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Redevelopment of a wooden roof construction under preservation order – Evaluation of reliability with updated information

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Abstract

Wooden structures are a great part of both our construction history and future. Timber is a natural grown building material, with a positive cumulative energy balance over its lifetime. Within wooden structures, carbon dioxide is bonded. The preservation of existing timber structures contributes to the withdrawal of this greenhouse gas from the environment for a long period. What is more, the preservation of outstanding timber constructions is of great social interest. However, different issues can lead to the need for an evaluation of the load-bearing capacity of an existing structure, these are e.g. change of loads, alterations or damage. The attempt to evaluate the performance of a historic structure applying the regulations of current Eurocodes often causes problems. Strength grading of elements in existing structures has to be improved by non- and semi-destructive means (Linke, Rug, & Pasternak, 2017). What is more, current Eurocodes do not contain options to include individual information into the semi-probabilistic safety concept.

The influence of an evaluation considering data gained in situ is illustrated by the case study presented in (Linke & Rug, 2018) in this conference. Within a qualified survey in situ as being done in this project, detailed information concerning load and material parameters of the structure has been collected. In the present contribution, a structural member is chosen to illustrate the effect of enhanced knowledge on the evaluation of load bearing capacities. A reliability analysis is performed and the result is compared to the requirements of DIN EN 1990:2010-12 (DIN, 2010b). The applicability of DIN EN 1990:2010-12 on existing structures is discussed.

Keywords

historic timber structures, reliability analysis, updated information, case study

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1 Introduction

Our built environment is a central part of our modern society. It is our responsibility to preserve, maintain and use our existing structures. They are part of our history, often of our cultural heritage, and objects to learn from for future constructions. What is more, our planetary boundaries remind us to act responsible with resources and energy. Hence, building with existing structures is an important social task and already a great part of the project volume in civil engineering. Especially timber constructions play an important role within the frame of existing structures. A significant share of historic structures has been built with timber, e.g. roof structures, timber beam ceilings, half-timbered houses and bridges, just to name a few. Due to its positive energy balance, its carbon dioxide neutral production and its pleasant appearance the use of timber already increases within the building industry.

Within the CEN member states, the so called Eurocodes form the basis of design and verification of load-bearing capacities of structures. Current Eurocodes do not contain special recommendations for the evaluation of existing structures. The principles for new structures are applied on existing structures, too. In some countries, special rules for existing structures are available. To be named here are the Swiss standard SIA 269:2011 (SIA, 2011) and Italian standards such as UNI 11119 and UNI 11138 (UNI, 2004a, 2004b). A common approach does not exist yet. Hence, the potential of a qualified survey in situ is not fully used and load-bearing capacities are often underestimated. It has to be analysed which changes in the design concept are necessary for the evaluation of existing structures and how it is possible to include data gained in situ in the evaluation.

For concrete structures, recommendations to adjust the partial safety factor depending on the coefficient of variation (COV) to be measured in situ are part of a German recommendation (DBV, 2013). What is more, in fib Bulletin no. 80 (FIB, 2016) the Design Value Method based on ISO 2394:2015 (ISO, 2015) is described to update partial safety factors for existing concrete structures. These are guiding developments for the evaluation of existing structures.

In this contribution, the potential of a qualified survey in situ to consider updated information within the evaluation of load-bearing capacities of an existing structure is analysed. First, the case study and the main results of the evaluation steps are described. Within the investigation, the strength class could be updated. The effect of this update within semi-probabilistic and probabilistic evaluation is studied in the next section.

2 Proposed framework for the evaluation of existing structures

To evaluate the load-bearing capacity of an existing structure, a concept is needed that is more flexible than the concept for design and planning which is part of the Eurocodes at state. This is why a stepwise procedure to include data of a qualified survey in situ into the verification of load-bearing capacities of existing structures is suggested. The concept is presented in (Loebjinski, Köhler, Rug, & Pasternak, 2018) and applied for a structural example in this contribution. Table 2.1 summarises the steps of evaluation and extends it to the steps of investigation.

