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REDEVELOPMENT OF A WOODEN ROOF CONSTRUCTION UNDER PERESERVATION ORDER

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Abstract

It lies in our responsibility to preserve, rehabilitate and use existing structures in a comprehensive manner. 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. Thus, the principles for new structures are applied in the case of a verification of the load-bearing capacity of an existing structure, as well.

However, the holistic redevelopment of existing timber structures requires a high standard of care and accuracy in all phases of planning and execution. In order to enable a substance-carful redevelopment, a detailed structural survey is required. In addition to the structural geometry, this also includes an exact assessment of the stability. Such an assessment can only be carried out if the load-bearing capacity of the timber members is determined as accurate and reliable as possible beforehand. Purely visual evaluations are usually insufficient, since visually detectable features only correlate slightly with the actual strength and stiffness. The additional use of non-/semi-destructive test methods can improve the accuracy and reliability of the grading process significantly.

This contribution presents the in-situ strength grading of timber members in existing structures using the example of a listed roof construction. Within a detailed survey in situ as being done, detailed information concerning load and material parameters of the structure has been collected. A structural member is chosen exemplary to illustrate the effect of enhanced knowledge on the update of the material model and partial safety factors (PSF). The applicability of DIN EN 1990:2010-12 on the evaluation of the load-bearing capacity of existing structures is discussed and a stepwise evaluation procedure for the evaluation of load-bearing capacity of a structural member using updated information is presented and applied.

1 INTRODUCTION

Our built environment is a central component of our modern infrastructure. 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 structures 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 [1] and Italian standards such as UNI 11119 and UNI 11138 [2, 3] (see also [4]). A common approach does not exist yet. Hence, the potential of a qualified survey in situ is not fully used and the load-bearing capacity is 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 into the evaluation.

For concrete structures recommendations to adjust the partial safety factor depending on the coefficient of variation (*cov*) that has to be measured in situ are part of a German recommendation [5]. What is more, in fib Bulletin no. 80 [6] the Design Value Method (DVM) based on ISO 2394:2015 [7] is described to update partial safety factors (PSF) for existing concrete structures. These are guiding developments for the evaluation of existing structures.

However, such an evaluation can only be carried out as long as a comprehensive and detailed investigation of the existing structure is conducted. This includes structural geometry and possible defects as well as an exact and reliable determination of the present load-bearing capacity of the timber members at hand. This is achieved by strength grading acc. to EN 14081-1 [8] which allows visual and mechanical grading procedures. The former are focussed on superficial visible and measurable growth characteristics whereas the latter apply non-destructive methods to determine material properties (see [9]). These grading techniques which were developed for new structural timber cannot or solely with significant restrictions be applied on timber members in existing structures (see [10]).

This decreases the frequency of an in-situ strength grading of timber members to very few cases. The present load-bearing capacity of timber members is assessed intuitively in most cases. The evaluation of the structural stability is then estimated considering the load-bearing capacity of "average-quality timber"– i.e. C24/D30 acc. to EN 338 [17]. Reserves and deficits of the load-bearing capacity cannot be detected by this procedure. This leads to possibly less considerate and unprofessional redevelopment measurements.

The strength grading of timber in existing structures in combination with the application of non- and semi-destructive test methods allows a more exact and reliable determination of the material properties. A purely visual evaluation of timber members is due to weak correlations between the visually determinable material features and the present strength and stiffness properties in most cases not sufficient [11, 12]. Applying non- and semi-destructive test methods additionally, a significant improvement of the accuracy and reliability of the in-situ evaluation of timber members can be achieved [9].

In this contribution, the potential of a qualified survey in situ to update the material strength of an existing structure and PSF is analysed. First, a case study and the main results of the evaluation steps are described. This includes the procedure of the in-situ strength grading. The effect of this enhanced knowledge within the update of the material strength and the PSF is studied in the next section.

