 %
Poldi	18	1.01	12 %
Vickers	10	0.89	18 %
Rockwell	5	1.00	7 %
All	119	0.99	12 %

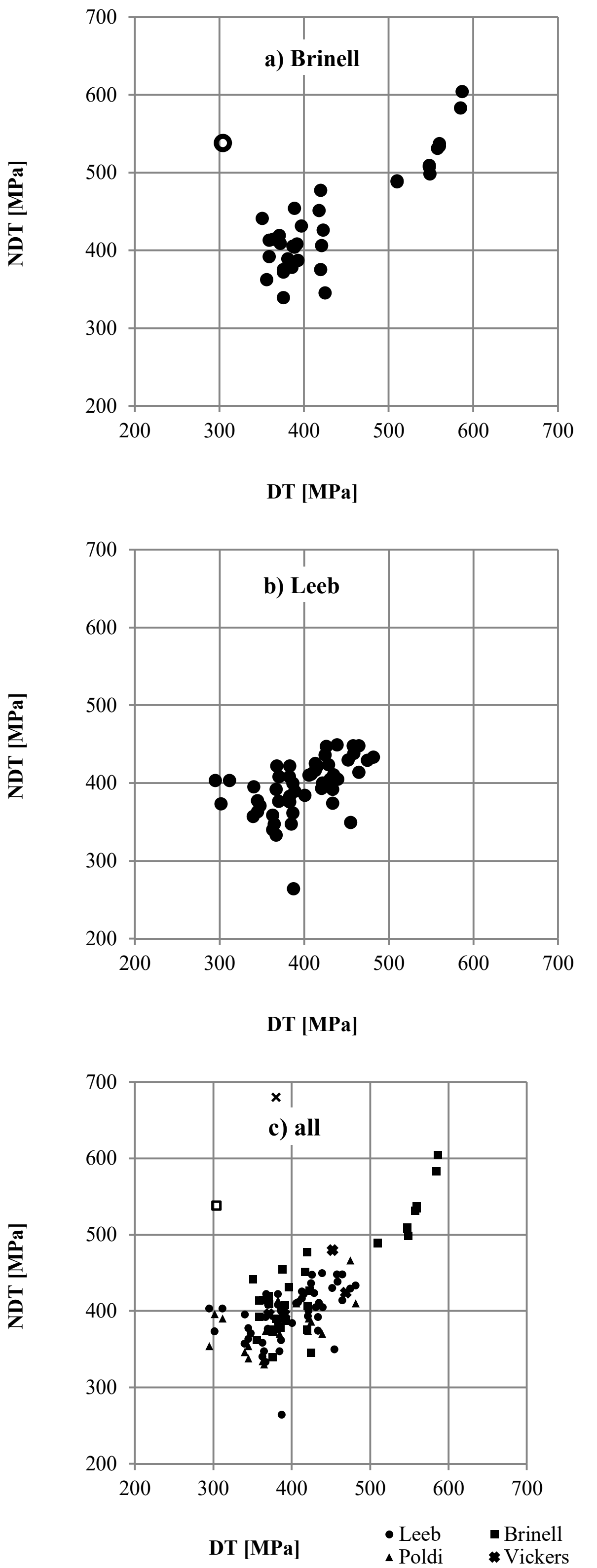

Fig. 1: Comparison of NDTs and DTs for a) Brinell, b) Leeb, and c) all hardness methods (outliers marked).

Note that these factors include skills and experience of the worker, quality of specimen surface, stiffness and mass of the specimen, repeatability of the testing device, homogeneity of hardness of the material, number of measurements to estimate hardness in one location, and partly also the slope of the investigated member (horizontal vs. vertical measurements though commonly compensated when converting hardness to strength).

Further, a lognormal distribution that is commonly adopted in conjunction with the multiplicative format of the model or measurement uncertainty [14] is assumed for the measurement uncertainty.

4. Uncertainty in Characteristic Strength Estimate

The effect of the measurement uncertainty on the estimate of characteristic ultimate strength is investigated by means of simulations:

1. Ultimate strength of wrought irons and historic steels is often similar to that of the modern steel S235, [3], [15] and [16]. The authors' database indicate that a true ultimate strength of the material of a particular investigated historic structure could be described by:

- characteristic ultimate strength f_{uk} = 350 MPa, V_{fu} = 5%, and μ_{fu} = 380 MPa, and
- a lognormal distribution.

