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Probabilistic Assessment of a Former Factory for Boiler Production

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ABSTRACT: Structures registered as industrial culture heritage are mostly of significant architectural, historic, technological or societal value. At present considerable effort is aimed at re-use of such structures in order to preserve their cultural and heritage value and to avoid wasting energy. Decisions about adequate construction interventions should be therefore based on the complex assessment of a structure considering actual material properties, environmental influences and satisfactory past performance. Probabilistic procedures seem to provide suitable tools in this context. Application of the procedures is illustrated by an example of the structural assessment of a former factory for boiler production from 1900s. Reliability of a long-span roof truss girder is verified. Two fundamental cases of probabilistic updating are described: (1) updating of the yield strength of steel using prior information and few newly obtained test data, and (2) direct updating of failure probability considering satisfactory past performance of the structure.

Keywords: industrial heritage, probabilistic updating, reliability assessment

1 INTRODUCTION

A number of factories, warehouses, power plants and other industrial buildings has been worldwide registered as industrial cultural heritage. Such structures are mostly of significant architectural, historic, technological or societal value. Protection (including adaptations and re-use) of these structures is an important issue, positively contributing to the sustainable development of urban areas by:

• Preservation of cultural values - the heritage value of the structure commonly originates from its uniqueness, quality of craft execution, relationship with an important event or person, urban context, importance as a landmark etc.;

• Recycling of potential resources and avoiding wasting energy;

• Facilitating the economic regeneration of regions in decline.

However, insufficient attention seems to be paid to systematic recognizing, declaring and protecting the industrial heritage in most countries. This is an alarming situation as the lack of attention and awareness of the industrial structures may gradually lead to their extinction. When out of use the industrial heritage buildings are degrading and often turning into ruins. Re-use and adaptation to hotels, museums, residential parks, commercial centres etc. help protect cities’ cultural heritage. Some of these structures are long-span roof or floor structures, flexible for future use. The protection of the industrial heritage is a multidisciplinary topic including historic, architectonic, civil engineering and ecological aspects. In 1978 the International Committee on the Conservation of the Industrial Heritage (TICCIH) was founded to study, protect, conserve and explain remains of industrialisation.

It has been recognised that many heritage structures do not fulfil requirements of present codes of practice. Decisions about adequate construction interventions should be based on the complex assessment of a structure. Minimisation of construction interventions is required in rehabilitation and upgrades, but sufficient reliability should also be guaranteed. Application of simplified procedures used for design of new structures may lead to expensive repairs and losses of the heritage value. In the paper a probabilistic procedure is thus accepted to improve the reliability assessment of industrial heritage buildings particularly with respect to:
• Better description of uncertainties related to the assessment and
• Facilitating inclusion of results of inspections and tests and the satisfactory past performance of a structure.

2 PROBABILISTIC RELIABILITY ASSESSMENT

Significant uncertainties related to actual material properties and structural conditions usually need to be considered in the reliability assessment. In design codes a limited number of safety factors is intended to cover all possible design situations. Therefore, verifications based on deterministic design procedures may be too conservative. Application of commonly used design procedures may thus lead to expensive repairs and losses of the heritage value. It follows that the use of deterministic design procedures may not be an appropriate approach.

It has been recognised that assessment of existing structures is a structure-specific task that is difficult to codify. In accordance with (EN 1990, 2002; ISO 13822, 2010) a general probabilistic procedure is thus accepted here to enhance the reliability assessment of the industrial heritage buildings. The procedure facilitates inclusion of results of inspections, testing and consideration of the satisfactory past performance.

Probabilistic methods may be useful for the assessment of existing structures where appropriate data can be obtained. Uncertainties can be greater than in structural design (such as the statistical uncertainty or uncertainties related to inaccessible members and connections) and can be adequately described by such methods. On the contrary, some of the uncertainties reflected (often implicitly) in the load and resistance factors (modelling approximations, deviations from specified dimensions and strengths) may be reduced by in-situ measurements (Ellingwood, 1996).

2.1 Specification of basic variables

Models for basic variables should be adjusted to the actual situation and state of a structure and verified by inspections and testing. The following principles should be taken into account:
• Material properties should be considered according to the actual state of a structure and verified by destructive or non-destructive testing.
• When significant deterioration is observed, an appropriate deterioration model should be used to predict changes in structural parameters due to unforeseen environmental conditions, structural loading, maintenance practices and past exposures, based on theoretical or experimental investigation, inspection and experience.
• Dimensions of structural members should be determined by measurements. When the original design documentation is available and no changes in dimensions exist, nominal dimensions given in the documentation may be used.
• Load characteristics should be introduced considering the values corresponding to the actual situation. For structures with significant permanent actions, the actual geometry should be verified by measurements and weight densities should be obtained from tests.
• Model uncertainties should be considered in the same way as at a design stage unless previous structural behaviour (especially damage) indicates otherwise.