2 CHURCH OF ST. NIKOLAI IN BAD WILSNACK

The building period of the protestant St. Nikolai church (also “Wunderblutkirche”, see Figure 1) in Bad Wilsnack (Brandenburg, Germany) embraces a time span of approximately 730 years. The first building was erected between 1286 and 1300. It was destroyed by fire in 1383. In 1384 the re-erection of the new church began. In the course of the destruction the legend of the “blood wonder” occurred, so that the new church became a pilgrimage site. This rapidly led to the necessity of a larger church to master the constant flow of pilgrims. Therefore, around 1450 the extension of the existing church began. The mostly continuous construction phase lasted well into the 16th century until the reformation brought it to an end. In the following centuries the construction was constantly rehabilitated and redeveloped.

Figure 1: St. Nikolai church, Bad Wilsnack – left: exterior view (from [12]), right: view on the roof structure above the main nave (Linke, 2018).

The ground plan of the church is cross-shaped with three naves (see Figure 2). The main nave is connected to the side naves by a two-bay cross-vaulting that spreads in between the main nave and the choir including a chapel on the east side. Further chapels as well as the sacristy are located in the south and north part of the church. The exterior walls are erected in the style of the North German Brick Gothic. They are interrupted by several stained-glass windows and buttresses.

The eventful history of the St. Nikolai church as well as the representation of several centuries of cultural history and development in structural engineering led to the decision to set the whole building under preservation order.

In 2015 a survey concerning the conservative state and the planning of redevelopment measurements began (see [13]). The predominant part of the planned measures comprises the timber roof structure.

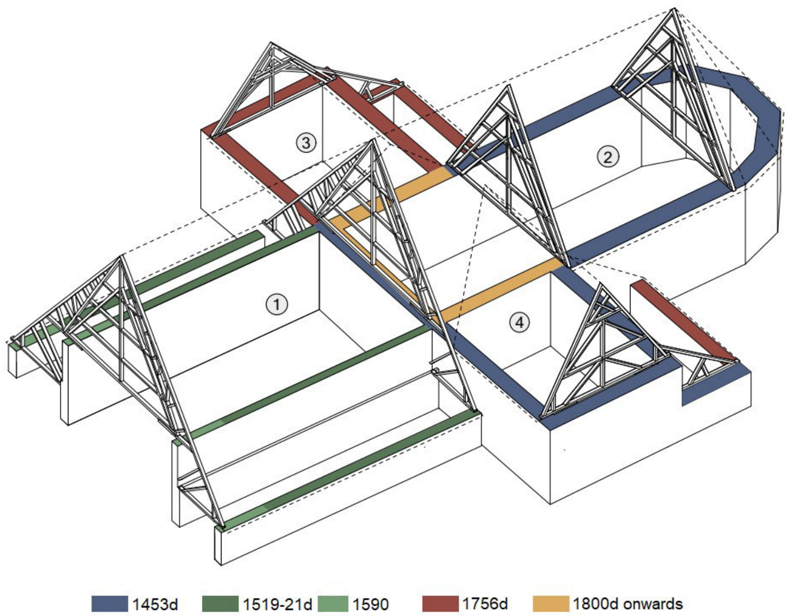

Figure 2: Roof construction with dating – (1) long house/main nave, (2) choir, (3) northern side nave, (4) southern side nave (Axel Seemann, 2015, Berlin).

3 INVESTIGATIONS ON THE LOAD-BEARING CAPACITY

In the course of the redevelopment of the roof structure an exemplary investigation concerning the quality and load-bearing capacity of the timber members was carried out in 2018. The aim of this investigation was the application and validation of an in-situ strength grading procedure. The results were also used to show the possibilities of a structural evaluation based on updated information and partial safety factors. The actual investigation of the roof structure concerning the planning of redevelopment measures was carried out beforehand (see [13]) and is not part of this contribution.

