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Calibration of simplified safety formats for structural timber design

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HIGHLIGHTS

- A framework for calibrating simplified safety formats is proposed.
- The increase of construction costs is minimized, without reducing safety.
- Two simplified safety formats for design of timber structures are proposed.
- Different failure modes, materials, climates and load scenarios are considered.
- Safety levels, costs and design simplicity are compared with Eurocodes.

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ABSTRACT

A framework for calibrating the reliability elements in simplified semi-probabilistic design safety formats is presented. The objective of calibration is to minimize the increase of construction costs, compared to the non-simplified safety format, without reducing the level of structural safety. The framework is utilized for calibrating two simplified safety formats which aim at reducing the number of load combinations relevant in structural timber design. In fact, the load-duration effect makes the design of timber structures more demanding since a larger number of load combinations need to be considered compared with other construction materials.

1. Introduction

Current standards for timber design, such as the Eurocode 5 [1], have reached a high level of sophistication, extensiveness, efficiency and completeness at a cost of increasing the number and complexity of design rules, principles and requirements. This is the result of a code-development process driven mainly by the need to extend the standards to new materials, solutions, technologies, calculation tools and mechanical models. The associated drawback is an increased, and sometimes unnecessary, complexity of structural design, particularly for common and simple structures. Therefore, code provisions should balance simplicity, economy, comprehensiveness, flexibility, innovation, and reality [2]. These properties are usually mutually exclusive and their adjustment must not affect the safety level of the design. In addition, the adequate complexity level depends on manifold factors, including the types of structures designed, the materials and technological solutions adopted, the design phase, and the experience of the engineers [2–4]. For example, complex structural solutions require detailed codes, while simple structures do not. Consequently, discussions about the adequate level of code sophistication are ongoing [3–6].

Simplification and improvement of the ease of use of codes are essential criteria in all code development projects, including the publication of the second generation of European structural design codes [7]. Sophistication is obviously required only when bringing benefits since unnecessary detailing will solely increase bureaucracy. Therefore, two research directions are of interest. The first is the assessment of modern codes, the quantification of the benefits given by sophistication compared with existing simpler alternatives. The second is the proposal of less complex solutions that can either substitute the complex ones (when the latter brings no benefits) or work as alternatives when the engineer needs a simpler and faster design for different reasons [3–6].

Part of the complexity of timber design standards is due to the wide range of material-specific phenomena, which can lead to a more demanding structural engineering design compared to other building materials. The most important phenomena are anisotropy, grain deviation, shrinkage, creep and the load-duration effect.

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These phenomena are influenced by the environmental conditions. The load-duration effect is considered in the ultimate limit state design with modification factors, as k_{mod} in Eurocode 5 [1], and has an effect on the determination of the decisive load combination. For other building materials, the load combination with the maximum load is automatically decisive for the design. This is not equally applicable to timber structures. In fact, due to the influence of load duration and service class -accounted for by the corresponding values for k_{mod} - the decisive load combination could also result in a lower absolute sum of loads if it has to be divided by a smaller modification factor. As a consequence, a larger number of relevant load combinations must be considered during structural design. This increases the engineering effort significantly, especially when hand calculations are performed, as is often the case for simple structures or structural components.

Beside the time-consuming search of the decisive load combination, there are further demanding aspects of the design of timber structures. There are a large number of values for timber specific factors (especially k_{mod}), depending on the materials and the regulations of the different countries. Thus, a harmonization and reduction of the corresponding values seem to be necessary and helpful.

Different simplifications of load combination rules for timber design have been discussed and proposed in the literature [4,5]. This article proposes two simplified safety formats that facilitate the detection of the decisive load combination. The work is partly a result of the European Cooperation in Science and Technology (COST) Action FP1402. Preliminary formats and concepts were developed and proposed in [6]. Previous investigations in the field of simplified rules for load combinations in structural timber design led to good results, comparing the design and economic aspects with the Eurocodes [1,8]. First rough calculations regarding reliability aspects showed that the designs identified by simplified rules led to higher reliability indices than the ones identified by the present Eurocodes [9]. However, further reliability analyses and calibrations were necessary for more profound results.

The purpose of the paper is not to advocate the simplification but to provide a scientific basis for the corresponding discussion in the code-committee.

2. Eurocode safety format

The Eurocodes [1,8] comprise the Load and Resistance Factor Design format (LRFD) as several other modern codes (see e.g. [10–12]). It is referred to as semi-probabilistic, i.e. the safety assessment of structural members is simplified and reduced to a comparison of the resistance design value r_d with the design value of the effect of actions e_d, i.e. the former has to be larger than the latter in order to provide appropriate reliability ($r_d > e_d$).