It follows that reliability verification of a heritage building should be backed up by inspection including collection of appropriate data. Evaluation of prior information and its updating using newly obtained measurements may be a crucial step of the assessment.

2.2 Probabilistic updating

The failure probability, related to the period from the assessment to the end of a working life \( t_0 \), can be obtained from a general probabilistic relationship

\[
p(t_0) = P\{\min Z|X(t)| < 0 \text{ for } 0 < t < t_0 \} = P\{F(t_0)\}
\]

(1)

where \( Z() \) = limit state function; \( X() \) = vector of basic variables including model uncertainties, resistance, permanent and variable actions; and \( F(t_0) = \text{failure in the interval (}0,t_0\)).

When additional new information \( I \) related to structural conditions is available, the failure probability may be updated as follows (ISO 13822, 2010)

\[
p^{\ast}(t_0|I) = P\{F(t_0) \cap I \} / P(I)
\]

(2)

The information should be selected to maximise correlation between the events \( \{F\} \) and \( \{I\} \). Strong correlation improves the posterior estimate of failure probability while weak correlation yields nearly the same estimates as based on Eq. (1) (Ellingwood, 1996). The new information may be based on:
1. Inspections that can for instance provide data for the updating of a deterioration model,
2. Material tests and in-situ measurements that can be taken to improve models of material or geometry properties,
3. Consideration of the satisfactory past performance,
4. Intensity of proof loading,
5. Static and dynamic response to controlled loading.

In the first two cases the new information is usually applied in the direct updating of (prior) distributions of relevant basic variables that are commonly based on experience from assessments of similar structures, long-term material production, findings in literature or engineering judgement. The third case may be very important for the industrial heritage buildings as described in detail below. The fourth case is substantially similar to the third one. In the fifth case known structural response to controlled loading can lead to reduction of resistance model uncertainties.

Note that it can be important to consider the satisfactory past performance (the third case) for instance for a structure originally used as a factory that is to be used as a museum or gallery. Such a structure may have resisted to loads much greater than those expected for a future use.

The satisfactory past performance of a structure during a period $t_A$ till the time of assessment may be included in the reliability analysis considering the conditional failure probability $p_f(t_0|t_A)$ that a structure will fail during a working life $t_0$ given that it has survived the period $t_A$. This probability may be estimated in several ways. When the load to which the structure has been exposed during the period $t_A$ is known with negligible uncertainties, the resistance or a joint distribution of time-invariant variables may be truncated (a lower bound is set to the value of load). Using the bounded distribution, the conditional (updated) probability $p_f^{*}(t_0|t_A)$ can be estimated. This approach, similar to the updating for proof loads (JCSS, 2001b), is illustrated elsewhere (Diamantidis et al., 2012). More generally, the updated failure probability may be determined using the following relationship

$$p_f^{*}(t_0|t_A) = \frac{P\{F(t_0) \cap F'(t_A)\}}{P\{F'(t_A)\}} \quad (3)$$

where $F'$ = complementary event to the failure. The updated probability can be determined by standard techniques for reliability analysis such as the FORM/SORM (First/Second Order Reliability Methods) or importance sampling.

Reliability verification can be based on either of the following (equivalent) relationships

$$p_f^{*}(t_0|t_A) < p_f, \quad \beta_f^{*}(t_0|t_A) = -\Phi^{-1}[p_f^{*}(t_0|t_A)] \geq \beta_f \quad (4)$$

where $p_f$ = target failure probability; $\Phi^{-1}$ = inverse cumulative distribution function of the standardised normal variable and $\beta_f$ = target reliability index. The target reliability levels that might be accepted for industrial heritage structures are discussed by (Sykora et al., 2013). Assuming moderate consequences of failure and moderate costs of safety measures $\beta_A = 3.1$ was suggested in accordance with (ISO 2394, 1998).

### 3 FORMER FACTORY FOR BOILER PRODUCTION

The probabilistic approach is applied in a case study of the reliability assessment of a former factory for boiler production built in 1900s (Figure 1). A reconversion is conducted to adjust the building for use as headquarters of a publishing house. An anticipated working life is 50 years.

Characteristics of the resistance and permanent action are specified considering results of on-site surveys and original design documentation. Effects of degradation are negligible. Deterministic assessment reveals that the critical structural member is a steel truss girder supporting the roof (Figure 1). The girder is statically determinate. Suction due to wind pressure, causing buckling of a long-span lower chord of the girder, was identified as the most unfavourable load case; axial and shear forces need not to be taken into account. The following analysis is considerably simplified to illustrate key steps of the probabilistic updating rather than to describe case-specific details. The purpose of the case study is two-fold:

![Figure 1. Former factory for boiler production under reconversion.](image-url)
1. To show development of the probabilistic model for steel strength using non-destructive and destructive tests.
2. To illustrate consideration of the satisfactory past performance.

![PDF](image)

Figure 2. Probability density function of the strength of steel based on results of the hardness tests.

