Short-Term Scientific Mission Report

Calibration and Simplification of Eurocode Safety Formats for Structural Timber Design

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1 Introduction and Purpose of the STSM

Many construction bureaus are well familiar with the design of concrete or steel structures, but lack experience with the use of timber in structural engineering. One of the reasons for that can be the avoidance of choosing timber as building material due to additional effort and unknown phenomena. A timber specific phenomenon is the effect of the load duration on the resistance, which has to be considered in the design by strength reduction using modification factors like k_{mod} in Eurocode 5 [5]. This has also an effect on the determination of the decisive load combination. Whereas for other building materials the load combination with the maximum load is automatically decisive for the design, this is not equally applicable for timber structures. In fact, due to the influence of load duration and service class -accounted by the corresponding values for k_{mod} -, the decisive load combination could also result in a lower sum of load. Therefore, simplifications for the detection of the decisive load combination for structural timber design seem to be desirable. First proposals were already presented and discussed within COST Action FP1402 Working Group 1 "Basis of Design" (see [7]) by Prof. Dr. François Colling and Michael Mikoschek. These previous investigations in the field of simplified rules for load combinations in structural timber design have led to encouraging results, considering the deviation in accordance to the rules of the Eurocodes. Moreover, first rough calculations regarding economic aspects and reliability were presented in a workshop of COST Action FP1402 [8]. They showed that the simplified rules lead to higher reliability indexes compared to the Eurocodes. However, further calculations and studies are necessary for more precise results and to consider the influence of the timber specific factors. Therefore, the involved researchers needed to deepen their knowledge in reliability analysis. The members of Working Group 1 agreed to continue the work in this topic and to organise a Short-Term Scientific Mission (STSM) for this purpose.

Beside the time-consuming search of the decisive load combination, there are further aspects that make the design of timber structures unnecessarily effortful. There are a large number of values for timber specific factors (especially for k_{mod}) in Eurocode 5, depending on the materials and the regulations of the different countries which are contained in the national annexes. Here, harmonization and reduction of the corresponding values seem to be necessary and helpful. This is even more true, since the additional effort in finding the decisive load combination is due to the large number of values for k_{mod}.

It is well known to the author, that simplifications in standards have always been a controversial topic. However, the fundamental questions of the necessity of simplifications or whom the Eurocodes should be addressed to, are no part of this work. Instead, it should be considered as basis for discussions. Furthermore, simplifications are not necessarily meant to replace the current precise design rules. Simplifications should rather be implemented in codes additionally for the design of simple structures under certain restrictions and conditions.

The work presented in this report contains some simplified safety formats in order to ease the design of timber structures and avoid additional effort compared to other building materials. The safety factors included in these safety formats are calibrated with the objective of achieving the same (or a higher) level of reliability of the current version of the Eurocode. All calculations related to the investigations stated herein were conducted by Michele Baravalle (PhD candidate at the NTNU) and supervised by Dr. Jochen Köhler at the host institution. The results of this STSM are the basis for further calculations and research, which shall be published in a joint paper.

2 State of the Art

The Eurocodes are semi-probabilistic design codes, adopting the Load and Resistance Factor Design format (LRFD). The safety assessment of structural members is greatly simplified and reduced to a comparison of the design value of the resistance r_d with the design value of the effect of actions e_d ($r_d > e_d$).

According to Eurocode 0 [4], r_d is written in general terms in Eq. (1) where a_d is the design value of geometrical data, x_k is the characteristic values of the materials properties, γ_M is the partial safety factor and k_{mod} is the modification factor for timber from Eurocode 5. The partial safety factor γ_M is covering: the deviation of the material property from its characteristic value, the random part of k_{mod}, the uncertainty on the resistance model as well as the geometric deviations.

$$r_d = r\left\{k_{\mathrm{mod}}\frac{x_k}{\gamma_M};a_d\right\} \tag{1}$$

The modification factor k_{mod} considers the time dependent decrease of the load bearing capacity of timber. It depends on the moisture content of the timber elements (defined in service classes) and the type of load, i.e. the load duration. Generally, the strength reduction is greater when the moisture is high and the load is being applied for longer periods. The values of the factors are usually determined empirically by experience or by using probabilistic methods which are referred to as damage accumulation models (see e.g. Gerhards model [11] or Barrett and Foschi's model [1, 2]). *Table 1* shows the k_{mod}-values for solid timber in accordance to Eurocode 5.