In Eurocode 0 [8], r_d is written in general terms as in Eq. (1) where $\mathbf{z}_d$ is the vector of design values of geometrical data, $f_{k,i}$ are the characteristic values of the material properties involved, $\gamma_{M,i}$ are the partial safety factors and η is the mean value of the conversion factor that keeps into account several effects including the load-duration effect. The partial safety factor γ_M is dependent on: the uncertainties on the material property, the uncertainties on η, the uncertainty on the resistance model as well as the geometric deviations.

$$r_d = r\left\{\eta \frac{f_{k,i}}{\gamma_{M,i}}; \mathbf{z}_d\right\} \tag{1}$$

For the ultimate limit state design of timber elements, the conversion factor is equal to the modification factor k_{mod} that 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 or, more precisely, 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 [13] or Barrett and Foschi's model [14,15]), example values are given in Table 1.

The effect of action e_d for the verification of structural ultimate limit states can be written in general terms as presented in Eq. (2), where one variable load is dominant and the remaining ones are accompanying. The partial safety factors for permanent actions γ_G and variable actions γ_Q cover the uncertainties on the actions, their effects and models. The load combination factors ψ_0 reduce the effect of accompanying actions since the coincidence of maxima has a low probability of occurrence.

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

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

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

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 of the load duration and moisture content. The assumption of linear models is maintained hereinafter.

$$r_d > e_d \rightarrow r \frac{f_{k,i}}{\gamma_{M,i}}; \mathbf{z}_d > \frac{e_d}{k_{\text{mod}}} = e_d^* \tag{4}$$

As is clear from Eq. (4) the load case with highest e_d^* is decisive for design. This requires the consideration of a larger number of load combinations compared to 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 Eqs. (5)–(7). The notation $k_{\text{mod},[\cdot]}$ stands for the k_{mod}-value corresponding to the action $[\cdot]$.

$$e_{d,1}^* = e\left\{\sum_{j \geqslant 1} \gamma_{G,j} g_{k,j}\right\} \Big/ k_{\text{mod},G} \tag{5}$$

$$e_{d,1+i}^* = e\left\{\sum_{j \geqslant 1} \gamma_{G,j} g_{k,j} + \gamma_{Q,i} q_{k,i}\right\} \Big/ k_{\text{mod},Q_i} \quad (i = 1, 2) \tag{6}$$

$$e_{d,3+i}^* = e\left\{\sum_{j \geqslant 1} \gamma_{G,j} g_{k,j} + \gamma_{Q,i} q_{k,i} + \gamma_{Q,h} \psi_{0,h} q_{k,h}\right\} \Big/ \max\left\{k_{\text{mod},Q_1}, k_{\text{mod},Q_2}\right\} \quad (i = 1, 2; h = 1, 2; h \neq i) \tag{7}$$

For $n_Q > 2$ the number of load combinations becomes $1 + 2n_Q + n_Q(n_Q - 1)$.

Table 1
Values for the modification factor k_{mod} for solid timber and glulam according to [16].

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
12–20%	2	0.60	0.70	0.80	0.90	1.10
>20%	3	0.50	0.55	0.65	0.70	0.90

3. Proposed simplified safety formats

3.1. General

In order to facilitate the search for the decisive load combination, two simplified rules for structural timber design are proposed below. The proposals are intended to simplify the design of structures when there are two or more variable loads in addition to permanent loads. For the case with one variable load, the simplification is not needed because two load combinations are to be considered only.

3.2. Simplified safety format I (SFI)

The simplified safety format in [6] is proposed and reviewed here. It is in accordance with the rules in the German standard DIN 1052:2004–08 [17] in § 5.2 (1). However, additional restrictions and statements are introduced for a better understanding and larger conservatism. A total of $1 + n_Q$ load combinations is to be considered for a structural element loaded by n_Q variable loads, see Eq. (8) and (9). The first equation introduces a "global" safety factor γ_F multiplying the sum of all characteristic values of loads. In previous investigations, 1.40 or 1.35 were used as values for γ_F with respect to $\gamma_G = 1.35$ and $\gamma_Q = 1.50$ [6,9]. The second equation combines the permanent load and only one variable load at a time.

$$e^*_{d,1} = e\left\{\gamma_F\left(\sum_{j\geqslant 1} g_{k,j} + \sum_{i=1}^{n_Q} q_{k,i}\right)\right\} \Big/ \max\left\{k_{\text{mod},Q_1}, \ldots, k_{\text{mod},Q_{n_Q}}\right\} \tag{8}$$

$$e^*_{d,1+i} = e\left\{\sum_{j\geqslant 1}\gamma_{G,j} g_{k,j} + \gamma_{Q,i} q_{k,i}\right\} \Big/ k_{\text{mod},Q_i} \quad (i = 1, \ldots, n_Q) \tag{9}$$