### 3.1 Updating of the steel strength

Dissimilar to present construction materials, prior information for historic materials may not be available. For instance iron and historic steel strengths vary in a wide range depending on a production process and producers. That is why models for properties of historic materials need to be solely based on measurements and standard Bayesian updating (combining prior information with test results) can hardly be performed. However, the technique of the Bayesian updating can be efficiently applied when combining results of non-destructive (affected by a measurement error) and destructive (deemed to be associated with negligible measurement error for at least metallic materials (Sykora & Holicky, 2013)) testing.

In the beginning of the analysis Brinnel hardness tests were performed at ten locations of the structure. Using a relationship based on long-term experience with the test method, results were converted to equivalents of outcomes of tensile tests. Statistical characteristics are obtained by the method of moments (Ang & Tang, 2007; Holicky, 2013)

\[
m_0' = 385 \text{ MPa, } s_0' = 20.5 \text{ MPa, } \\
v_0' = s_0' / m_0' = 0.053, \ n' = 10, \ v' = n - 1
\]

where \( m_0' \) = point estimate of the population mean; 
\( s_0' \) = point estimate of the standard deviation; 
\( v_0' \) = coefficient of variation; 
\( n' \) = sample size and 
\( v' = \) number of degrees of freedom for the standard deviation.

A lognormal distribution with the origin at zero (hereafter simply “lognormal distribution”) is considered as an appropriate probabilistic model for the steel strength \( f \). The probability density function based on the point estimates \( m_0' \) and \( s_0' \) is plotted in Figure 2.

Long-term experience with the Brinnel method indicates a particular measurement \( f_0' \) be affected by an unbiased measurement error \( e \) (mean \( \mu_e = 1 \) with a standard deviation \( \sigma_e = 0.15 \). An actual (true) value of the strength is estimated as the product of a test result and measurement error, \( f_i' = e_i f_0' \). To account for \( e \) the point estimates of the sample characteristics are modified as follows (Holicky, 2013)

\[
m' = \mu_e m_0' = 385 \text{ MPa, } s' = m' \sqrt{(V_e^2 + v_0'^2 + V_0'^2)} = 61.3 \text{ MPa, } v' = s' / m' \approx 0.16
\]

where \( V_e = \sigma_e / \mu_e \) = coefficient of variation of the measurement error.

The measurement error significantly affects the coefficient of variation of \( f \) as also demonstrated in Figure 2. The probability density function of the lognormal distribution corresponds to a greater dispersion and the estimate of a 5% fractile (commonly the characteristic value, (EN 1990, 2002)) considerably decreases. The effect on the design value is even more substantial.

To verify results of the non-destructive testing and improve the material model, three samples were cut from replaced members. Tensile strengths are as follows: \( f_1 = \{ 371, 351, 418 \} \) (in MPa). The following statistical characteristics are obtained by the method of moments

\[
m = 380 \text{ MPa, } s = 34.4 \text{ MPa, } n = 3, \ v = 2
\]

The updated characteristics (combining prior information - non-destructive measurements here - and results from tensile tests) can be estimated as (ISO 12491, 1997; JCSS, 2001b)

\[
n'' = n' + n = 13; \ v'' = v' + v + \delta(n') = 12; \ m'' = (n'm'' + nm'') / n'' = 384 \text{ MPa}; \\
s'' = \sqrt{((v'(s')^2 + n'(m')^2 + vs^2 + nm^2) - n''(m'')^2) / v''} = 55.0 \text{ MPa}
\]

where \( \delta(n') = 0 \) for \( n' = 0 \) and \( \delta(n') = 1 \) otherwise.

The updated standard deviation is lower than that based on the Brinnel method, however it is still considerably greater than the standard deviation obtained from tensile tests. It could be thus accepted to develop the model of \( f \) using the tensile tests only.
However, the increase of the standard deviation due to measurement error is compensated by a considerable increase of the degrees of freedom (v = 2 and ν* = 12) that positively affects the left tail of the distribution.

Table 1. Models of basic variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symb.</th>
<th>Dist.</th>
<th>( \mu_X / \bar{x} )</th>
<th>( V_X )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel strength (updated)</td>
<td>f</td>
<td>Lognorm.</td>
<td>1.36</td>
<td>0.14</td>
</tr>
<tr>
<td>Permanent load effect</td>
<td>G</td>
<td>Normal</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Wind pressure (50-y. max.)</td>
<td>W</td>
<td>Gumbel</td>
<td>0.7</td>
<td>0.35</td>
</tr>
<tr>
<td>Effect of survived load</td>
<td>S</td>
<td>Normal</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Resistance uncertainty</td>
<td>( K_R )</td>
<td>Lognorm.</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Load effect uncertainty</td>
<td>( K_L )</td>
<td>Lognorm.</td>
<td>1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\( \bar{x} \) = characteristic value

This can be demonstrated for instance by the estimates of the characteristic value \( f_k \) in accordance with (EN 1990, 2002). The greatest estimate is obtained for the updated distribution, \( f_k = 282 \) MPa; when considering either non-destructive or destructive tests a lower estimate by about 15-20 MPa is obtained. Note that the difference becomes more significant for design values (commonly ~1% fractiles).