Table 1. Values for the modification factor k_{mod} for solid timber and glulam, according to Eurocode 5

Moisture content	Service class	Load-duration class of action				
		Permanent	Long-term	Medium-term	Short-term	Instantaneous
< 12%	1	0.60	0.70	0.80	0.90	1.10
13-20%	2	0.60	0.70	0.80	0.90	1.10
> 20%	3	0.50	0.55	0.65	0.70	0.90

The effect of action e_d for the verification of structural ultimate limit states (ULS) can be written in general terms in Eq. (2). The partial safety factors for permanent actions γ_G and variable actions γ_Q cover the deviation of the loads from their characteristic values and the load model uncertainty. The load combination factor ψ_0 reduces the effect of accompanying actions. It takes into account, that the probability of simultaneous occurrence of the maximum value of different variable loads is low.

$$e_d = e\left\{\gamma_{G,j}\, g_{k,j};\gamma_{Q,1}q_{k,1};\gamma_{Q,i}\psi_{0,i}q_{k,i}\right\} \quad \left(j \geq 1; i > 1\right) \tag{2}$$

For each relevant load case, the design effect of action shall be determined by combining the effects of actions that can occur at the same time. The combination of actions in Eq. (2) is expressed as in the Eurocode 0 Equation 6.10, see Eq. (3) where the symbol "$+$" means "to be combined with". The factor k_{mod} on the resistance side should be chosen as the one corresponding to the load with the shortest duration considered in the combination.

$$\sum_{j\geq 1}\gamma_{G,j}g_{k,j}+\gamma_{Q,i}q_{k,1}+\sum_{i\geq 1}\gamma_{Q,i}\psi_{0,i}q_{k,i} \tag{3}$$

For resistance models which are linear in the material property, the design check can be rewritten as in Eq. (4), where the resistance side is independent from the load duration and moisture content. The assumption of linear models is maintained hereinafter.

$$r_d > e_d \rightarrow r\left\{\frac{x_k}{\gamma_M};a_d\right\}\geq\frac{e_d}{k_{\mathrm{mod}}}=e_d^* \tag{4}$$

As stated in Eq. (4), the highest ratio between the effect of the combined actions e_d and the corresponding value of k_{mod} is decisive for design. This requires consideration of a larger number of load combinations compared to what is done for other construction materials where the combination giving the largest e_d is decisive. For the case with permanent loads and two variable loads ($n_Q = 2$) five load combinations should be considered, see Eq. (5), (6) and (7). The notation $k_{\mathrm{mod},[\cdot]}$ stands for the k_{mod} -value corresponding to the load $[\cdot]$.

$$e_d^* = e\left\{\sum\nolimits_{j\geq 1}\gamma_{G,j}g_{k,j}\right\}\Big/k_{\mathrm{mod,G}} \tag{5}$$

$$e_d^* = e\left\{\sum\nolimits_{j\geq 1}\gamma_{G,j}g_{k,j}+\gamma_{Q,i}q_{k,i}\right\}\Big/k_{\mathrm{mod},Qi} \quad (i=1,2) \tag{6}$$

$$e_d^* = e\left\{\sum\nolimits_{j\geq 1}\gamma_{G,j}g_{k,j}+\gamma_{Q,i}q_{k,i}+\gamma_{Q,h}\psi_{0,h}q_{k,h}\right\}\Big/\max\left\{k_{\mathrm{mod},Q1},k_{\mathrm{mod},Q2}\right\} \quad (i=1,2;h\neq i) \tag{7}$$

For $n_Q > 2$ the number of load combinations can be calculated with $1+2n_Q+n_Q\left(n_Q-1\right)$.

3 Considered Simplifications

In order to ease the effortful search of the decisive load combination and further design rules, three simplifications for structural timber design are considered below. They are following the approach of introducing simplified formulas and the reduction of the numbers of modification factors. The intention is to simplify the design of structures when two or more variable loads occur in addition to permanent loads. In fact, there is no need for simplification with regard to the relevant situation dealing with only one variable load.

3.1 Simplified Safety Format I (SFI)

The simplified load combination rules proposed in [7] are examined further here. They are basically in accordance with the rules in the German standard DIN 1052:2004-08 in § 5.2 (1). However, additional restrictions and statements were introduced for a better understanding and higher conservatism. A total of $1+n_Q$ load combinations are to be considered for a structural element loaded by n_Q variable loads, see Eq. (8) and (9). The first load combination introduces a global safety factor γ_F for multiplying the sum of all characteristic loads without load combination factors. The second load combination considers the permanent load and only one variable load. The more unfavourable action has to be used for the design.