3.3. Simplified safety format II (SFII)

A second simplified format is proposed consisting of the load combination rules of the Eurocode 0 [8] with a fixed value of the modification factor $k_{\text{mod}} = k'_{\text{mod}}$. This format reduces the number of different load duration factors, which is indeed the cause of the additional effort for finding the decisive load combination in structural timber design. In addition, this format requires considering the same number of load combinations as for any other construction material (e.g., structural steel and reinforced concrete). A total of n_Q load combinations is to be taken into account, see Eq. (10).

$$e^*_{d,i} = e_{d,i} \big/ k'_{\text{mod}} = e\left\{\sum_{j\geqslant 1}\gamma_{G,j} g_{k,j} + \gamma_{Q,i} q_{k,i} + \sum_{h\neq i}\gamma_{Q,h}\psi_{0,h} q_{k,h}\right\} \Big/ k'_{\text{mod}} \quad (i = 1, \ldots, n_Q) \tag{10}$$

4. Calibration of safety formats

4.1. General

The reliability level associated with the proposed simplified safety format are assessed and compared with the safety level given by the Eurocodes. In general, when the complexity of a code brings benefits, such as higher structural efficiency, any simplification will reduce the engineering costs, but likely also reduce the efficiency of the resulting design and/or limit the code's application domain. Consequently, the safety factor γ_F introduced in *SFI* and the k'_{mod} introduced in *SFII* are calibrated by established techniques ([18–23]) applied in a novel manner to satisfy the objective of minimizing the reduction of structural efficiency without compromising the structural safety level. For this purpose, the safety level associated with the design just satisfying the design equations (i.e. $e_d \equiv r_d$) is evaluated using the First Order Reliability method (FORM). The FERUM package [24] is used in Matlab® [25] for this purpose. First rough calculations regarding the reliability analysis of the simplification (*SFI*) were performed and published in [9]. These calculations are extended and performed more precisely. As in [9], 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 ultimate limit state failure modes at the full member level (i.e., excluding joints and construction details): bending, tension and compression parallel to the grain.

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

4.2. Reliability analyses and probabilistic models

Normalized and standardized limit state functions (LSFs) in Eqs. (11)–(15) have been considered for the reliability analyses as in [19]. $\mathbf{X} = [F, \Theta_R, G, \Theta_{Q_1}, Q_1, \Theta_{Q_2}, Q_2]^T$ and $\mathbf{p} = [z, k_{\text{mod}}, \alpha_G, \alpha_Q]^T$ are the vectors of random variables and deterministic parameters, respectively. All random variables in $\mathbf{X}$ are considered uncorrelated. The description of the random variables and the stochastic models representing them are summarized in the Appendix. The limit states functions are normalized implying that the random variables have all unitary mean except for the model uncertainties which might have different mean values for representing 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 by varying the parameters α_Q and α_G in the limit state functions. The equations are standardized meaning that they can represent different failure modes. For example, the representation of failure in bending considers the general material property F to be the bending strength F_m and the design parameter z to be the cross-section modulus. Geometric properties are assumed deterministic and equal to their nominal or design value. The k_{mod} -values included in the limit state functions are assumed to be known (deterministic) and equal to the ones given in the Eurocodes. Their uncertainty is assumed to be included in the resistance model uncertainty (Θ_R). Therefore, the load damage models are 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 observed that the failure probability of the union is always governed by one of the five limit states. Hence, for simpli-

Table 2
Different climatic conditions and relative parameters of the load models and recommended ψ_0 and k_{mod} values from Eurocodes.

Case	Wind					Snow				
	Load dur.	k_{mod}	ψ_0	n_p	n_r	Load dur.	k_{mod}	ψ_0	n_p	n_r
1 - Germany	Short/inst.	1.00	0.60	365	365	Short	0.90	0.50	100	11
2 - Austria	Short/inst.	1.00				Medium	0.80	0.70	150	
3 - Denmark	Inst.	1.10				Short	0.90	0.50	100	
4 - Norway	Inst.	1.10				Medium	0.80	0.70	150	

fication purposes, the reliability index is calculated as the minimum reliability index among the ones obtained from the five limit state functions.