The conducted investigation included several non- and semi-destructive test methods, as listed below:

- Visual strength grading according to EN 14081-1 [8] and DIN 4074-1/-5 [14, 15] based on the in situ measurable criteria (i.e. knots, wane, slope of grain, cracks)
- Determination of the moisture content according to EN 13183-2 [16]
- Ultrasonic time-of-flight measurements
- Determination of the density and compressive strength of extracted core drill samples

The investigation has been focussed on the roof structure above the main nave (see Figure 2, No. 1). Overall 19 timber members in four trusses made from pine and oak were examined.

The results of the visual strength grading are depicted in Figure 3. Two thirds of the examined pine wood members are classified into class S10 acc. to DIN 4074-1 (average load-bearing capacity). The remaining pine wood members met the requirements of class S13 acc. to DIN 4074-1 (high load-bearing capacity). The examined oak members showed a comparable yield, whereas 57% were classified into class LS10 acc. to DIN 4074-5 (average load-bearing capacity). Another member was classified into class LS13 acc. to DIN 4074-5 (high load-bearing capacity). The remaining two oak members had to be classified as LS7 (low load-bearing capacity). The decisive criteria were knots and slope of grain.

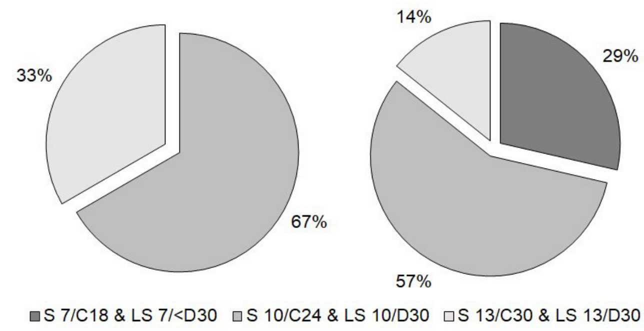

Figure 3: Result of the visual strength grading.

The examined members have also been graded based on the measured ultrasonic velocity. This was achieved by applying the limiting values proposed in [9]. The resulting grading yield is shown in Figure 4. The comparison of the results of visual and ultrasonic grading shows that the predominant part of the examined timber members could be assigned to a higher class. Approximately 20 % of the timber members were assigned to the same class. Only one member (≈ 5 %) had to be classified into a lower class.

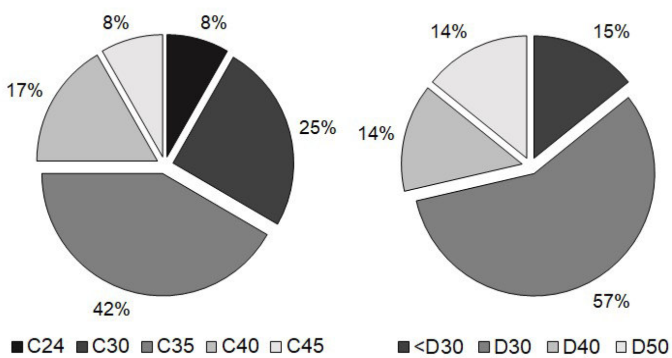

Figure 4: Result of the ultrasonic grading.

The results of the ultrasonic grading are verified by the results of the laboratory tests. Approximately 90 % of the examined timber members can be assigned to the same class based on the ultrasonic velocity and the determined density and compressive strength. This proves, that solely visual grading underestimates the load-bearing capacity [11, 12]. Furthermore, the improvement of the grading yield by applying multiple test methods could be verified in this exemplary investigation.

4 DETAILED ANALYSIS OF SINGLE STRUCTURAL MEMBER – PARTIAL SAFETY FACTORS AND MATERIAL MODEL UPDATE

4.1 General framework and exemplary element for parameter update

The load-bearing capacity of the truss has been evaluated by the engineering office *ibs Ingenieurbüro für Baustatik und Sanierungsplanung*. Results of the investigation are considered within this contribution by friendly permission. The aim of the research project is to develop a standardised procedure to make use of updated parameters of a qualified investigation in situ within the evaluation of the load-bearing capacity. The procedure illustrated in Table 1 is proposed, see also [17]. The procedure is applied to update the load-bearing capacity of a rafter.