$$e_d^* = e\left\{\gamma_F\left(\sum\nolimits_{j\geq 1}g_{k,j}+\sum\nolimits_{i=1}^{n_Q}q_{k,i}\right)\right\}\Big/\max\left\{k_{\mathrm{mod},Q1},\ldots,k_{\mathrm{mod},Qn_Q}\right\} \tag{8}$$

$$e_d^* = e\left\{\sum\nolimits_{j\geq 1}\gamma_{G,j}g_{k,j}+\gamma_{Q,\mathrm{i}}q_{k,\mathrm{i}}\right\}\Big/k_{\mathrm{mod,Qi}} \quad \left(i=1,\ldots,n_Q\right) \tag{9}$$

3.2 Simplified Safety Format II (SFII)

The additional effort for finding the decisive load combination in structural timber design is caused by the number of different load duration factors k_{mod}. Therefore, it is proposed in this simplification to use one fixed value of k_{mod} (hereinafter referred to as k_{mod}^{*}) in combination with the rules of *SFI*. The number of load combinations, which has to be checked, are $1+n_Q$ just as for SFI. The advantage of this approach is that non-decisive load combinations can be excluded easily by comparing the characteristic values of the different variable loads.

$$e_d / k_{\text{mod}}^{*} = e\left\{\gamma_F \left(\sum\nolimits_{j\geq 1} g_{k,j} + \sum\nolimits_{i=1}^{n_Q} q_{k,i}\right)\right\} \Big/ k_{\text{mod}}^{*} \qquad (10)$$

$$e_d / k_{\text{mod}}^{*} = e\left\{\sum\nolimits_{j\geq 1} \gamma_{G,j} g_{k,j} + \gamma_{Q,\text{i}} q_{k,\text{i}}\right\} \Big/ k_{\text{mod}}^{*} \quad \left(i = 1,\ldots,n_Q\right) \qquad (11)$$

3.3 Simplified Safety Format III (SFIII)

Using a fixed value of the load duration factor k_{mod} (hereinafter referred to as k'_{mod}) would also be simplification with the load combination rules according to Equation 6.10 in Eurocode 0, see Eq. (3). This simplification is leading to a number of load combinations which is equal to the ones considered for any other construction material. In fact, the number of load combinations is equal to the number of variable loads n_Q:

$$e_d / k'_{\text{mod}} = e\left\{\sum\nolimits_{j\geq 1} \gamma_{G,j} g_{k,j} + \gamma_{Q,\text{i}} q_{k,\text{i}} + \sum\nolimits_{h\neq i} \gamma_{Q,h} \psi_{0,h} q_{k,h}\right\} \Big/ k'_{\text{mod}} \quad \left(i = 1,\ldots,n_Q\right) \qquad (12)$$

4 Calibration of the Simplified Safety Formats

The reliability level associated to the proposed simplified safety formats are assessed and compared with the safety level, given by the Eurocodes. The safety factor γ_F introduced in *SFI* and the fixed k_{mod}-values introduced in *SFII* and *SFIII* are calibrated in order to reach satisfactory levels of safety. For this purpose, the safety level associated with the design just satisfying the design equations is evaluated using the First Order Reliability method (FORM). The FERUM package [13] is used in Matlab® for this purpose. As already mentioned, first rough calculations regarding the reliability analysis of the simplification *SFI* with γ_F =1.40 were performed and published in [8]. These calculations are extended and performed more precise herein. As in the previous calculations, the work is restricted to:

- service classes: 1 and 2 (see Table 1),
- two variable loads: wind (Q_1) and snow (Q_2),
- two materials: solid timber (*ST*) and glulam (*GL*),
- three failure modes: bending, tension and compression parallel to the grain.

These restrictions are representing the most common cases of typical wooden structures (e.g. roof constructions) for which the simplifications are aimed at.

4.1 Reliability Analysis and Probabilistic Models

The description of the random variables and the stochastic models used for the reliability analysis are summarized in *Table 2*. All random variables are considered uncorrelated.

*Table 2. Stochastic model for the reliability analysis from [14] unless otherwise specified (§ [16], *yearly maxima).*