Table 2.1 Proposed stepwise procedure for the investigation and evaluation of existing structures, extended from (Loebjinski et al., 2018)

Knowledge Level	Investigation format	Evaluation format	
KL 0	Rough investigation No determination of strength grade	Semi-probabilistic: → PSF to be calibrated	At state not applicable in some countries, e.g. Germany as strength grading is obligatory!
KL 1	Visual strength grading	Semi-probabilistic → PSF from current Eurocodes	
KL 2	Improved strength grading using technical means	Semi-probabilistic → Updated PSF using ref. property Probabilistic → Updated material properties from ref. property	
KL 3	Determination of parame-ters by direct measurement	Probabilistic → Updated distribution function using updated property	

3 Case study – Structural system, loads and evaluation of most critical elements in KL 1

3.1 General description

A wooden roof structure has been investigated. The structure is a listed timber frame-work and should be reused. Hence, its load-bearing capacities are analysed considering additional loads from a heating installation and snow load. The engineers figured out by a structural evaluation, that these loads could be carried, if the structure is strengthened according to the methods developed by the engineers. Another requisite was that the quality of the structural timber can be proved to be at least class S10 according to DIN 4071-1:2012-06 (DIN, 2012), respectively strength class C24 according to EN 338:2016-07 (DIN, 2010a). For more details see (Linke & Rug, 2018).

3.2 Structural system and loads

The structure is illustrated in Figure 3.1, the analysed elements are highlighted. Measures are in millimetres.

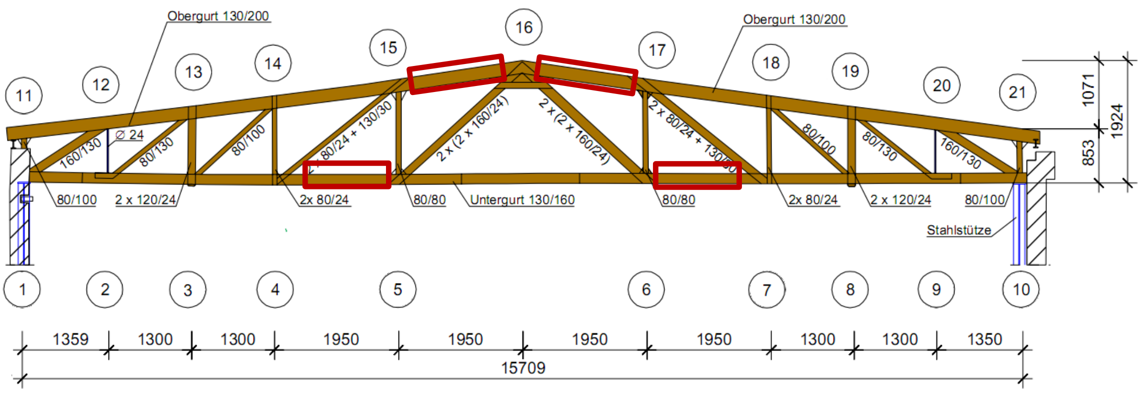

Fig. 3.1 Case study – cross section (copyright: Public experts office Prof. Dr.-Ing. W. Rug)

The structure has been evaluated in 2013. To illustrate the effect of considering updated material properties on the verification of the load bearing capacity, the elements subjected to the greatest strain are analysed, internal forces are taken from the documents. The critical elements of the truss are the rods number 14 and 15, (nodes 15 & 16 and 16 & 17) and rods number 4 and 6 (the nodes 4 & 4 and 6 & 7), highlighted in Figure 3.1). The upper cord is continuous. Within a first visual inspection, the material is graded to S10 of DIN 4074-1 (DIN, 2012) and therefore to strength class C24 of EN 338 (DIN, 2010a). Loads, geometry and material parameters of strength class C24 needed here are given in Table 2.1.