$$g_1(\mathbf{x},\mathbf{p}) = z k_{\text{mod},G} f \theta_R - \alpha_G g \leqslant 0 \tag{11}$$

$$g_2(\mathbf{x},\mathbf{p}) = z k_{\text{mod},Q_1} f \theta_R - \alpha_G g - (1-\alpha_G)[\alpha_Q \theta_{Q1} q_1] \leqslant 0 \tag{12}$$

$$g_3(\mathbf{x},\mathbf{p}) = z k_{\text{mod},Q_2} f \theta_R - \alpha_G g - (1-\alpha_G)[(1-\alpha_Q) \theta_{Q2} q_2] \leqslant 0 \tag{13}$$

$$\begin{aligned} g_4(\mathbf{x},\mathbf{p}) = {} & z \max\{k_{\text{mod},Q_1}, k_{\text{mod},Q_2}\} f \theta_R - \alpha_G g \\ & - (1-\alpha_G)[\alpha_Q \theta_{Q1} q_{1L} + (1-\alpha_Q)\theta_{Q2} q_{2A}] \leqslant 0 \end{aligned} \tag{14}$$

$$\begin{aligned} g_5(\mathbf{x},\mathbf{p}) = {} & z \max\{k_{\text{mod},Q_1}, k_{\text{mod},Q_2}\} f \theta_R - \alpha_G g \\ & - (1-\alpha_G)[\alpha_Q \theta_{Q1} q_{1A} + (1-\alpha_Q)\theta_{Q2} q_{2L}] \leqslant 0 \end{aligned} \tag{15}$$

The five LSFs represent different failure events due to: only permanent load G (LSF g_1), permanent load with a single variable load (LSFs g_2 and g_3), and permanent load with the simultaneous occurrence of the two variable loads (LSFs g_4 and g_5). The yearly maxima of the variable loads (Q_1, Q_2) are used in the LSFs g_2 and g_3. The Ferry Borges and Castanheta load combination rule is applied in the LSFs g_4 and g_5 (see e.g. [18]) combining together the loads' maxima over reference periods of different length. This is done considering one load as leading (q_L) and the other one as accompanying (q_A). The two loads are represented by a Poisson rectangular pulse process. The loads are present n_p days a year and have a number of independent realizations a year equal to n_r, a similar combination model is included in e.g. [26].

Four major types of climate are regarded by combining snow and wind actions with different characteristics. The parameters of the processes representing the loads, the associated modification factors, and load combination factors are reported in Table 2. For the snow load on the ground, a fundamental distinction is made between continental climate (covered by Cases 2 and 4) and maritime or mixed climates (Cases 1 and 3) [27]. Continental climate is characterized by snow accumulation through the winter and is typical for European sites above 1000 m a.s.l., and for the Nordic countries Finland, Iceland, Norway, and Sweden. Maritime and mixed climates are characterized by significant melting between snow events and are typical for European sites below 1000 m a.s.l. Wind action is represented by 365 independent repetitions a year based on the macro-meteorological period, i.e. the period of passage of a fully developed weather system, that is typically between 1 and 7 days in Europe (see e.g. [28]). According to Eurocode 5, wind action can be considered as short-term or instantaneous with corresponding recommended k_{mod} -values given in Table 1. Classifying wind as short-term, i.e. load-duration up to one week, seems very conservative. This is supported by the fact that several European countries classify wind as instantaneous. Other countries, including Germany and Austria, classify wind as short-term/instantaneous. For all these reasons wind is considered, in this work, short-term/instantaneous (Cases 1 and 2) and instantaneous (Cases 3 and 4). The national choices might be considered including the country-specific climate characteristics. The four cases might represent the climates and the national choices for, in order: Germany (locations below 1000 m a.s.l.), Austria (locations above 1000 m a.s.l.), Denmark and Norway.

The self-weight of structural and non-structural parts (G) is classified as permanent action and therefore has a modification factor $k_{\text{mod}} = 0.60$ for service classes 1 and 2 (see Table 1).

4.3. Reliability level of the current Eurocodes

The proposed simplified load combinations are calibrated in order to provide safety levels which are equal to or larger than the safety levels implicitly provided by the Eurocodes. 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 the strength of solid timber.
- $\gamma_{M,GL} = 1.25$ for the 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 properties (w_F) are assigned with engineering judgment representing the frequency of occurrence in real structures, see Table 3. Two cases have been investigated. The first considers solid timber as dominant material. The simplified design equations presented in this article are expected to be applied in the design of simple housing structures that are mostly made of solid timber. The second considers glulam timber as the dominant material representing industrial buildings. The first case can also be considered as a conservative selection of w_F -values since it weighs more the material presenting the largest uncertainties.

Different load scenarios are included in the study. They are characterized by the proportions between the different loads expressed as $\chi_G = g_k/(g_k + q_{1,k} + q_{2,k})$ and $\chi_Q = q_{1,k}/(q_{1,k} + q_{2,k})$. The required values of χ_G and χ_Q are obtained by varying the parameters α_G and α_Q in the limit state functions (Eqs. (11)–(15)). Load scenarios are divided into two domains as listed below, representing different typologies of structures:

- Structures with dominating permanent loads (e.g. green roofs): $\chi_G \geqslant 0.6$ and $0 \leqslant \chi_Q \leqslant 1$.
- Structures with dominating variable loads (e.g. common buildings): $0 \leqslant \chi_G \leqslant 0.6$ and $0 \leqslant \chi_Q \leqslant 1$.