Random variable			Distr. type	Mean (μ)	COV	Charact. fractile
Solid timber (ST)	Resistance model uncertainty	$\theta_{R,ST}$	Logn.	1.00	0.07	/
	Bending strength	$F_{m,ST}$	Logn.	1.00	0.25	0.05
	Tension parallel to grain	$F_{t,0,ST}$	Logn.	1.00	1.2*0.25	0.05
	Compression aprallel to grain	$F_{c,0,ST}$	Logn.	1.00	0.8*0.25	0.05
Glulam (GL)	Resistance model uncertainty	$\theta_{R,GL}$	Logn.	1.00	0.07	/
	Bending strength	$F_{m,GL}$	Logn.	1.00	0.15	0.05
	Tension parallel to grain	$F_{t,0,GL}$	Logn.	1.00	1.2*0.15	0.05
	Compression aprallel to grain	$F_{c,0,GL}$	Logn.	1.00	0.8*0.15	0.05
Dead load		G	Normal	1.00	0.10	0.5
Wind time-invariant part (gust c_g ,pressure c_{pe} and roughness c_r coefficients)		θ_{Q_1}	Logn.	1.00	0.27	0.78 (c_{pe}) (μ for c_g, c_r)
Wind mean reference velocity pressure *		Q_1	Gumbel	1.00	0.25	0.98
Snow time-invariant part (model uncertainty and shape coefficient)		θ_{Q_2}	Logn.	1.00	0.20§	(μ)
Snow load on roof*		Q_2	Gumbel	1.00	0.35§	0.98

Normalized and standardized limit state functions (LSF) in Eq. (13) have been considered for the reliability analyses as in [10]. The limit states functions are normalized in the sense that the random variables have a unitary mean, except for the model uncertainties which might have different values for biased models. In this way, different load scenarios (i.e. different ratios between actions induced by self-weight, first and second variable loads) are represented varying the parameters α_Q and α_G in the limit state functions. The equations are standardized in terms of the representation of different failure modes. For example, failure in bending is represented by the material property X , which is the bending strength in this case, and the design parameter z representing the cross-section modulus. The k_{mod} -values included in the limit state functions are assumed to be known (deterministic) and equal to the ones given in Eurocode 5. Their uncertainty is considered included in the resistance model uncertainty (θ_R). Load damage models are therefore not considered explicitly. The probability of failure of the structural element is the union of the failure events represented by the five limit state functions. For the specific problem at hand, it is apparent that the failure probability of the union is determined by one of the five limit sates. Hence, for simplification purposes, the reliability index is calculated as the minimum reliability index among the ones obtained from the five limit state functions (LSF g_1 to g_5).

$$
\begin{aligned}
&g_1(...) = zk_{\text{mod,G}} x\theta_R - \alpha_G g \le 0 \\
&g_2(...) = zk_{\text{mod},Q1} x\theta_R - \alpha_G \cdot g - (1-\alpha_G)\cdot\left[\alpha_Q \theta_{Q1} q_1\right] \le 0 \\
&g_3(...) = zk_{\text{mod},Q2} x\theta_R - \alpha_G \cdot g - (1-\alpha_G)\cdot\left[\left(1-\alpha_Q\right)\theta_{Q2} q_2\right] \le 0 \\
&g_4(...) = z\max\left\{k_{\text{mod},q1}, k_{\text{mod},Q2}\right\} x\theta_R - \alpha_G g - (1-\alpha_G)\left[\alpha_Q \theta_{Q1} q_{1L} + (1-\alpha_Q)\theta_{Q2} q_{2A}\right] \le 0 \\
&g_5(...) = z\max\left\{k_{\text{mod},Q1}, k_{\text{mod},Q2}\right\} x\theta_R - \alpha_G g - (1-\alpha_G)\left[\alpha_Q \theta_{Q1} q_{1A} + (1-\alpha_Q)\theta_{Q2} q_{2L}\right] \le 0
\end{aligned}
\tag{13}
$$

The design parameters z are given for all examined simplifications in Eq. (14), Eq. (15) and Eq. (16).

$$
\begin{aligned}
&z_1 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\alpha_Q \cdot q_{1,k}\cdot\gamma_Q\right]\cdot\frac{\gamma_M}{k_{\text{mod},Q1}\cdot x_k} \\
&z_2 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\left(1-\alpha_Q\right)\cdot q_{k,2}\cdot\gamma_Q\right]\cdot\frac{\gamma_M}{k_{\text{mod},Q2}\cdot x_k} \\
&z_3 = \left[\alpha_G \cdot g_k \cdot \gamma_F + (1-\alpha_G)\cdot\left[\alpha_Q \cdot q_{1k}\cdot\gamma_F + (1-\alpha_Q)\cdot q_{2k}\cdot\gamma_F\right]\right]\cdot\frac{\gamma_M}{\max\left\{k_{\text{mod},Q1}, k_{\text{mod},Q2}\right\}\cdot x_k} \\
&z = \max\left\{z_1, z_2, z_3\right\}
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
&z_1 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\alpha_Q \cdot q_{1,k}\cdot\gamma_Q\right]\cdot\frac{\gamma_M}{k^*_{\text{mod}}\cdot x_k} \\
&z_2 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\left(1-\alpha_Q\right)\cdot q_{k,2}\cdot\gamma_Q\right]\cdot\frac{\gamma_M}{k^*_{\text{mod}}\cdot x_k} \\
&z_3 = \left[\alpha_G \cdot g_k \cdot \gamma_F + (1-\alpha_G)\cdot\left[\alpha_Q \cdot q_{1k}\cdot\gamma_F + (1-\alpha_Q)\cdot q_{2k}\cdot\gamma_F\right]\right]\cdot\frac{\gamma_M}{k^*_{\text{mod}}\cdot x_k} \\
&z = \max\left\{z_1, z_2, z_3\right\}
\end{aligned}
\tag{15}
$$