Table 3.1 Case study – geometry and internal forces of most critical elements

Geometry			Internal forces						
Elements 14 and 15 (upper chord)									
l	1.97	m	Permanent load	N_{gk}	-53.3	kN	M_{gk}	0.78	kNm
b	130	mm							
h	200	mm	Snow load	N_{qk}	-96.0	kN	M_{qk}	1.39	kNm
Elements 4 and 6 (lower chord)									
l	1.95	m	Permanent load	N_{gk}	52.5	kN			
b/h	130/160	mm	Snow load	N_{qk}	94.6	kN			

3.3 Verification of load-bearing capacity of most critical members

The load bearing capacity has originally been analysed using DIN 1052:1988. A German guideline of the commission ARGEBAU (2008) allows the verification of load-bearing capacities of historical elements of structures using historic codes (Fachkommission Bautechnik der Bauministerkonferenz [ARGEBAU], 2008). For this contribution the load-bearing capacity is evaluated using the principles of EN 1990:2010-12 and EN 1995-1-1:2010-12 to compare the results first. Internal forces are taken from the documents as shown in Table 3.1. Partial safety factors are taken as given in Table 3.2.

Table 3.2 Material parameters and partial safety factors from current codes

Material parameters strength class C24 (EN 338:2016-06)			Partial safety factors & modification factor (EN 1990:2010-12, EN 1995-1-1:2010-12)	
$f_{t,0,k}$	14,4	N/mm²	γ_G	1.35
$f_{c,0,k}$	21	N/mm²	γ_Q	1.5
$f_{m,k}$	24	N/mm²	γ_M	1.3
$E_{0.05}$	7400	N/mm²	k_{mod}	0.9

The evaluation of these elements using current Eurocodes gives

$$\eta_{14/15\_s} = 0.90 < 1 \quad \textit{Eq. 3.1}$$

and for members 4 and 6 (tension) gives

$$\eta_{4/6\_t} = 1.02 \approx 1 \quad \textit{Eq. 3.2}$$

The load-bearing capacities of the structure could be verified, the results are very similar to the original evaluation of these elements. However, as the overall condition of the structure is described as bad and the load-bearing capacity can only be verified if the material can be graded certainly to class S 10 according to DIN 4074-1, an investigation of the structure has been carried out as described in (Linke & Rug, 2018). The results are summarised briefly in the following section. Afterwards it is discussed, how the enhanced knowledge of concerning the structure could be used for an adjusted safety evaluation of the structure.

4 Case study – Evaluation using information from qualified survey in situ

4.1 General remarks

The Public experts office Prof. Dr.-Ing. W. Rug has been commissioned to evaluate the strength class of the structural timber used in the construction. Three steps of investigation have been performed:

1. Investigation and visual classification according to the standards DIN 4074-1:2012-06 which has been inaugurated by the building authorities in Germany
2. Accompanying ultrasonic time-of-flight measurements
3. Core drillings for strength testing in the laboratory (testing done at HNE Eberswalde)

4.2 Objective and challenges for the considered case study

However, applying the test results from the core drilling samples to update the evaluation of load-bearing capacities includes two major issues:

1. The tests have been performed on small core drillings and have been converted into the complying values for standard test specimen using a method developed at HNE Eberswalde. However, these are still values for defect-free timber. For a verification of load-bearing capacities the strength values for structural timber are needed.
2. Strength values of timber are correlated. Relations for defect-free timber have been published in (JCSS, 2006) and in an older version of EN 338 (DIN, 2010a).

Using this information to directly update the material strength is difficult, as a conversion from defect-free wood to structural material is not possible. However, using this information the strength grading can be improved. A classification into a grading class of (DIN, 2012) and by using EN 1912 (DIN, 2013) into a strength class of EN 338 (DIN, 2010a) is possible with higher accuracy. What is more, the results of the USM can be used. The most critical element were the tension members number 4 and 6. They are analysed with by a reliability analysis (FORM analysis) in the following section.

4.3 Quantitative results of testing for an exemplary truss

The construction consists of 21 trusses. For an exemplary consideration of updated material properties truss number 7 is chosen. Table 5.1 gives the information generated with different tools. This truss is chosen as ultrasonic measurements were also possible at the lower chord what has not been possible on every truss due to attached elements.