Table 3
Weights for material properties (w_F) for ST dominating (case of GL dominating in brackets).

	Bending F_m	Tension $F_{t,0}$	Compression $F_{c,0}$	Total (per material)
Solid Timber (ST)	0.42 (0.06)	0.07 (0.01)	0.21 (0.03)	0.70 (0.10)
Glulam (GL)	0.18 (0.54)	0.03 (0.09)	0.09 (0.27)	0.30 (0.90)
Total (per failure mode)	0.60	0.10	0.30	

All load scenarios are equally weighted, i.e. the weights associated with different χ_Q and χ_G values are equal ($w_{\chi_G} = w_{\chi_Q}$). This considers the load scenarios equally frequent. The sum of all weights is fixed to unity $\left(\sum_i \sum_j \sum_k w_{F,i} w_{\chi_G,j} w_{\chi_Q,k} = 1\right)$.

4.4. Calibration objective

Tentative values of the reliability elements γ included in the proposed simplified safety formats (γ_F, k'_{mod}) were calibrated solving the minimization problem in Eq. (16). The term in squared brackets is a skewed penalty function proposed in [18]. It penalizes under-design ($\beta < \beta_t$) more than over-design ($\beta > \beta_t$). In fact, under-design is associated with larger expected costs due to larger expected failure costs, see e.g. [29] for more details. The sums are extended over the six considered material properties (or failure modes) and the different values of χ_G and χ_Q. The objective of the calibration was to obtain a level of safety equal to or larger than the level given by the current standard. Therefore, the target reliability index was selected as $\beta_t = E[\beta_{EC}]$, where $E[\beta_{EC}]$ is the weighted mean reliability index associated with the design given by the Eurocode.

$$\min_{\gamma}\left\{\sum_{i=1}^{6}\sum_{j=1}^{10}\sum_{k=1}^{10} w_{F,i} w_{\chi_G,j} w_{\chi_Q,k}\left[\frac{\beta_{ijk}(\gamma)-\beta_t}{d} - 1 + \exp\left(-\frac{\beta_{ijk}(\gamma)-\beta_t}{d}\right)\right]\right\} \quad (d \approx 0.23) \tag{16}$$

It is to be highlighted that the estimation of the target reliability β_t from the existing codes and the calibration of reliability elements are performed with the same probabilistic models. Therefore, the (nominal) reliability indices are used to compare safety levels rather than expressing the "exact" level of safety. As expected, the absolute value of $E[\beta_{EC}]$ is sensitive to the stochastic models adopted. Nevertheless, the calibrated reliability elements are seen to be almost insensitive to changes of the coefficients of variation of the distribution functions within the realistic domain. For this reason, the random variables are represented by simplified stochastic models (Table A1). For the same reason, the biases of the resistance and load models were not considered. Beside the difficulty of their estimation, their inclusion will affect the values of β considerably, but 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. [30] for wind load model).

5. Results and discussion

5.1. Results

The calibrated reliability elements are calculated for the different cases included in the study and summarized in Table 4. The influence of the dominating material on the calibrated reliability elements is observed to be of little importance within each case. The differences in the calibrated values of k'_{mod} among the 4 different cases are considered small for dominating permanent load. All k'_{mod} -values are indeed close to $k_{\text{mod},G}$ that is 0.60. This might suggest the use of a single value for all four cases. In contrast, larger differences are observed for dominating variable loads. In fact, the reliability level was observed to be quite sensitive to small variations of k'_{mod}. This suggests representing the suggested k'_{mod} values, as precise as practically feasible in the possible revision of the design format. In general, the calibrated modification factors are all within the range of the standardized values in Table 1. For *SFI*, γ_F is varying in the same magnitude among the four cases. For permanent load dominating, the calibrated γ_F are close to $(\gamma_G \cdot k_{\text{mod},Q})/k_{\text{mod},G}$ as expected.

The two proposed formats and the Eurocode format are compared in terms of safety levels, structural dimensions, and number of relevant load cases.

The reliability levels associated with the calibrated reliability elements are compared with the Eurocode format in Fig. 1 for solid timber (ST) dominating. Detailed plots are illustrated in Fig. 2 for a selected case. The boxplots for the case with dominant glulam (GL) are very similar to the ones in Fig. 1 in terms of minimum, maximum, average and skewness of the reliability indices. For this reason, they are not shown in the paper. Both cases show larger safety level and scatter in reliability indices compared to the considered design code due to the selected objective function. The performance of *SFI* and *SFII* are quite similar and no significant differences in terms of reliability are observed for the case with dominant permanent loads.

The proposed simplified formats drastically reduce the number of load combinations as summarized in Table 5. The reduction is increasing with the number of variable loads n_Q. *SFII* always requires one load combination less compared to *SFI* and, as already mentioned, it requires the same number of load combinations for any other construction material.