3.2 Updating of failure probability of the girder

Deterministic verification reveals that reliability of the girder is insufficient as the actual resistance is by 10% lower than required by Eurocodes for new structures (considering the updated steel strength). Probabilistic reliability analysis is based on the limit state function \( Z(c) \) for the member exposed to buckling

\[
Z(X) = K_R \chi A f - K_E [G + W]
\]

where \( \chi = \) nominal buckling reduction factor and \( A = \) deterministic cross-section area. Notation and probabilistic models of the basic variables \( X \) (statistically independent) are given in Table 1 (JCSS, 2001a). Variability of the buckling reduction factor is covered by the uncertainty in model resistance; variability of the cross-section area obtained from in-situ measurements is negligible.

Using the FORM method and Eq. (1) the reliability index \( \beta \approx 2.8 \) is lower than the accepted target reliability level \( \beta_t = 3.1 \). The reliability is then updated considering the satisfactory past performance to improve this estimate. Available measurements from a neighbouring meteorological station reveal that in 2007 the structure was exposed to an extraordinary wind storm causing a wind pressure \( S \) exceeding 1.4-times the characteristic value. Based on an expert judgement uncertainties in the survived load effect are described by a normal distribution with the mean equal to the observed value and coefficient of variation 0.1. Given the survival of the load \( S \), the updated reliability index \( \beta \) follows from the conditional failure probability based on Eq. (3)

\[
p^m_t (t_{03} \mid S) = P\{[K_R \chi A f - K_E (G + W)] < 0] \cap [K_R \chi A f - K_E (G + S) > 0]\} \div P\{K_R \chi A f - K_E (G + S) > 0\}
\]

Note that the present conditions of the girder are assumed to be the same as those at the time of exposure to the load \( S \). It is emphasised that information on previous loads should be always considered carefully and related to a relevant uncertainty.

4 MEASURES IN CASE OF INSUFFICIENT RELIABILITY

In many practical situations predicted reliability is lower than a target level. In general five options can then be considered:

1. To improve information on variables significantly affecting structural reliability by inspections, tests or applying more advanced theoretical models (in the case study additional destructive tests of the steel strength could be performed and/or more advanced models for both resistance and wind action effect could be applied).

2. To strengthen structural members with low reliability (case study - reducing the buckling length of the lower chord of the truss girder by appropriate bracing).

3. To propose an adequate limit on the imposed action.

4. To accept a shorter remaining working life such as 15 years and after that re-assess the girder (using 15-year maxima of the wind pressure the updated reliability index \( \beta \) is 3.4 is obtained from Eq. (10)).

5. To derive optimum target reliability following the principles provided by (ISO 2394, 1998).

5 CONCLUDING REMARKS

Reliability verifications of the industrial heritage buildings should be backed up by inspection including collection of appropriate data. Assessments based on simplified conservative procedures used for structural design may lead to
expensive repairs and losses of the heritage value. Probabilistic methods can thus better describe uncertainties and take into account results of inspections and tests as well as satisfactory past performance. Numerical example reveals that it may be important to consider measurement errors related to non-destructive techniques. Direct updating of the failure probability can be effectively performed by the FORM/SORM methods and may improve reliability assessment. Reliability appraisal can be performed by implementing appropriate, cost-optimal target levels for existing structures.

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Evaluation of Properties of Historic Materials Considering Measurement Uncertainties

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ABSTRACT: Historic structures are made of different materials with unknown characteristics and testing methods are used to obtain information on material properties. Requirements on the protection of a heritage value often lead to applications of non- and minor-destructive testing while use of destructive testing is minimized. In general measurement uncertainty associated with the testing methods should be considered in the evaluation of obtained results. In the contribution the measurement uncertainties of methods used in the testing of historic structures are overviewed. Evaluation of a material property obtained by combining testing methods is then discussed considering the maximum likelihood method and Bayesian updating. Numerical example focused on the assessment of steel strength of an industrial heritage building reveals small differences between both methods.

Keywords: measurement uncertainty, historic material, characteristic value, non-destructive techniques

1 INTRODUCTION

Historic structures are made of different materials with unknown properties. Various testing methods are used to obtain information on the material properties of masonry components, structural iron or steel etc. Due to the protection of a heritage value, non-destructive (such as Schmidt hammer or Brinell hardness tester) and minor-destructive testing (using small cores) is preferred to destructive testing (ISO 13822, 2010). In general measurement uncertainties associated with testing methods should be considered in the evaluation of obtained results.

The measurement uncertainty of various methods used in the testing of historic structures may be related to considerable variability (Sykora & Holicky, 2013a; Sykora & Holicky, 2013b) that may be comparable or exceed the variability of an investigated property. The coefficients of variation of an individual outcome of non-destructive testing (NDT) or minor-destructive testing (MDT) may reach up to 100%.