Table 4.1 Case study – Quantitative test results for exemplary truss 7

<table>
<tr><td rowspan="3">Element</td><td rowspan="3">Visual grading</td><td colspan="3">US Measurements</td><td colspan="4">Core drillings[1]</td></tr>
<tr><td rowspan="2">Strength class EN 338</td><td rowspan="2">Dynamic MOE [N/mm²]</td><td rowspan="2">Char. Bending strength [N/mm²]</td><td colspan="4">Density</td></tr>
<tr><td>μ [kg/cm³]</td><td>σ [kg/cm³]</td><td>COV</td><td>n</td></tr>
<tr><td>Upper chord</td><td>Min. S10 (C24)</td><td>C35</td><td>14511</td><td>40</td><td>0.48</td><td>0.03</td><td>0.06</td><td>7</td></tr>
<tr><td>Lower chord</td><td>Min. S10 (C24)</td><td>C30</td><td>12832</td><td>34</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="9">[1] The core drillings are taken from elements 11-12, but as it is a continuous beam results are applicable to the considered part</td></tr>
</table>

4.4 Evaluation in KL 2

4.4.1 Semi-probabilistic evaluation with updated PSF

The Swiss standard SIA 269:2011 (SIA, 2011) allows a modification of the PSF γ_G for permanent action to $\gamma_G = 1.2$ if the geometries are measured in situ and permanent actions are determined exactly. This has been done here. Hence the evaluation changes to

$$\eta_{14/15\_s} = 0.86 < 1 \qquad \textit{Eq. 4.1}$$

For members 14 and 15 (compression) and for members 4 and 6 (tension) to

$$\eta_{4/6\_t} = 0.98 < 1 \qquad \textit{Eq. 4.2}$$

The partial safety factor for the material γ_M may be updated for existing structures, too. Earlier studies have shown, that the variability of the tension strength is very high, so that the load-bearing capacity of a tension member has to be studied in the special case and should not be evaluated using an overall PSF that should be applicable to bending and compression strength as this would be too unfavourable for the latter. As the content of this contribution is part of an ongoing research project, calibration work for modified PSF for bending and compression and the requirements of their applicability have not been finished yet.

Using the information from a qualified survey in situ directly, the material factor may be updated by taking into account reference properties. It is possible to utilise the ultrasonic measurements to update the strength parameter. A formula has been developed in (Loebjinski et al., 2018) to update the PSF of a variable by measuring a reference property for fixed sensivity factors and will be published later this year.

In the frame of a probabilistic evaluation within level KL 2, the reliability of the tension member as a critical element is analysed.

4.4.2 Probabilistic evaluation without parameter update – lower chord

Within a reliability analysis the target reliability is a central aspect. A first step is the classification of a structure into a consequence class (CC) of EN 1990:2010-12. For this structure CC 2 is assumed. In EN 1990:2010-12 (DIN, 2010b) target values can be found for new structures. For existing structures, the values should be modified. Reasons are the increased amount of information concerning load and material is available compared to new structures (see e.g. (DBV, 2013) and (Diamantidis, Holický, & Sýkora, 2017)), that increased costs for safety measures compared to new structures before erection (see e.g. (Holický & Diamantidis, 2013), (Diamantidis et al., 2017) and (Vrouwenvelder, 2002) and that the erection period and first years of use have been passed without damages (Matousek & Schneider, 1976). Within the project presented above, the visual strength grading of the material has been supported by ndt/sdt measurements. Hence, uncertainties have been reduced. Based on a literature study a target reliability index for existing structures $\beta_{t,exis} = 3.2$ and a minimum value $\beta_{0,exis} = 2.5$ for a reference period *of* $T_{ref} = 50a$ has been set. The target value for new structures according to EN 1990:2010-12 Annex for a reference period of $T_{ref} = 50a$ and consequence class CC2 is $\beta = 3.8$.

The tension members (4 & 5) have been analysed with a FORM analysis. Parameters are shown in Table 4.1. Variables are modelled taking the characteristic values from current codes. i.e. EN 1990:2010-12 and EN 338:2016-06 and recommendations from the literature concerning coefficients of variation.