$$
\begin{aligned}
&z_1 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\left[\alpha_Q \cdot q_{1k}\cdot\gamma_Q + (1-\alpha_Q)\cdot q_{2k}\cdot\gamma_Q\cdot\psi_{0,q2}\right]\right]\cdot\frac{\gamma_M}{k'_{\text{mod}}\cdot x_k} \\
&z_2 = \left[\alpha_G \cdot g_k \cdot \gamma_G + (1-\alpha_G)\cdot\left[\alpha_Q \cdot q_{1k}\cdot\gamma_Q\cdot\psi_{0,q1} + (1-\alpha_Q)\cdot q_{2k}\cdot\gamma_Q\right]\right]\cdot\frac{\gamma_M}{k'_{\text{mod}}\cdot x_k} \\
&z = \max\left\{z_1, z_2\right\}
\end{aligned}
\tag{16}
$$

The Ferry Borges and Castanheta load combination rule is applied (see e.g. [9]). Load combinations are obtained considering a single variable load (LSF g_2 and LSF g_3) as well as the simultaneous occurrence of the two loads (LSF g_4 and LSF g_5). For the first cases, the yearly maxima are used. For the second cases, the maxima of loads over different reference periods are combined together considering one load leading ($q_{.,L}$) and one accompanying ($q_{.,A}$). Both loads are represented by a Poisson rectangular pulse process and are present n_p days a year and have a number of repetitions equal to n_r, a similar combination model is included in [6].

Four different cases are regarded by combining short-term and medium-term snow action with short-term/instantaneous and instantaneous wind action. The parameters representing the loads and the associated modification factors and load combination factors are reported in *Table 3*. Permanent action G, e.g. self-weight of structural and non-structural parts, has the modification factor $k_{\text{mod}} = 0.60$.

Table 3. Different cases for climatic conditions and relative parameters for the load models and recommended ψ_0 and k_{mod} values from Eurocodes.

<table>
<tr><th rowspan="2">Case</th><th colspan="5">Wind</th><th colspan="5">Snow</th></tr>
<tr><th>Load dur.</th><th>k_{mod}</th><th>ψ_0</th><th>n_p</th><th>n_r</th><th>Load dur.</th><th>k_{mod}</th><th>ψ_0</th><th>n_p</th><th>n_r</th></tr>
<tr><td>1</td><td>Short /inst.</td><td>1.00</td><td rowspan="4">0.60</td><td rowspan="4">365</td><td rowspan="4">365</td><td>Short</td><td>0.90</td><td>0.50</td><td>100</td><td rowspan="4">11</td></tr>
<tr><td>2</td><td>Short /inst.</td><td>1.00</td><td>Medium</td><td>0.80</td><td>0.70</td><td>150</td></tr>
<tr><td>3</td><td>Inst.</td><td>1.10</td><td>Short</td><td>0.90</td><td>0.50</td><td>100</td></tr>
<tr><td>4</td><td>Inst.</td><td>1.10</td><td>Medium</td><td>0.80</td><td>0.70</td><td>150</td></tr>
</table>

4.2 Reliability Level of the Current Eurocodes

The proposed simplified safety formats are calibrated in order to provide safety levels which are equal to or larger than the safety levels implicitly provided by the codes in use that are estimated in this paragraph. The partial safety factors recommended in the Eurocodes are:

- $\gamma_G = 1.35$ for all permanent loads (self-weight of structural and non-structural parts);
- $\gamma_Q = 1.50$ for all variable loads;
- $\gamma_{M,ST} = 1.30$ for strength of solid timber;
- $\gamma_{M,GL} = 1.25$ for strength of glulam timber.

The weighted mean and standard deviation of the reliability indices obtained for different material properties and different load scenarios are calculated. The weights for the different material and load scenarios are assigned with engineering judgement for representing the frequency of occurrence in real structures. In detail, all load scenarios are equally weighted, i.e. are considered equally frequent in reality, while the assigned weights of the materials and material properties are shown in *Table 4*. The sum of all weights is equal to 1.00.