In the present contribution principles of (EN 1990, 2002) for basis of structural design and (ISO 13822, 2010) for assessment of existing structures (including historic structures) are considered. Evaluation of the material property obtained by combining testing methods is discussed considering different levels of the measurement uncertainty. A general procedure based on the likelihood representation of uncertainties (requiring use of numerical integration or simulations) is firstly employed. For practical applications analytical relationships based on conjugate distributions in the framework of Bayesian updating are then provided to reduce computational demands. Numerical example of the assessment of steel strength illustrates practical application of both methods.

2 MEASUREMENT UNCERTAINTY

Measurement uncertainty is considered here as a parameter, associated with the result of a measurement, which characterizes the dispersion of the values that could reasonably be attributed to an investigated property (variable), (JCGM 100, 2008). Measurement uncertainty generally includes random (related to an individual measurement) and systematic components. For considered NDT and MDT methods it is hereafter assumed that the systematic component has been reduced by appropriate conversion factors based on long-term experience and that the random component dominates the measurement uncertainty. The
multiplicative or additive definition of the measurement uncertainty \( \varepsilon \) can be accepted:

\[
\begin{align*}
 f_i &= \varepsilon x_i; \text{ or} \\
 f_i &= x_i + \varepsilon
\end{align*}
\]

where \( f_i \) = actual (true) value of an investigated property (here strength \( f \)); and \( x_i \) = measurement. In particular cases the measurement uncertainty can be represented by more complex relationships.

Measurement uncertainty is commonly considered as a random variable independent of the magnitude of measurement and should be expressed in accordance with (JCGM 100, 2008) that provides a necessary statistical background. Normal or two-parameter lognormal distribution with the origin at zero (hereafter ‘lognormal distribution’) is often accepted for the measurement uncertainty.

From a purely statistical point of view the multiplicative relationship (1) is more appropriate when the investigated property and the measurement uncertainty are described by lognormal distributions. If \( X \) and \( \varepsilon \) are lognormal, \( f \) is lognormal likewise. Similarly, the additive formula (2) may be preferable when normal distributions are relevant. It is worth noting that Equation (1) can be transformed to Equation (2) using the logarithmic transformation:

\[
\ln f_i = \ln x_i + \ln \varepsilon
\]

and the product of lognormal variables \( X \) and \( \varepsilon \) becomes the sum of normal variables \( \ln X \) and \( \ln \varepsilon \).

The lognormal distribution is a commonly accepted for properties of construction materials. That is why lognormal measurement uncertainty and relationship (1) is considered hereafter.

Table 1 gives indicative coefficients of variation of the uncertainty of an individual measurement for selected test methods widely used for the investigation of historic masonry, iron and steel structures. All the methods should be applied by experienced staff to provide unbiased results.

The presented values follow from the comparison of hundreds of strengths obtained by test methods with destructive tests. The measurement uncertainty has been assessed using the method for statistical determination of resistance models (EN 1990, 2002).

The presented coefficients of variation are based on limited experimental data, covering incomplete range of conditions that may appear when investigating historic structures. These values are thus indicative only. Further information on the assessment of measurement uncertainty is provided e.g. by (Sommer et al., 2009).

### Table 1. Indicative coefficients of variation of the uncertainty related to NDT and MDT applied for historic structures.

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Testing method</th>
<th>( V_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masonry</td>
<td>compressive strength of masonry units</td>
<td>- tests in a press on small specimens \n- modified percussion drill with indenter complemented by revolution counter and sensor of acting force (general calibration curve) \n- Schmidt hammer (type L, calibration curve verified for tests of bricks by laboratory)</td>
<td>0.05**</td>
</tr>
<tr>
<td></td>
<td>compressive strength of mortar</td>
<td>- modified percussion drill (general calibration curve) \n- hardness tester developed at Klokner Institute (KI) for tests of mortar strength (calibration curve verified by KI)</td>
<td>0.7**</td>
</tr>
<tr>
<td>Iron, steel</td>
<td>tensile strength</td>
<td>- Brinell hardness tester</td>
<td>0.9**</td>
</tr>
</tbody>
</table>

Conservative value. **Assuming at least three tests in a press are used to calibrate a test method for a specific structure.***

3 COMBINATION OF PRECISE AND IMPRECISE MEASUREMENTS

Dissimilar to present construction materials, information based on long-term experience with production (often referred to as ‘prior information’) is commonly unavailable for historic materials. For instance strengths of historic iron and steel vary in wide ranges depending on a production process and producers. The models for properties of historic materials are thus mostly based on measurements.