The proposed simplified formats lead in average to larger design solutions, i.e. increased construction costs. This is the price of the simplifications introduced. The structural dimensions are compared in Table 6 through the weighted average over-design $E[\Delta z]$, calculated from Eq. (17), where $z_{ijk}^{(SF)}$ is the design obtained by the simplified safety format proposed and $z_{ijk}^{(EC)}$ is the design according to Eurocode. It is important to highlight that the average increase in construction costs is lower than the $E[\Delta z]$ values in Table 6 since a large part of the construction costs is independent of the structural dimensions z. Weighted over-design averages were found higher for the case of dominant permanent loads. For variable loads dominating, it was found that the absolute maximum over-design was around 25% for *SFI*, and very close to the average over-design for *SFII*. The maximum Δz were found to be around 60% for cases where the permanent load is dominating.

Table 4
Calibrated reliability elements.

Dominant material	Dominant loads	Rel. element (Safety format)	Case			
			1 - Germany	2 - Austria	3 - Denmark	4 - Norway
ST	Permanent	γ_F (SFI)	2.14	2.17	2.35	2.38
		k'_{mod} (SFII)	0.63	0.62	0.63	0.62
	Variable	γ_F (SFI)	1.46	1.48	1.56	1.58
		k'_{mod} (SFII)	0.89	0.84	0.92	0.86
GL	Permanent	γ_F (SFI)	2.16	2.18	2.37	2.39
		k'_{mod} (SFII)	0.63	0.62	0.63	0.62
	Variable	γ_F (SFI)	1.42	1.42	1.51	1.53
		k'_{mod} (SFII)	0.90	0.82	0.93	0.84