Table 1: Proposed procedure for the investigation and evaluation of existing structures, extended from [17].

Knowledge Level	Investigation format	Evaluation format
KL 1	Visual strength grading	***Semi-probabilistic*** → *PSF from current Eurocodes*
KL 2	**a)** Detailed visual grading & inspection, analysis of loads	***Semi-probabilistic*** → $\gamma_{G,up}$ *for permanent actions* → $\gamma_{M,up}$ *under development*
	b) Improved strength grading using tech. devices	***Semi-probabilistic*** → *updated strength class*
	c) Determination of updated ref. properties by nd/sd tech. devices	***Semi-probabilistic*** → $\gamma_{M,up}$ *from updated reference property*
KL 3	Parameter update from measurement	***Probabilistic*** → *Updated material properties e.g. Bayes update*

4.2 Partial safety factors and material model in knowledge level 1

Within the original evaluation, the material has been graded to class S10 strength class C24 respectively. Parameters are taken from current codes (Table 2).

Table 2: Material parameters and partial safety factors from current codes – KL 1.

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	$f_{m,k}$	24	N/mm²	γ_G	1.35	γ_M	1.3
$f_{c,0,k}$	21	N/mm²	$E_{0.05}$	7400	N/mm²	γ_Q	1.5	k_{mod}	0.9

The evaluation of the load-bearing capacity by *ibs Ingenieurbüro für Baustatik und Sanierungsplanung* applying the values from the Eurocode resulted in

$$\eta \approx 0.89 < 1 \tag{1}$$

The authorative evaluation is interaction of compression and bending. The load-bearing capacity could be verified. However, as the structure is a listed cultural heritage potential resulting from a detailed investigation of the members shall be analysed.

4.3 Partial safety factors and material model in knowledge level 2

4.3.1. KL 2a – Update of Partial safety factors

PSF for permanent actions

SIA 269 [1] allows a reduction of the PSF for permanent actions to $\gamma_G = 1.20$, if geometry and weights of structural members are determined on site. As this has been done here, it is suggested to adopt this option. What is more, by detailed visual strength grading, the strength class could be updated to C30.

PSF for material resistance

Further potential can be analysed considering the statistical uncertainty of the basic variables for the individual case. Within ongoing work, modified PSF are calibrated and optimised for different structural members fulfilling the requirement (see [22])

$$\sum_{j=1}^{n} w_j \left(\beta_j - \beta_T\right)^2 \overset{!}{=} Min \tag{2}$$

with β_j the reliability of a considered case, w_j a weight factor and β_t the target reliability. These studies are not finished yet.

An exemplary value is calculated for the individual case. The target reliability is $\beta_t = 3.2$. and $\gamma_G = 1.20$. Eq. (2) is considered. The load shares from static calculation are 0.44/0.04/0.52 (permanent/ snow/ wind) and roof slope α = 52.6°. The limit state function (LSF) is

$$g = z_d \cdot k_{\text{mod}} \cdot R_m \cdot \theta_{R,m} - \left(S_G \cdot \theta_{S,G} + S_{Q,S} \cdot \theta_{S,S} + S_{Q,W} \cdot \theta_{S,W} \right) \tag{5}$$

with z_d the design parameter for a 100% workload (see [23]), k_{mod} the modification factor, R_m the resistance variable, S_G the variable for permanent action, $S_{Q,S}$ the variable for snow load $S_{Q,W}$ the variable for wind load and ϑi the model variables, see Table 3. Loads are combined using the Ferry Borges & Castanheta load combination rule. The result is $\gamma_{M,\,up} = 1.22$. This value is not applicable for standardization and just valid for the special case. An optimisation considering more design situation for practical application will increase the value.