The investigation of historic materials typically comprises results of NDT/MDT. In addition few destructive tests may be available. As an example Figure 1 indicates strengths of structural steel of the industrial heritage building from 1900s (Sykora & Holicky, 2014). Brinell hardness tests were performed at ten locations. Using a relationship based on experience with the test method, results were converted to equivalents of outcomes of tensile tests. Each of the measurements is associated with uncertainty described by the lognormal distribution with the mean \( \mu_x \) and coefficient of variation \( V_x \) (Table 1). This is expressed in Figure 1 by the probability density function \( f_x \) and by the intervals of 90% confidence.
To verify the NDT results and improve the material model, three tensile tests were conducted (Figure 1). Tensile tests of metallic materials are associated with a very low measurement uncertainty ($V_e \approx 0.01$, (Sykora & Holicky, 2013b)) that is negligible when compared to the measurement uncertainty of NDT/MDT and variability of the investigated property.

4 MAXIMUM LIKELIHOOD METHOD

In the maximum likelihood method (MLM) the underlying distribution of the investigated property, described by the probability density function $f(x)$, needs to be known. The parameters $\Theta$ (mean, standard deviation, skewness, scale parameter etc.) of this distribution are to be statistically inferred from the sample of a size $n$; $(x_i: i = 1..n)$. Measurements $x_i$ are assumed to be statistically independent. Considering negligible measurement uncertainty, the parameters $\Theta$ can be estimated by maximizing the likelihood function:

$$\Theta_{MLM} = \max_\Theta \{ \prod_i f(x_i | \Theta) \}$$

Statistical uncertainty can be expressed by treating the estimates as random (generally correlated) parameters (Lindley, 1980).

(Sankararaman & Mahadevan, 2011) extended the MLM to combinations of precise (point) and imprecise (interval) data. Using their results, the MLM estimate can be obtained considering sample sizes $n_{NDT}$ and $n$ of imprecise and precise data, respectively, and lognormal $\varepsilon$ as follows:

$$\Theta_{MLM} = \max_\Theta \{ \prod_i f(x_i | \Theta) \times \prod_j \left[ f(\varepsilon x_j | \Theta) \right]_{de} \}$$

where $i = 1..n$; and $j = 1..n_{NDT}$. Neglecting the statistical uncertainty, the posterior (updated) probability density function is obtained as $f(x | \Theta_{MLM})$.

The application of the MLM is thus straightforward. However, integration over the measurement uncertainty is necessary and the numerical search for maximum may become demanding and unstable. To overcome these drawbacks and facilitate practical applications, Bayesian updating in conjunction with conjugate distributions (JCSS, 2001) is proposed to infer the parameters $\Theta$ in a simplified manner.

5 BAYESIAN UPDATING

5.1 Information based on NDT/MDT tests

Bayesian updating enables to combine information from different sources. Commonly prior information (e.g., based on experience from assessments of similar structures, long-term material production, findings reported in literature or engineering judgement) is updated by new information. This can be obtained by material tests, inspections or proof loading (Sykora et al., 2013b). In this study prior information represented by NDT/MDT results is updated by outcomes of destructive tests.

(ISO 12491, 1997) suggests the procedure limited to a normal variable $X$ for which the prior joint probability density function $\Pi'(\mu, \sigma)$ is given as:

$$\Pi'(\mu, \sigma) = C \sigma^{-(n'+2)} \exp\{-(\nu' s'^2 + n' (\mu - m')^2)/(2\sigma^2)\}$$

where $C$ = normalising constant; $m'$ = unbiased estimate of the population mean (prior sample mean); $s'$ = best estimate of the population standard deviation; $n'$ = hypothetical sample size for the prior mean; $\nu'$ = hypothetical number of degrees of freedom for the prior standard deviation; $\delta(n') = 0$ for $n' = 0$ and $\delta(n') = 1$ otherwise. The parameters $\Theta$ thus include $\mu$, $\sigma$, $n$ and $\nu$. Note that the symbol $\delta$ denotes the prior characteristics, symbol $\Pi'$ the posterior (updated) characteristics and results of destructive tests are indicated without quotation marks.

The prior parameters $m'$, $s'$, $n'$ and $\nu'$ should include the influence of the measurement uncertainty described by the lognormal distribution with $\mu_e$ and $V_e$. Using Equation (3) the product of the lognormal variables is transformed into the sum of
normal variables. For convenience the following notation is accepted: \( \ln f = \varphi; \ln x = \xi; \ln \varepsilon = \theta \).

The task is now to estimate characteristics of \( \varphi \) by statistical interference from the NDT/ MDT results \( \xi_j \) and probabilistic characterisation of \( \theta \). A test result \( \xi_j \) is an outcome of the true value (random value from an underlying distribution of the property) and randomness of the uncertainty \( \theta \). The parameter \( m^* \) can be obtained as:

\[
m^* \approx m^*_2 - \mu_0 \tag{7}
\]
\[
\mu_0 \approx \ln[(1+V_i^2-3\sigma_{\xi}^2)/\mu_\xi] + 0.5\ln(1+V_i^2)
\]

While estimating the parameters \( s^* \) and \( v^* \), two cases are distinguished:

1. Variability of the property is dominated over the variability of the measurement uncertainty. This can be approximately expressed as \( V_i > 3\sigma_{\xi} \) where \( V_i \) denotes the coefficient of variation of the investigated property empirically estimated.

