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Quantification of different NDT/SDT methods in respect to estimate the load-bearing capacity

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HIGHLIGHTS

- Quantification of different NDT/SDT inspection methods.
- Estimation of the load-bearing capacity of structural components.
- Bayes updating using equality type information and inequality type information.
- Decision support for the corresponding engineer.

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ABSTRACT

In the presented paper, different NDT, SDT and DT inspections methods are introduced and their efficiency in respect to a quantitative estimation of the load-bearing capacity are discussed. Thereby it is particular focused on inspections methods for the estimation of the load-bearing capacity of glued laminated timber. The estimation of the load-bearing capacity of structural components, based on different types of information, is presented by using Bayes updating. For this purpose, the information is classified according to their characteristics and the corresponding procedures for estimation of the load-bearing capacity are presented. The paper concludes with a discussion about the application of Bayes updating for the decision support, of partly damaged constructions.

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1. Introduction

Inspection methods for the evaluation of the status of timber structures or single timber components are widely-spread. Typically, they are only used for a qualitative status description and not for a quantitative one. However, in many situations a quantitative estimation of the material properties of the structural components is needed. Examples are the conversion of a structure due to a change of use or partly damaged construction. The presented paper focuses more on the latter one, but can also be applied for non-damaged structures.

In timber constructions a significant number of failures and damages have been detected within the last decades, well-known documentations are e.g. [10,1,15]. In many cases, the structure is only damaged partly (e.g. a single structural component, a single connection, a group of components, etc.), whereas the remaining (non-failed) structural members are apparently unaffected. However, the remaining structural members might be also damaged due to additional loading caused by load redistribution.

If a construction is only partly damaged the corresponding engineer has to make a decision for e.g. different repair alternatives. This might be the replacement of the failed member(s), reinforcement of the non-failed members or in the worst case a complete renovation of the entire construction. However, to make the optimal decision, it is essential to estimate the load-bearing capacities of the remaining structural members.

In this paper selected non-destructive, semi-destructive and destructive inspection methods (referred to as NDT, SDT and DT) are introduced and their efficiency in respect to a quantitative estimation of the load-bearing capacity are discussed. Thereby, it is particular focused on inspections methods for the estimation of the load-bearing capacity of glued laminated timber (referred to as GLT). For the estimation of the load-bearing capacity of structural components, based on different types of information, Bayes

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updating can be used. Therefore, at first, the principle about Bayes updating is introduced.

2. Bayes updating

The property of interest that has to be predicted, as in the present case the load-bearing capacity or the stiffness of structural components is represented by the variable x. As we are uncertain what value x will take we define x as being a random variable X following a corresponding probability density function $f_X(x)$. The estimation of x is always conditional on information I. Information I might be available in different forms, and any statement on x will be conditional on I. The conditional form of the density function is thus $f_{X|I}(x|I=i)$.

In general the state of information is changing in time and the probability density function has to represent the current state of information that is in fact the accumulated information over time. That can be consistently done by applying Bayesian Statistics, i.e. utilizing Bayes law.

In Bayesian updating the prior density of random variables represents the uncertainty of the variable conditional to information available at time t_i, the posteriori density represents the uncertainties conditional to information available at time $t_{(i+1)}$, i.e. the information gain between t_i and $t_{(i+1)}$ is integrated. The so-called likelihood defines the connection of the gained information to the variable of interest.

2.1. Classification of information

The updating procedure is dependent on the type of the information gain e.g. in form of results of NDT/SDT inspection methods. It can be generally distinguished between so-called *equality type information* and *inequality type information* (see e.g. [13]). Equality type information are measured variables, and inequality type information denotes information that some variable is greater than or less than some predefined limit. Furthermore, it can be differentiated between direct information (direct measurements of the quantity of interest) and indirect information (measurement of some indicator of the quantity). Consequently, the information can be subdivided into four types; summarized in Table 1. Dependent on the type of information, the prior information can be updated (e.g. [17,6,7,9]).