These assumptions are in a broad agreement with the information on historic metals given in ČSN 73 0038 – the Czech standard on the assessment of existing structures – as well as with the generic models for modern steels provided in [14] and with empirical experience [17]. It is emphasised that these characteristics apply for a homogeneous material – it is often observed in surveys of historic bridges that material properties differ amongst various members such as between main girders and secondary members, beam and plate members etc.

2. The number of NDTs, n_{NDT} (study parameter here) is typically determined by the need to have a reasonable survey of the structure, or of its larger part; it is commonly relatively large, say around 25. NDT results are sampled as follows:

- A random realisation of a true strength, $f_{u,i}$ (i = 1..n_{NDT}), is simulated from a lognormal distribution with the assumed mean and CoV.
- Using Eq. (1), the NDT result is simulated as $f_{u,NDT,i} = f_{u,i} / \varepsilon_i$ where the denominator is a random value obtained from the lognormal distribution with μ_ε = 1 and V_ε = 12%.
- The estimate of characteristic strength based on n_{NDT} results, $f_{uk,NDT}$, is obtained using the approach in Annex D of EN 1990:2002 (assuming a lognormal distribution and "unknown CoV").
- The error in the estimate then becomes $\theta_j = f_{uk} / f_{uk,NDT,j}$ = 350 MPa / $f_{uk,NDT,j}$.

3. This procedure is repeated n_{sim}-times (j = 1..n_{sim}), to obtain mean and CoV of the error unaffected by statistical uncertainty. In this study n_{sim} is 1000.
4. To highlight the effect of the measurement uncertainty, similar simulations are generated considering that a number of DTs, n_{DT}, is available. In this situation the measurement uncertainty is negligible and DT results are assumed to be equal to $f_{u,i}$. The estimate of characteristic strength, $f_{uk,DT}$, is again obtained using Annex D of EN 1990:2002. The error in the estimate then becomes θ_j = 350 MPa / $f_{uk,DT,j}$.

The variability of the mean, CoV and confidence intervals of the error θ with a number of tests is displayed in Fig. 2. While the mean μ_θ already approaches unity effectively for a very small number of DTs, say up to five, the measurement uncertainty results in a scatter of NDT results and μ_θ is far from unity (converging to about 1.15). This suggests that, on average, the true characteristic strength is by ~15% larger than that based on a very large number of NDTs while already for n_{DT} = 5 the f_{uk} estimate becomes reasonably unbiased, μ_θ = 1.03. The similar trends are observed for the CoV of the error θ. Both mean and CoV are then reflected by the confidence intervals plotted in Fig. 2c). It is observed that for higher numbers of tests, say n_{NDT} > 15 and n_{DT} > 5, the expected difference between $f_{uk,NDT}$ and $f_{uk,DT}$ is around 15%. This represents the expected gain when the characteristic value is estimated based on five DTs instead of a large number of NDTs.

5. Discussion

The present study provides the background information for further research that will be aimed to deliver the methodology for estimating design strength values of historic metals based on NDTs and a small number of DTs. When deriving the partial factor, the uncertainty in geometry and model uncertainty need to be considered in addition to the variability of a material property [2], [7] and [18].

According to the best present practice, material properties based on NDTs only are only used in preliminary reliability assessments (see ISO 13822:2010 for the assessment of existing structures and the background material for developing the guidance on existing structures in Eurocodes [19]). The detailed assessments should always be based on results of DTs or at least on NDTs properly calibrated by few DTs. This is also in partial agreement with the study on wrought iron bridges by Gordon and Knopf [20] who concluded that, as a consequence of the composite nature of the material, there is a poor correlation between strength and hardness and the standard conversions between different measures of hardness do not apply.