2. Other cases when variability of the property is comparable or lower to that of the measurement uncertainty.

In the first case the effect of the measurement uncertainty can be approximately neglected. Alternatively, the following relationships may be applied:

\[
s^* \approx \sqrt{2n^*(s^*_2 - \sigma_0^2)/(2n^* + 1)}; \quad v^* \approx n_{\text{NDT}} - 1 \tag{8}
\]

with \( s^*_2 = \sum_j (\xi_j - m_2)^2 / v^* \); \( \sigma_0 = \sqrt{\ln(1+V_i^2)} \approx V_i \)

The second case is relevant for most historic materials investigated by NDT/ MDT. It makes little sense to explain variability of the property on the basis of test results that are dominated by variability of the measurement uncertainty. In such cases it seems reasonable to estimate \( V_i \) or \( \sigma_0 \) on the basis of previous experience. Conservate values are commonly accepted.

As a first approximation the coefficients of variation of strengths of historic iron and steels may be 0.2 and 0.1, respectively. For historic concrete 0.2 might be accepted. In case of masonry the mean strengths of masonry units and mortar are commonly inferred from measurements (Syrkora et al., 2013a) for which Equation (8) provides sufficient guidance.

Obviously the estimate of \( V_i \) should be lower than the sample coefficient of variation: \( V_i \approx \sigma_0 < s^*_2 \approx V_i \). Otherwise the assumption of significant variability of the measurement uncertainty is hardly reasonable.

Considerable uncertainty related to a rather subjective choice of \( V_i \) should be expressed by a relatively low number of degrees of freedom \( s^* \). For concrete compressive strength (ISO 2394, 1998) indicates \( v^* = 5 \) while (ICSS, 2001) suggests \( v^* = 10 \). From excessive concrete-production data (Rackwitz, 1983) derived \( v^* = 3\) for site-mixed concretes, \( v^* \approx 6 \) for ready-mixed concretes, and \( v^* = 4.5\) for concrete for precast structural members. In view of this information the conservative estimates of \( V_i \) may be associated with \( v^* = 5 \) for historic steel, and \( v^* = 3 \) for historic iron and concrete.

The prior parameter \( n^* \) is obtained as follows:

\[
\begin{align*}
\text{case 1: } & n^* \approx n_{\text{NDT}} s^*_2 / (s^*_2 + V_i^2) \\
\text{case 2: } & n^* \approx n_{\text{NDT}} V_i^2 / (V_i^2 + V_i^2) \tag{9}
\end{align*}
\]

For historic masonry, case 2 is likely relevant and the estimation of \( V_i \) may be difficult. In such a case \( s^*_2 \) can be applied in the estimate of \( n_{\text{NDT}} \):

\[
n^* \approx n_{\text{NDT}} s^*_2 / (s^*_2 + V_i^2) \tag{10}
\]

Note that the relationships for \( m_2^* \) and \( s_2^* \) in Equations (7) and (8) are based on the method of moments (Ang & Tang, 2007; Holicky, 2013). Alternatively, they can be obtained by the MLE or other appropriate statistical method.

### 5.2 Updating by results of destructive tests

The posterior distribution function \( \Pi'(\mu, \sigma) \) is of the same type as the prior distribution function in Equation (6), but with the updated parameters \( m_2^*, n^*, s^* \) and \( v^* \):

\[
n^* = n^* + n; \quad v^* = v^* + v + \delta(n^*); \quad m^*n^* = n^*m^* + n^* \tag{11}
\]

where the characteristics for destructive tests are:

\[
m = \sum_j \xi_j / n; \quad s = \sqrt{\sum_j (\xi_j - m)^2 / v}; \quad v = n - 1 \tag{12}
\]

The updated characteristics of the (normally distributed) logarithm of the investigated property are thus determined from analytical relationships (11) with no computational efforts.

Denoting \( \Theta_{\text{Bayes}} = \{m^*, n^*, s^*, v^*\} \), the posterior cumulative distribution function \( F(f/\Theta_{\text{Bayes}}) \) and probability density function \( f(f/\Theta_{\text{Bayes}}) \) are obtained as (Rackwitz, 1983):

\[
\begin{align*}
F(f/\Theta_{\text{Bayes}}) &= F_{f_{\text{cr}}}((\ln f - m^*) / s^* \times \sqrt{n^*/(n^*+1)}) \\
f(f/\Theta_{\text{Bayes}}) &= \sqrt{n^*/(n^*+1))} / s^* f_{f_{\text{cr}}}((\ln f - m^*) / s^* \times \sqrt{n^*/(n^*+1)}) \tag{13}
\end{align*}
\]

where \( F_{f_{\text{cr}}}(-) \) and \( f_{f_{\text{cr}}}(-) \) is cumulative distribution and probability density functions of Student’s \( t \)-distribution with \( v^* \) degrees of freedom, respectively.