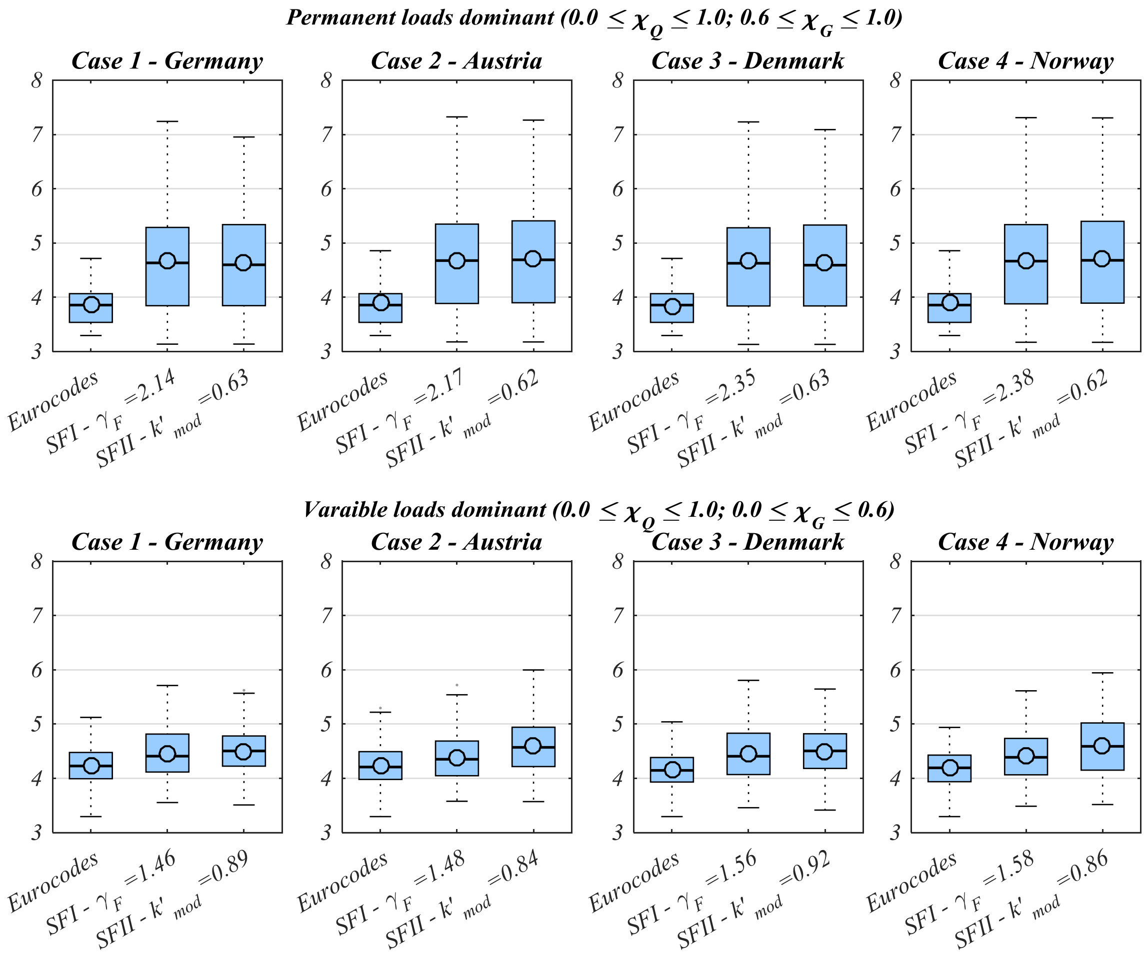

Fig. 1. Reliability indices corresponding to the design performed with Eurocodes and the two simplified safety formats with calibrated reliability elements for ST dominating (Box-and-whisker plot with boxes from first to third quartiles with median (line) and mean value (circle), whiskers from minimum to maximum).

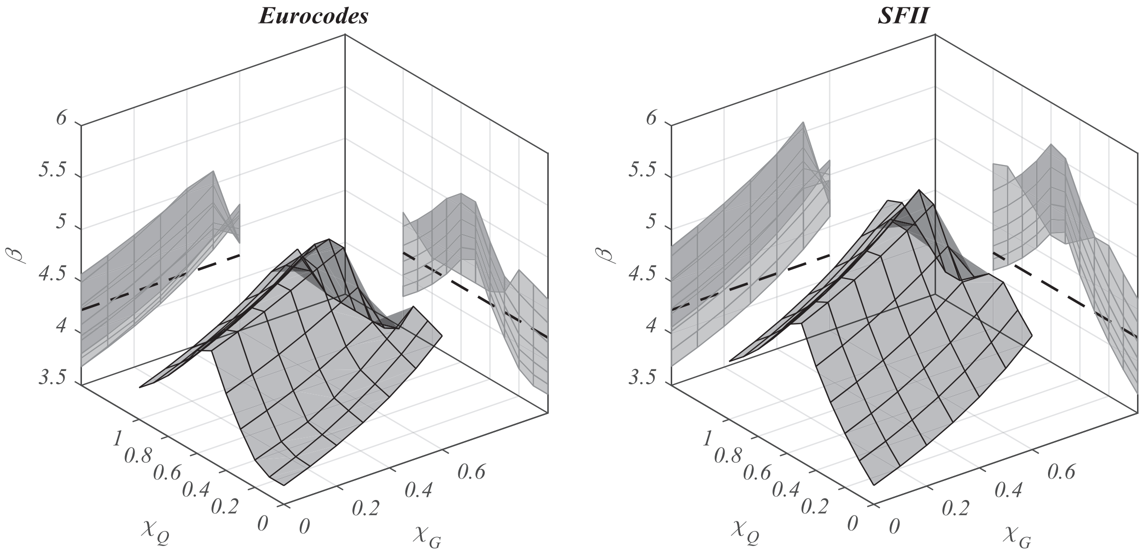

Fig. 2. Reliability indices for Case 1, compression parallel to grain $F_{c,0}$, dominating variable loads and solid timber: Eurocodes (left), calibrated SFII (right) and Eurocodes weighted average (dashed line).

$$E[\Delta z]=\sum_{i=1}^{6}\sum_{j=1}^{10}\sum_{k=1}^{10} w_{F,i}\, w_{\chi_G,j}\, w_{\chi_Q,k}\left[\frac{z_{ijk}^{(SF)}}{z_{ijk}^{(EC)}}-1\right] \qquad (17)$$

It is important to note that the monetary benefit/loss associated with the use of simplified safety formats cannot be assessed by accounting the construction costs only. In fact, simplified safety formats can significantly reduce the effort in engineering work

Table 5
Number of relevant load combinations to consider in design.

n_Q	Eurocodes	SFI	SFII
1	2	2	1
2	5	3	2
3	13	4	3
4	21	5	4

and associated costs. The quantification of these savings in a general way is not an easy task and is left to code-committees who will assess whether it is more efficient to use a simplified or a sophisticated format. The framework proposed in this paper will support this assessment in a rational way. Further, larger safety levels reduce the risk associated with the event of failure, where risk is defined as costs associated with failure times the probability of failure. The weighted average expected failure costs were found to be between 30% and 60% lower compared to the Eurocode. This is clearly a consequence of the higher safety levels reached with the simplified formats. The net benefit (or loss) obtained from the increase in construction costs and the decrease in both the engineering and failure costs can only be assessed by knowing the absolute values of these costs. However, this was beyond the scope of the work at hand.