2.2. Updating using equality type information

Using equality type information, such as the load-bearing capacity of a failed structural component, the material properties of the other structural members can be updated. The inspected parameter, here the load-bearing capacity of the structural members, is represented by the variable X with the probability distribution function $F_X(x)$. The parameters $\boldsymbol{\theta} = (\theta_1, \theta_2, \ldots, \theta_n)^T$ of the distribution function are not precisely known; they are product of engineering knowledge, physical understanding or earlier observations of the quantity. In general the parameters $\boldsymbol{\theta}$ are expressed as random variables specified by the so-called prior density function $f'_{\Theta}(\boldsymbol{\theta})$. The uncertain parameters $\boldsymbol{\theta}$ can be updated with new information (new observations of realizations of the variable $X, \hat{\mathbf{x}} = (\hat{x}_1, \hat{x}_2, \ldots, \hat{x}_n)^T$). The general scheme for updating of the parameters $\boldsymbol{\theta} = (\theta_1, \theta_2, \ldots, \theta_n)^T$ is given in Eq. (1). There, $f''_{\Theta}(\boldsymbol{\theta}|\hat{\mathbf{x}})$ denotes the posterior distribution function of the parameters $\boldsymbol{\theta}$, $L(\boldsymbol{\theta}|\hat{\mathbf{x}})$ denotes the likelihood function (representing the knowledge gained by the new information), and n is the number of observations.

$$f''_{\Theta}(\boldsymbol{\theta}|\hat{\mathbf{x}}) = \frac{f'_{\Theta}(\boldsymbol{\theta})L(\boldsymbol{\theta}|\hat{\mathbf{x}})}{\int f'_{\Theta}(\boldsymbol{\theta})L(\boldsymbol{\theta}|\hat{\mathbf{x}})d\boldsymbol{\theta}} \quad \text{with} \quad L(\boldsymbol{\theta}|\hat{\mathbf{x}}) \propto \prod_{i=1}^{n} f_{X|\Theta}(\hat{x}_i|\boldsymbol{\theta}) \tag{1}$$

Based on the posterior distribution function $f''_{\Theta}(\boldsymbol{\theta}|\hat{\mathbf{x}})$ it is possible to calculate the predictive distribution according to:

$$f'''(x) = \int f_X(x|\boldsymbol{\theta}) f''_{\Theta}(\boldsymbol{\theta}|\hat{\mathbf{x}}) d\boldsymbol{\theta} \tag{2}$$

For specific cases, such as a normal or log-normal distributed variable with a known standard deviation, the approach can be simplified. Analytical solution for such cases is presented in e.g. [17,6,9].

The principle of updating using equality type information is illustrated in Fig. 1. There, the bending strength f_{m} of GLT beams (strength class GL24h) is updated with the results of three bending test $f_{\mathrm{m},i} = 22,\ 30,\ 35$ MPa. The characteristic value of the bending strength of this strength class is $f_{\mathrm{m,k}} = 24$ MPa. The bending strength f_{m} is assumed to be log-normal distributed with a coefficient of variation COV = 0.15, in accordance to JCSS [12] (expected value $\mathrm{E}[f_{\mathrm{m}}] = 30.4$ MPa). Thus, the logarithm of the bending strength is normal distributed: $ln(f_{\mathrm{m}}) \sim N(\mu', \sigma_z)$, with $\sigma_z \approx \mathrm{COV} = 0.15$.

For Bayes updating the quality of the prior information has to be quantified. In this example a standard deviation of the uncertain mean value $\sigma' = 0.10$ is assumed. Furthermore, the standard deviation of the prior is assumed to be known (due to the uncertainty of the mean value $\sigma' = 0.10$ the characteristic value of the estimation is reduced $f_{\mathrm{m,k}} = 22.8$ MPa). Consequently, an analytical solution for the predictive distribution of the bending strength exists. The logarithm of the bending strength is normal distributed $ln(f_{\mathrm{m}}) \sim N(\mu'', \sigma''')$. n is the number of observations and $\bar{x}$ is the logarithm mean of the observations:

$$\mu'' = \frac{n\bar{x} + \mu' n'}{n' + n} \quad \sigma''' = \sqrt{\frac{\sigma_z^2}{n' + n} + \sigma_z^2} \quad n' = \frac{\sigma_z^2}{\sigma'^2} \tag{3}$$

In this example all three test results are within the expected range of GLT beams of strength class GL24h, but the mean value $\bar{x} = 29$ MPa is slightly below the expected value of the prior distribution $\mu' = 30.5$ MPa. As a result the distribution of the predictive bending strength of the remaining GLT beams is slightly modified. The expected value $\mathrm{E}[f'''_{\mathrm{m}}] = 29.3$ MPa and the characteristic value $f'''_{\mathrm{m,k}} = 22.5$ MPa .

2.3. Updating using inequality type information

The load-bearing capacity of the structural members can also be updated having inequality type information. Assuming a structural member will be proof loaded up to specific load effect σ_l without failure. Thus the load-bearing capacity of the structural member can be represented by the variable X conditional on the event of survival [14]:

Table 1
Examples for inspection methods to gain different types of information.

	Direct information	Indirect information
Equality type information	**Type A** Bending tests	**Type C** Stress waves
Inequality type information	**Type B** Proof loading	**Type D** Status inspection

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