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Fractile \( f_p \) of the posterior distribution of the investigated property, corresponding to specified probability \( p \), is obtained as:

\[
f_p = \exp(m'' + q_i(p, \nu'')\sqrt{1 + 1/n''}) \times s''
\]  

where \( q_i = p \)-fractile of Student’s \( t \)-distribution for the number of degrees of freedom \( \nu'' \).

Typically the Bayesian updating may require subjective judgements concerning the variability of the investigated property (expressed here by \( \nu' \)) and importance of such information (\( \nu'' \)). This can be seen as a drawback since incorrect judgements may yield an erroneous posterior model. On the other hand this allows supplementing experimental data by experience of the analyst. Supplementary information on Bayesian updating can be found elsewhere (Ang & Tang, 2007; JCSS, 2001).

6 NUMERICAL EXAMPLE

6.1 Experimental data

In the numerical example experimental data of steel strength obtained in the investigation of a former factory for boiler production built in 1900s are analysed (Sykora & Holicky, 2014). The data shown in Figure 1 consist of:

- 10 results of Brinell hardness tests converted to outcomes of tensile tests, \( f_j = \{403, 365, 375, 385, 392, 371, 361, 370, 426, 400\} \) in MPa \((j = 1..\text{NDT}; \ n_{\text{NDT}} = 10)\), each of these assumed to be affected by the lognormal measurement uncertainty with \( \mu_e = 1 \) and \( \nu_e = 0.15 \);

- Three steel strengths obtained by tensile tests, \( f_i = \{371, 351, 418\} \) in MPa \((i = 1..n; \ n = 3)\); associated with negligible measurement uncertainty.

6.2 Maximum likelihood method

Figure 2 shows the probability density functions of the steel strength obtained from Equation (5) for two alternatives: the measurement uncertainty is taken into account and neglected. The effect of the measurement uncertainty on variability of the steel strength seems to be insignificant. This is also demonstrated by the estimates of a 5% fractile (commonly the characteristic value (EN 1990, 2002)). Considering \( e \) the characteristic value \( f_k = 336 \text{ MPa} \) is obtained from Equation (14) while 347 MPa is estimated when \( e \) is neglected. However, it should be kept in mind that statistical uncertainty is not captured in Equation (5).

6.3 Bayesian updating

Assuming a lognormal distribution of the steel strength, all the test results are lognormally transformed; \( \tilde{f}_{ij} = \ln f_{ij} \). The measurement uncertainty is considered significant (case 2), and \( \nu' \approx 0.1 \) and \( \nu'' \approx 5 \) are taken into account. Equations (7) to (12) then yield:

\[
\begin{align*}
m' & \approx 5.94; \ s' \approx V' = 0.10; \ n' \approx 3.1 \\
m & = 5.94; \ s' = 0.089; \ n = 3; \nu = 2 \\
m'' & \approx 5.94; \ s'' \approx 0.091; \ n'' \approx 6.1; \nu'' \approx 6
\end{align*}
\]

The measurement uncertainty in this case significantly affects variability of the prior mean (and thus reduces \( n' \)). It also increases variability of \( f \) (Figure 3). When considering \( e \) and all the data,
the probability density function corresponds to a
greater dispersion than when \( \varepsilon \) is neglected.

Consideration of \( \varepsilon \) reduces the characteristic
value by 8\%, \( f_k = 344 \) MPa decreasing to 317 MPa.
The effect on the design value (commonly \( \sim 1\% \)
fractile) is even more substantial.

Figure 3 indicates the positive effect of only three
destructive tests. Inclusion of the destructive tests
increases the characteristic value from \( f_k = 302 \) MPa
to 317 MPa (by 5\%).

5 CONCLUDING REMARKS

Historic structures are made of different materials
with unknown characteristics and tests are
conducted to acquire information on material
properties. When using non- and minor-destructive
testing, measurement uncertainty associated with the
testing method should be considered in the
evaluation of experimental results. The maximum
likelihood method and Bayesian updating provide
suitable tools in this regard. The Bayesian procedure
adapted here is based on analytical relationships and
thus may be very efficient for practical applications.
Typically the Bayesian updating requires subjective
judgements about the investigated property and
about importance of such information. This can be
seen as a drawback since incorrect judgements may
yield an incorrect posterior model. On the other hand
this allows supplementing experimental data by the
experience of an analyst. Both methods may be
useful not only in assessments of historic structures,
but generally in assessments of existing structures.
Numerical example indicates small differences
between both methods.

The presented contribution is a part of an ongoing
research. The achieved findings are thus to some
extend indicative and are expected to be improved.
Further research should be focused on:
• Investigation of the systematic component of
  measurement uncertainty and its due consideration
  in interpretations of outcomes of test results;
• Expression of statistical uncertainty due to limited
  data in the maximum likelihood method;
• Detailed guidance for estimating mean properties
  of masonry components.

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