Table 3: Probabilistic parameters for exemplary calibration.

Variable	mean	cov	Distr.	Remarks
Bending strength	1	0.25	LN	
Permanent action	1	0.10	N	
Snow load	1	0.25	GUM	$T_{ref} = 50a$
Wind load	1	0.16	GUM	$T_{ref} = 50a$
Resistance model uncertainty	1	0.07	N	Multiplicative
Permanent action model uncertainty	1	0.05	N	
Snow load model uncertainty	1	0.10	N	
Wind load model uncertainty	1	0.10	N	

4.3.2. KL 2b – Update of strength class from grading with technical devices

Table 3 shows the results of the investigation and strength grading for the chosen member. The highest strength class a timber member can be assigned to by purely visual grading is C30. However, investigation with technical devices allows a classification into S15/LS 15. Thus, based on the results in Table 4, the member is classified into strength class C35.

Table 4: Results of strength grading based on different devices – KL 2b.

Grading method	Result	Strength class
Visual grading	S13	C30
US mean value from tests	5503 [m/s]	C35
ρ mean value from tests	525 [g/cm³]	C50
$f_{c,0}$ mean value from tests	30 [N/mm²]	C45

In further work, a reduction of the variability of the material strength depending on the grading procedure may be possible and considered within an update of the PSF

4.3.3. KL 2c – Update of material properties and PSF from nd/sd measurements

The investigation using technical devices enhance the knowledge of the material quality. Thus, a possible update of the PSF γ_M as described in [17] is analysed.

$$\gamma_{m,up} = \exp\left(\frac{cov_{y,target} \cdot \sqrt{1-\rho_{x,y}^2}}{1+\rho_{x,y} \cdot cov_{y,target} \dfrac{x_{meas}-\mu_{x,ref}}{\mu_{x,ref} \cdot cov_{x,ref}}} \cdot \left(\alpha_R \cdot \beta + \Phi^{-1}(q) \right) \right) \tag{3}$$

$$\gamma_{M,up} = \gamma_{Rd} \cdot \gamma_{m,up} \tag{4}$$

With $cov_{y,target}$ the cov of the target variable y, $cov_{x,ref}$ the cov of the reference variable x, $\mu_{x,ref}$ the mean value of the reference variable x, $\rho_{x,y}$ the correlation coefficient, α_R the sensivity factor of the material resistance ($\alpha_R = 0.8$ from EN 1990:2010-12 [21]), β the target reliability, q the quantile for the definition of the characteristic value of the target variable used for design ($q = 0.05$) and γ_{Rd} the model factor that should be calculated from a normal distribution and the 50%-quantile considering the adjustment for a nondominant variable (see EN 1990:2010-12 [21] or ISO 2394:2015 [7]). Results are shown in Table 5 ($\beta = 3.2$, $T_{ref} = 50a$)

Table 5: Updated PSF based on measurements in situ – KL 2c.

	Update based on measurement of			**Remarks**
	USM	**Density**	**Compression strength**	
$\mu_{x,ref}$	5300 [m/s] [9]	470 [kg/m³] [20] with [19]	35.3 [N/mm²] [20] with [19]	Reference value from strength class C35 (US from own studies)
$cov_{x,ref}$	0.06 [9]	0.10 [19]	0.20 [19]	
$cov_{y,target}$	0.25 [19]	0.25 [19]	0.25 [19]	Based on prior information
$\rho_{x,y}$	0.27 [18]	0.54 [18]	0.8[1] [19]	
x_{meas}	5503 [m/s]	525 [kg/m³]	35 [N/mm²]	Mean value
$\gamma_{M,up}$	1.30	1.27	1.24	

[1] in JCSS PMC [19] $\rho = 0.8$ as indicative value for "high correlation"

4.4 MATERIAL MODEL IN KNOWLEDGE LEVEL 3

4.4.1. Bayesian update

Using the results of the determination of the compression strength from analysing core samples in the laboratory, a Bayesian update of the material model for the compression strength is performed, see Figure 5 and Table 6.

