



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.

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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.

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

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.

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

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.

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

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.

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

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 $k_{\text{mod},[i]}$ stands for the k_{mod} -value corresponding to the action $[i]$.

$$e_{d,1}^* = e \left\{ \sum_{j \geq 1} \gamma_{G,j} g_{k,j} \right\} / k_{\text{mod},G} \quad (5)$$

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

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

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

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