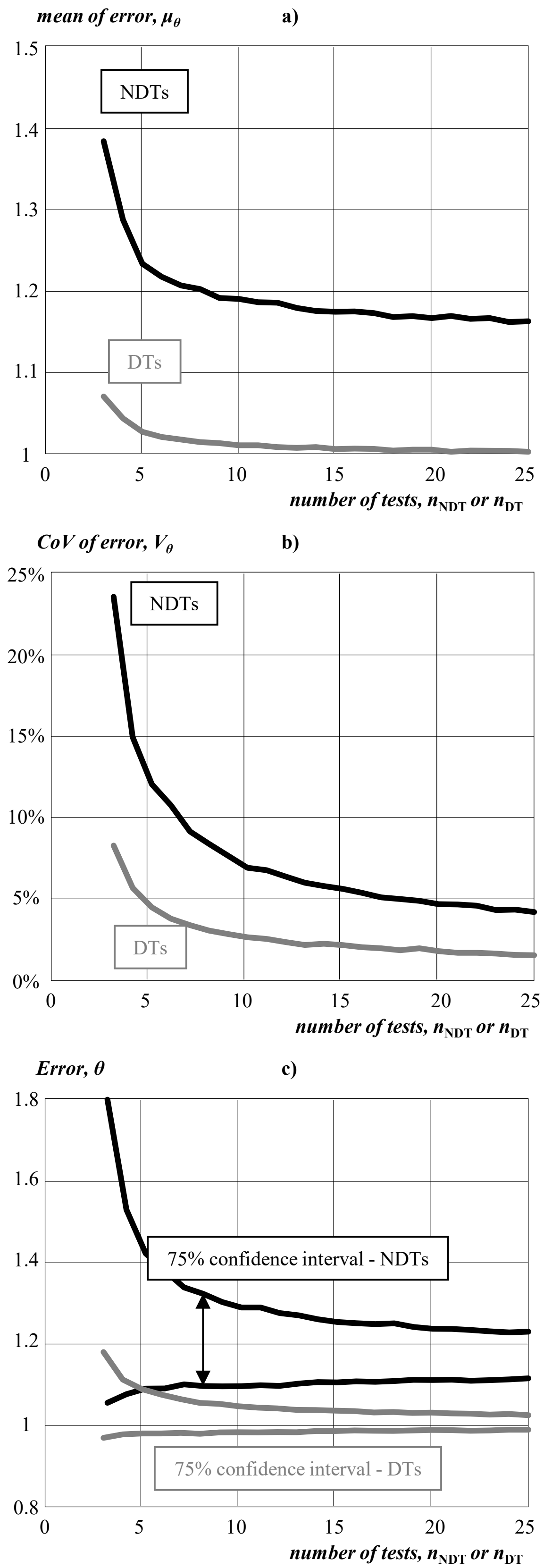

Fig. 2: Variability of the characteristics of the error θ with a number of tests: a) mean, b) CoV, c) confidence intervals.

In practice, the ultimate strength is typically utilised in a limited number of cases; e.g. when assessing resistance of rivets, joints or of sections with holes. Mostly f_u needs to be converted to yield strength, f_y. The authors' large database consists of 265 pair measurements of ratio $\alpha = f_y / f_u$ for historic bridges dated back to 1865-1940. The preliminary analysis indicates that the ratio α:

- exhibits no trend with time, yield or ultimate strength,
- could be described by the mean value of 0.8 and CoV of 10 %.

It thus appears that the CoV of α is comparable to that of measurement uncertainty and it is considerably larger than V_{fu}. As the ratio α largely depends on the chemical composition of the alloy, further investigations are needed to improve the information on its statistical properties and propose a procedure on how to include the uncertainty in α in practical reliability assessments.

Further research will also be focused on:

- investigating the ability of NDTs in identifying non-homogeneity of the material,
- detailed analysis of NDT uncertainty with respect to the type of the method and type of an investigated material,
- critical comparison of the additive and multiplicative formats for measurement uncertainty,
- providing a methodology for estimating resistance characteristics of historic metal structures, considering also previous studies in this field [21] and [22]; see also the first results in [23].

6. Concluding Remarks

As the mechanical properties of historic metal materials exhibit a considerable scatter, the information for reliability assessments needs to be commonly based on measurements and tests only. This contribution explores the measurement errors associated with common NDT hardness techniques and quantifies related uncertainties in characteristic strength estimates. The numerical analysis indicates that:

- Unity mean and coefficient of variation of 12% might be adopted for the measurement uncertainty of the methods under study (Brinell, Leeb, Poldi, Vickers, Rockwell) as a first approximation.
- While the mean of the error in the estimate of characteristic ultimate strength (5% fractile) approaches unity effectively for a very small number of DTs, the measurement uncertainty results in a scatter of NDT results and the mean of the estimate is far from unity. On average it is expected that the true characteristic strength is by ~15% larger than that based on a very large number of NDTs. This represents the expected gain when the

characteristic value is estimated based on five DTs instead of a large number of NDTs.

- To derive the design value, the estimate of a 5% fractile needs to be divided by a partial factor that accounts for the uncertainty in geometry and model uncertainty in addition to the variability of strength (and possibly other factors such as target reliability or relative importance of the resistance variables with respect to the limit state under consideration).

It is emphasised that detailed reliability assessments should always be based on results of DTs or at least on NDTs properly calibrated by DTs.

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