Table 4.2 Case study – Variables for the reliability analysis for T_{ref} = 50a – not updated

Variable	μ	σ	***COV***		***Distr.***
Width	130	-	-	constr. doc.	-
Height	160	-	-	constr. doc.	-
Tension strength	24.53	7.20	0.30	(JCSS, 2006)[1]	LN
Permanent load (snow load)	52530	5253	0.10	(JCSS, 2001)	N
Variable load	101480	25332	0.25	(Grünberg, 2004)	GUM
Model uncertainty tension strength	1	0.05	0.05	eng. judg.	N
Model uncertainty permanent load[2]	1	0.05	0.05	eng. judg.	N
Model uncertainty variable load[2]	1	0.05	0.10	eng. judg.	N
[1] timber of "middle" quality	[2] model uncertainties are applied on loads, for other LMS an allocation to internal forces might be more appropriate				

The analysis resulted in β ≈ 2.96, which is acceptable according to the values named above for existing structures, but strengthening would be recommended. A sensivity analysis gives the influence of the certain variables on the reliability.

Table 4.3 Case study – Sensivity factors

Variable	$\lvert\alpha\rvert$	**Variable**	$\lvert\alpha\rvert$
Tension strength	0.80	Model uncertainty tension strength	0.14
Permanent load (snow load)	0.07	Model uncertainty permanent load	0.13
Variable load	0.56	Model uncertainty variable load	0.10

The tension strength has the greatest impact on the reliability analysis. Tests are needed allowing an estimation of the strength including COV for a certain, critical element.

4.4.3 Reliability analysis with parameters from updated strength class – lower chord

A visual inspection resulted in a minimum strength class of C24, ultrasonic measurements, which are not allowed as a single grading tool in Germany by the building authorities yet, gave a strength class of C30 (see Table 5.1). The coefficient of variation (COV) is defined as

$$COV_x = \frac{\sigma_x}{m_x} = \frac{\sqrt{Var[x]}}{E[x]} \qquad \textit{Eq. 4.3}$$

If the expected value increases, the COV is reduced. Table 5.2 the COV (*COV = 0.30*) was taken for timber of middle quality from JCSS Probabilistic Model Code (PMC). Assuming a characteristic value of $f_{t,0,k} = 14.5\ N/mm^2$ (EN 338:2016-06), the standard deviation is $\sigma = 4.35\ N/mm^2$. Based on US measurements the material could be graded to C30. If the standard deviation remains, the COV becomes *COV = 0.26*. Applying these values to the reliability analysis gives $\beta = 3.39$. This value is satisfying regarding the requirements for existing structures and shows the great impact of updating the strength value.

4.4.4 Reliability analysis with updated reference properties from ultrasonic measurements – lower chord

Köhler suggested in (Köhler, 2011) a formula to update the mean value and the standard deviation from a target variable by measuring a correlated reference variable

$$\mu_{X|moe_{ist}} = \mu_X \left(1 + \rho_{X.MOE} \upsilon_X \frac{moe_{ist} - \mu_{MOE}}{\mu_{MOE} \nu_{MOE}} \right) \quad \textit{Eq. 4.4}$$

$$\sigma_{X|meas} = \nu_X \mu_X \sqrt{1 - \rho_{X,MOE}^2} \quad \textit{Eq. 4.5}$$

where $\mu_{X|moe_{ist}}$ is the mean value of a variable *X* depending on a measured variable *MOE_{ist}*, μ_X is the mean value of the target variable (e.g. from a code), $\rho_{X.MOE}$ is the correlation coefficient of target and reference variable, υ_X is the coefficient of variation of the target variable, moe_{ist} is the measured reference variable (here modulus of elasticity), μ_{MOE} is the mean value of the reference variable (e.g. from a code) and ν_{MOE} is the coefficient of variation the reference variable. The parameters for this update are given in Table 5.4 they are based on a classification of the material into strength class C30 according to EN 338:2016-06 and the results of the ultrasonic measurement.