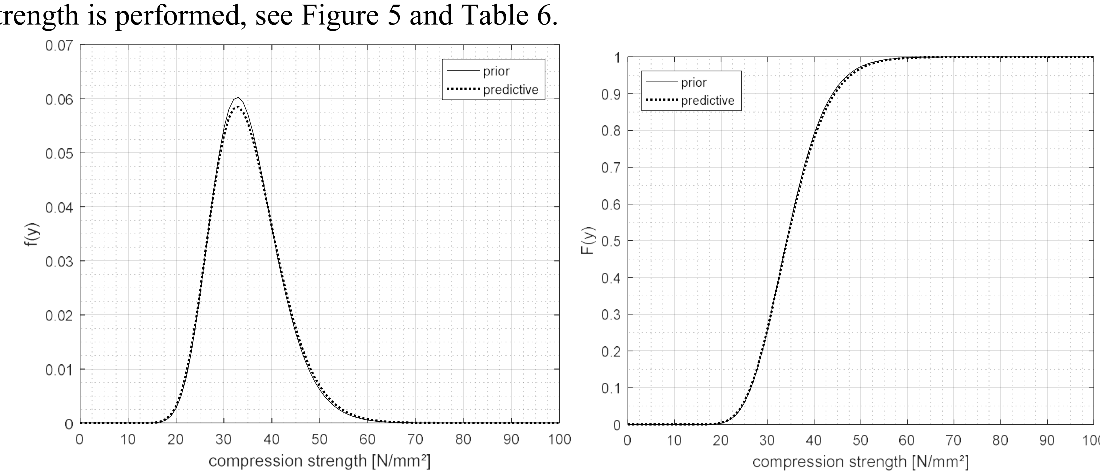

Figure 5: Bayesian update of compression strength.

Table 6: Bayesian update of the compression strength.

		m [N/mm²]	cov	x_k [N/mm²]
Compression strength	Prior (C35, EN 338)	34.74	0.20	25
	Predictive	34.96	0.21	24.35

The update shows, that no big difference of the prior model (based on the improved grading applying technical means) and the predictive model occurs. Thus, the investigation techniques seem to provide a good estimate of the load bearing capacity. To model the bending strength, the characteristic value of EN 338 for C35 and the cov from [19] are assumed.

4.5 SUMMARY

Table 7 summarises the results of the updating procedure.

Table 7: Material model and PSF dependant on Knowledge Level for practical example.

Knowledge Level		**Material model**					
		Semi-probabilistic					*Remarks*
		PSF			$f_{m,k}$	$f_{m,d}$	
		γ_G	γ_Q	γ_M	[N/mm²]		
1		1.35	1.5	1.30	24	16.6	
2	**a)**	1.20	1.5	(1.22)	30	(22.1)	*Not for standardisation*
	b)	1.20	1.5	(1.22)	35	(25.8)	*Not for standardisation*
	c)	1.20	1.5	1.3/1.27/1.24	35	24.2/24.8/25.4	*Update based on USM/ρ/$f_{c,0}$*
		Probabilistic					
		μ [N/mm²]	σ [N/mm²]	*cov* [-]	Distr.		
3		54.09	13.52	0.25	LN		

5 CONCLUSION

The results of the in-situ strength grading showed that a detailed survey concerning the material quality adds to the accuracy of the structural evaluation. The investigation also showed that it is possible to use partially high load-bearing reserves by updating the material model. Simultaneously, deficits in the load-bearing capacity can only be detected accurately by a detailed investigation. To combine information gained from material studies, the development of multiple correlation models is needed. This is part of the ongoing research work. What is more, modified PSF applicable for different load scenarios as optimised values considering an improved strength grading in situ are needed. This is also part of ongoing work.

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