5.2. Discussion

The resulting calibrated formats are shown to greatly reduce the number of load combinations with a minimal increase in structural dimensions and construction costs. This proves, as expected, that the complexity of the load combination rules provided in [1] does lead to more efficient structural design compared with the simplified formats. Therefore, it is important to emphasize that the formats proposed do not have the desire to substitute the existing combination rules, but rather to be alternatives that engineers can choose any time they need a rougher and faster design and/or they believe that these simpler formats reduce the engineering costs more than the increase in construction costs. In addition, simplified formats might be useful for checking the plausibility of results obtained from structural analyses performed by computer software with a large number of detailed load combinations. In this manner, analysis errors might be identified.

Both proposed safety formats with the calibrated reliability elements meet the requirement of simplifying design without decreasing the level of safety. Based on the performed calculations, the format *SFI* has the potential to be more economical in average but also leading to the largest absolute differences in design compared to the current version of the Eurocodes. The *SFII* includes a lower number of load combinations. In addition, *SFII* is expected to be easier implemented within the Eurocode framework, since it basically proposes to use the same load combination rules as used for the other materials. Hence, it follows the fundamental requirement of having material-independent load combinations. *SFII* can indeed be seen as a simplified way for accounting the load-duration effect on the material properties by dividing the material partial safety factor by a fixed factor (k'_{mod}).

The proposed formats were derived specifically for the cases with dominating variable loads, which are the most common for timber structures. As expected, they provide a balance between simplification and additional costs within this restriction. On the contrary, quite high over-design was obtained for the cases with dominating permanent load. These cases are seldom in timber structures and were mostly given for sake of completeness and for showing that, with different additional costs, the proposed formats lead to acceptable levels of safety in all cases. The work was limited to load combinations with snow, wind and permanent loads.

6. Conclusions

Two simplified safety formats have been proposed for simplifying the design of timber structures. Due to the timber specific load-duration effect on the material strength, the design of timber structures is more demanding compared to other construction materials. The first format consists of novel load combination rules maintaining the current modification factor values. On the contrary, the second format maintains the current combination rules while reducing the modification factor values to a single fixed one. Simplifications in design imply different design costs, different safety levels or both. For these reasons, the proposed formats have been calibrated in order to reach a satisfactory level of safety and limiting the increase in construction costs. The resulting calibrated formats greatly simplify the design. At the same time, they limit the additional costs and maintain (or increasing) the resulting safety level of the designed structures compared to the current Eurocodes.

The work at hand is expected to provide a generic framework applicable to further assessments and refinements of simplified safety formats. A higher degree of detail requires considering specific contexts including country-specific climates (see e.g. [31,32]), load damage models, construction habits and normative requirements included in the National Annexes to the Eurocodes.

Although the investigations are strictly focusing on the Eurocodes, the proposed simplifications, concepts and calculations are in principle also applicable to other standards.

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Appendix A.

Table 6
Weighted average over-design $E[\Delta z]$ (values in percentage).

Dominant material	Dominant loads	Safety format	Case			
			1 - Germany	2 - Austria	3 - Denmark	4 - Norway
ST	Permanent	*SFI*	+21.7	+21.3	+21.7	+21.3
		SFII	+21.7	+21.9	+21.7	+21.9
	Variable	*SFI*	+8.1	+5.4	+11.8	+8.4
		SFII	+10.0	+13.1	+13.2	+16.3
GL	Permanent	*SFI*	+22.6	+21.9	+22.6	+21.9
		SFII	+22.6	+22.5	+22.6	+22.5
	Variable	*SFI*	+5.4	+2.9	+9.0	+6.2
		SFII	+9.1	+15.9	+11.8	+19.1

Table A1
Stochastic models for the reliability analysis from [33] unless otherwise specified (§[34], *yearly maxima).

Random variable			Type	Mean	COV	Characteristic fractile
Solid timber (ST)	Resistance model uncertainty	$\Theta_{R,ST}$	Lognormal	1.00	0.07	/
	Bending strength	$F_{m,ST}$	Lognormal	1.00	0.25	0.05
	Tension parallel to grain	$F_{t,0,ST}$	Lognormal	1.00	1.2 0.25	0.05
	Compression parallel to grain	$F_{c,0,ST}$	Lognormal	1.00	0.8 0.25	0.05
Glulam (GL)	Resistance model uncertainty	$\Theta_{R,GL}$	Lognormal	1.00	0.07	/
	Bending strength	$F_{m,GL}$	Lognormal	1.00	0.15	0.05
	Tension parallel to grain	$F_{t,0,GL}$	Lognormal	1.00	1.2 0.15	0.05
	Compression parallel to grain	$F_{c,0,GL}$	Lognormal	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}	Lognormal	1.00	0.27	0.78 (c_{pe}) $(\mu\ for\ c_g, c_r)$
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}	Lognormal	1.00	$0.20^{\S}$	(μ)
Snow load on roof*		Q_2	Gumbel	1.00	$0.35^{\S}$	0.98

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