Table 4. Weights for materials and failure modes.

	Bending F_m	Tension $F_{t,0}$	Compression $F_{c,0}$	Total (per material)
Solid Timber (ST)	0.42	0.07	0.21	0.70
Glulam (GL)	0.18	0.03	0.09	0.30
Total (per failure mode)	0.60	0.10	0.30	

These values were agreed assuming that the proposed simplified safety formats are expected to be used for the design of simple structures that are mostly made of solid timber (e.g. roof structures or ceilings in houses). However, these weights could be discussed considering the fact that simple structures can also occur in industrial buildings where glulam is rather used. The failure modes and corresponding weights could be chosen different in regard to the addressed building type, too.

The load scenarios are characterized by the proportions between the different loads expressed as $\chi_G = g_k / (g_k + q_{1,k} + q_{2,k})$ and $\chi_Q = q_{1,k} / (q_{1,k} + q_{2,k})$. Load scenarios are divided into three domains listed below representing, for example, a storage building with dominating permanent loads, a common building in areas with predominant short/medium-term loads (e.g. snow) and a common building in areas with dominating instantaneous loads (e.g. wind).

1. Structures with dominating permanent loads: $\chi_G > 0.6$ and $0 \le \chi_Q \le 1$;
2. Structures with dominating short/medium-term loads: $0 < \chi_G \le 0.6$ and $0 \le \chi_Q \le 0.6$;
3. Structures with dominating instantaneous loads: $0 < \chi_G \le 0.6$ and $0.6 \le \chi_Q \le 1$.

4.3 Calibration Objectives

Tentative values of the reliability elements included in the proposed simplified safety formats (γ_F, k^*_{mod} and k'_{mod}) are calibrated considering three different objectives.
The first (O1) consists into maintaining the same mean reliability level given by the Eurocodes and maximizing the homogeneity among the different design situations and material properties considered. The relevant reliability elements $\boldsymbol{\gamma}$ for each simplified format are calibrated solving the minimization problem in Eq. (17) with a target reliability index $\beta_t = E[\beta]_{EC}$ where $E[\beta]_{EC}$ is the weighted mean reliability index associated with the Eurocode. The sums are extended over the six considered material properties and the different combinations of χ_G and χ_Q values.

$$\min_{\boldsymbol{\gamma}} \left\{ \sum_{i=1}^{6} \sum_{j=\chi_{G,\min}}^{\chi_{G,\max}} \sum_{k=\chi_{Q,\min}}^{\chi_{Q,\max}} w_{ijk} \left(\beta_{ijk}(\boldsymbol{\gamma}) - \beta_t \right)^2 \right\} \tag{17}$$

An alternative calibration objective (O2) is following the minimization of the sum of squared differences in Eq. (17) imposing at the same time that the minimum reliability index is equal to or larger than the minimum reliability index associated with the Eurocode ($\beta_{\min,EC}$).
A third calibration is implemented by using a skewed penalty function (O3) in Eq. (18) proposed in [9] that penalizes under-design ($\beta < \beta_t$) more than over-design ($\beta > \beta_t$). In fact, under-design is associated to larger expected costs due to predominant expected costs of structural failure, see e.g. [15]. This penalty function penalizes low β-values, without including a strict lower bound as the previous one.

$$\min_{\boldsymbol{\gamma}} \left\{ \sum_{i=1}^{6} \sum_{j=\chi_{G,\min}}^{\chi_{G,\max}} \sum_{k=\chi_{Q,\min}}^{\chi_{Q,\max}} w_{ijk} \left[\frac{\beta_{ijk}(\boldsymbol{\gamma}) - \beta_t}{d} - 1 + \exp\left(-\frac{\beta_{ijk}(\boldsymbol{\gamma}) - \beta_t}{d} \right) \right] \right\} \quad (d \approx 0.23) \tag{18}$$

It is to be highlighted that the absolute values of the reliability indices reported in this work are of secondary importance, since both the estimation of the target reliability β_t from the existing codes and the calibration of reliability factors are performed with the same probabilistic models. As expected, the absolute values of $E[\beta]_{EC}$ and $\beta_{\min,EC}$ are sensitive to the stochastic models adopted. Nevertheless, the calibrated reliability elements are seen to be almost insensitive to changes within the domain of realistic stochastic models. The (nominal) reliability indices are therefore used to compare safety levels rather than expressing the “exact” level of safety. For such a reason, the random variables are represented with simplified stochastic models (see *Table 2*). For the same reason, the biases of the resistance and load models are not considered. Beside the difficulty of their estimation, their inclusion will affect the values of β consistently and not the values of the calibrated reliability elements. Larger reliability indices are expected due to the conservativeness (bias larger than 1) of the Eurocode models (see e.g. [12] for wind load model).