Table 4.4 Case study – Variables for to update the strength parameter by reference property

$\mu_X = 30.76$	*Based on EN 338*	$\upsilon_X = 0.26$	*See section 5.3.3*
$\mu_{MOE} = 12000$	*EN 338:2016-06*	$\nu_{MOE} = 0.13$	*JCSS PMC Part 3.5*
$moe_{ist} = 12832$	*Measurement*	$\rho_{X.MOE} = 0.6$	*JCSS PMC Part 3.5*
$\mu_{X|moe_{ist}} = 33.32 N/mm^2$		$\sigma_{X|meas} = 6.40 N/mm^2$	

Using these updated variables from the ultrasonic measurements, the reliability is $\beta = 4.70$. This great increase compared to section 5.3.3 is due to

- The classification into a higher strength class by the ultrasonic measurement
- The consideration of an even higher modulus of elasticity that has been measured in situ compared to the recommended value from EN 338:2016-06 and an update of the strength value using the correlation coefficient from JCSS PMC Part 3.5

4.5 Evaluation in KL 3 – lower chord

An evaluation in KL 3 would include an update of the material parameters directly by measurements. This is not possible here as the tension strength cannot be updated directly from the core drilling samples, as they are taken from the upper chord. It was not possible to take samples from the lower chord as this would reduce the cross section which is critical for tension stresses, especially in this case where the stresses are high.

4.6 Discussion of results and findings with respect to the development of an adjusted safety concept for the evaluation of existing timber structures

It has been shown, that an evaluation based on EN 1990:2010-12 and EN 1995-1-1:2010-12 (KL 1) was critical. In KL 2 more information has been collected on the structure, the results were analysed for an exemplary truss. Ultrasonic measurements and core drillings enabled the classification of the material into higher strength classes. Thus, the evaluation of the load-bearing capacity was acceptable. In KL 2, the reliability of the tension member has been analysed for the original and for the updated strength class. A direct update of strength values as suggested for KL 3 was not possible here, as core drillings could not be extracted from a critical tension member. Table 5.5 summarizes the results of the stepwise evaluation.

Table 4.5 Summary of stepwise evaluation

Level	Format	Results
KL 1 (upper + lower chord)	Semi-probabilistic *PSF from current codes*	Satisfying results for upper chord Critical results for lower chord → *strengthening recommended*
KL 2 (lower chord)	Semi-probabilistic *Updated PSF*	Update of PSF only for permanent action possible → *result acceptable*
	Probabilistic evaluation *Reference properties*	Reliability analysis without updated information → *result acceptable for target reliability of existing structures, strengthening recommended*
		Reliability analysis with updated strength class → *results fine*
		Reliability analysis with updated strength from reference property (US measurement) → *very good result*
KL 3	Probabilistic evaluation *Direct update of prop.*	Not possible

5 Concluding remarks

A considerate preservation of existing timber structures is a major issue in today's building economy. Historic structures have to be analysed carefully by a qualified investigation in situ. The Eurocodes for the design of structures do not contain adjusted regulations for existing structures, code calibration work has to be carried out. This contribution shows the impact of a qualified survey in situ using technical means on the evaluation of load-bearing capacities. A tension member of a timber truss has been analysed stepwise. The tension strength of timber has a high variability as small factors have a big influence on the load bearing capacity. Thus tension members should always be analysed carefully concerning knots and other structural deviations. The results of the case study show, that the variability of strength parameters and variable loads have a great influence on the reliability of a structural element. What is more, core drillings help to update density and compression strength of the material.

Besides, by a semi-probabilistic evaluation the load-bearing capacity could be verified. However, the reliability calculated for this example is lower than the target value of EN 1990:2010-12 Annex C. It can be assumed, that a modified target reliability for the calibration of partial safety factors for the evaluation of existing structures should be based on a minimum and a target reliability that should be derived for existing structures. In this case, it has to be emphasized, that the variability of the tension strength very high. Thus, a distinction between timber material parameters for existing structures might be reasonable to evaluate a realistic load-bearing capacity as internal forces subjected to an element within an existing structure are fixed and will in most cases not completely change. In this contribution, no economic optimisation has been performed to compare the costs for strengthening measures to the costs of a detailed investigation in situ. This is an important part of the decision process, what has been evaluated for every single structure separately.

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