5 Results of the Calibration

The calibrated reliability elements are summarized in the following tables for the different simplified safety formats, cases and calibrations objectives which were considered.

Table 5: Calibrated values of global load factor γ_F in SFI

	permanent load dominating			medium/short load dominating			instantaneous load dominating		
Case	O1	O2	O3	O1	O2	O3	O1	O2	O3
1	1,78	2,25	2,10	1,28	1,35	1,46	1,33	1,35	1,49
2	1,81	2,25	2,13	1,30	1,35	1,40	1,38	1,35	1,53
3	1,96	2,47	2,31	1,28	1,48	1,53	1,35	1,48	1,57
4	1,99	2,47	2,34	1,31	1,48	1,13	1,39	1,49	1,60

Table 6: Calibrated values of global factor γ_F and fixed k^*_{mod} in SFII

		permanent load dominating			medium/short load dominating			instantaneous load dominating		
Case		O1	O2	O3	O1	O2	O3	O1	O2	O3
1	γ_F	1,10	1,42	1,43	1,00	1,15	1,00	1,00	1,26	1,00
	k^*_{mod}	0,73	0,63	0,68	0,86	0,85	0,80	0,92	0,94	0,85
2	γ_F	1,10	1,46	1,41	1,00	1,32	1,56	1,01	1,22	1,00
	k^*_{mod}	0,72	0,65	0,66	0,80	0,95	0,92	0,90	0,91	0,83
3	γ_F	1,43	1,48	1,46	1,39	1,39	1,00	1,27	1,39	1,44
	k^*_{mod}	0,80	0,66	0,70	1,06	1,03	0,82	1,06	1,03	1,01
4	γ_F	1,10	1,46	1,42	1,00	1,11	1,00	1,00	1,33	1,36
	k^*_{mod}	0,72	0,65	0,67	0,81	0,82	0,77	0,98	0,99	0,94

Table 7: Calibrated values of fixed k'_{mod} in SFIII

	permanent load dominating			medium/short load dominating			instantaneous load dominating		
Case	O1	O2	O3	O1	O2	O3	O1	O2	O3
1	0,76	0,60	0,64	0,97	0,95	0,89	1,00	0,94	0,85
2	0,75	0,60	0,63	0,91	0,95	0,83	1,00	1,00	0,91
3	0,76	0,60	0,64	1,01	0,95	0,92	1,09	0,96	0,94
4	0,75	0,60	0,64	0,93	0,95	0,85	1,09	0,99	0,95

6 Discussion

The simplified safety formats (*SFI*, *SFII* and *SFII*) and the Eurocodes (EC) are compared in terms of: underlying calibration objectives and reliability levels in Figure 1. Therein, the upper dots represent the maximum values of β, while the lower dots represent the minimum values resulted by the "optimal" calibrations of case 3 as example. Obviously, the dots in between are the mean values of β.

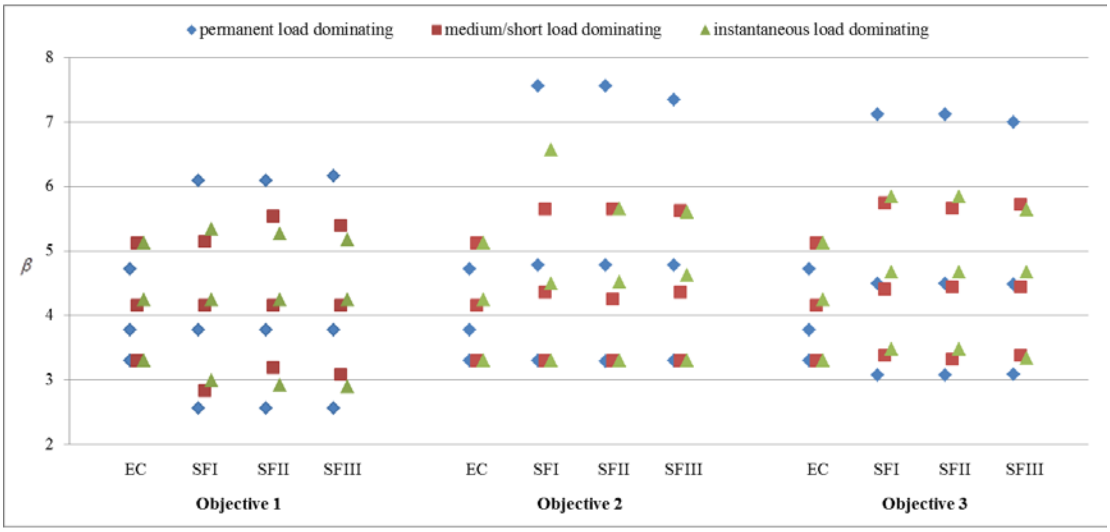

Figure 1. Values of β (maximum, mean and minimum) for Case 3

It can be seen, that calibrations with Objective 1 give minimum values of β, which are significantly lower than the values corresponding to the Eurocodes. For safety reasons, this objective should rather be excluded for further calibrations. It works differently with Objective 2 and 3, where the reliability indices are very similar and mostly above the Eurocode level. Quite high over-design was obtained for the cases with permanent load dominating. These cases are considered rare in timber structures and were given mostly for sake of completeness. Facing the need of choosing one objective to resume work, Objective 3 would probably be the better decision, because it comes closer to "real design situations" by penalizing under-design more than over-design.

Looking at the calibrated values of the global safety factor and fixed k_{mod}, it can be recognized, that the values are fairly close to each other for medium/short-term and instantaneous loads. These two load duration classes could may be merged in further calibrations.

In summary, all calibrated safety formats result in roughly the same levels of safety with similar scatter. Therefore, the simplified safety formats should be rather compared by the number of relevant load combinations. The total numbers of load combinations which have to be checked for finding the decisive one, are shown in *Table 8*. They are depending on the number of variable loads n_Q.

Table 8. Number of load combinations with permanent load and n_Q variable loads.

n_Q	*EC*	*SFI*	*SFII*	*SFIII*
1	2	2	2	1
2	5	3	3	2
3	13	4	4	3
4	21	5	5	4

All of the proposed simplified safety formats are reduce the number of load combinations significantly. Since the additional effort in structural timber design is caused by the number of values for k_{mod}, *SFII* and *SFIII* seem to be favoured. However, *SFII* could be "hard to sell" in discussions, because introducing simplified load combination rules and a reduction of load duration factors at the same time, are a strong encroachment in current design principles. This is not the case in *SFI* and *SFIII*, which are following only one of both approaches for simplification. On the one hand, SFI needs only to be implemented with two additional equations and some small restrictions in the codes, while other rules stay unchanged. On the other hand, *SFIII* is more intuitive and reduces the number of load combinations to the same number as for other materials.

7 Conclusion and Outlook

The load duration factor k_{mod} can cause a large number of load combinations in the design of timber structures. This leads in general to a more demanding design compared to other construction materials. For the reduction of the effort in design, three simplified safety formats have been considered and their reliability elements have been calibrated in order to reach the same or higher safety level of the Eurocodes. Different cases were accounted in order to represent different climatic regions, types of dominating loads, materials and material properties. The proposed simplified formats have been compared with the Eurocode under different aspects and they were found performing well for the case of dominating variable loads, which is the most common case for timber structures. The work was limited to load combinations with snow, wind and permanent loads only.

The question, of which type of simplification is to be preferred, has to be discussed in further investigations or expert groups. This will be surely done in Working Group 1 "Basis of Design" of COST Action FP1402 and in other relevant meetings.

It is clear that simplification can lead (in some cases) to an over-design of a structural element, which results in higher building costs. Further calculations regarding the costs of simplifications will be included in a joint paper.

Moreover, other simplification formats can be evaluated with the methods described in this report. For example, the approach of simplifying by excluding the load combination factor ψ_0 (see [3]) should be checked further in terms of reliability and safety.

Finally, correctness and accuracy of current k_{mod}-values is still at question. It seems to the author that there is little knowledge of how the values have been determined for Eurocode 5. Here, additional investigations and reviews seem to be necessary, too.

8 Acknowledgements

The author gratefully acknowledges COST Action FP1402 Management Committees and the representatives of the COST Office for the STSM grants, which contributed to a successful outcome of this research. The local host Dr. Jochen Köhler and the PhD candidate Michele Baravalle are gratefully thanked for the collaboration and support throughout the STSMs.

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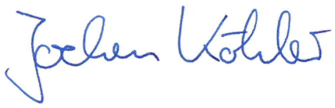
10 Confirmation by the host institution of the successful execution of the STSM

This is to confirm the Mr. Michael Mikoschek performed a short term scientific mission at the Institute of Structural Engineering at the Norwegian University of Science and Technology in Trondheim in the period of 19. – 30. September 2016.



Jochen Köhler