Finite element based design of timber structures

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1 Introduction

1.1 Background and motivation

The use of finite element (FE) simulations is one of the key factors behind significant advances in digitalisation in most engineering fields. The digitalisation of the structural design process began decades ago and is now present in most of its steps, from the production of construction drawings, up to the point of an entirely electronic data exchange for official permits. For structural analysis in particular, the use of numerical models, namely FE models, is now ubiquitous for the determination of internal forces, stresses, displacements, strains, or eigenfrequencies. This use is in line with the current verification methods based on structural design standards, including the Eurocodes, which mainly provide guidance regarding specific design situations (actions and combinations of actions), material properties (stiffness and strength), geometry (including, e.g. initial deformations), and performance verification criteria (e.g. maximum stresses or displacements) mostly based on analytical and empirical models.

This use of FE analyses frequently faces challenges, especially for more advanced structural designs. These can be related to technical and software limitations (*what can and cannot be modelled*), to available guidance and education (*what we know how to* *model*), to model validation (*how reliable are the models*), and to design standards (*how design standards address FE analyses*). Structural design codes often set requirements on the aspects that models must take into account, but correctly leave the choice of the modelling strategy to the designer.

However, since design codes cannot cover all situations and rightly focus on the most common ones, there are situations for which an adequate FE model could lead to a safe and economical design, but for which current design standards do not provide verification methods.

Beyond linear static and linear dynamic analyses, the use of FE models is strongly related to the availability of material models that are able to capture further relevant aspects of the mechanical behaviour, e.g. non-linear material behaviour, or hysteresis. Advanced constitutive models for steel and reinforced concrete can be regarded as state of the art already (e.g. prEN 1993-1-14, 2022). However, for timber and wood-based materials this is often not the case due to the high complexity of their anisotropic behaviour, the highly variable material properties and the huge variety of different wood-based materials. A wider use of FE analyses for the design of specific aspects of timber members (e.g. notches) and connections (e.g. elastic stiffness) is currently beyond their traditional use, and is neither included in the current, nor in the 2nd generation Eurocode 5.

The currently increasing demand for more complex timber structures and the almost universal use of FE based structural analysis software poses a serious challenge, also due to a potential lack of education and awareness, which may lead to simply clicking through menus and predefined options by inexperienced users. Therefore, in addition to more education on FE modelling and on the suitability of different modelling approaches, design codes represent an important potential and first-hand opportunity to provide guidance regarding the use of FE models, and to describe design verification methods that allow for exploiting the full potential of FE analyses.

1.2 Objectives and scope

The objectives of this paper are to: (i) give an overview on how FE models are being addressed in the 2nd generation Eurocodes; (ii) assess the needs of timber engineering practice and show preliminary results of a survey on the use of FE models in the design of timber structures; (iii) present methods on how FE based design could be integrated in the safety concept of the Eurocodes; (iv) show two examples of advanced use of FE analyses for structural design (Beam-on-Foundation models and design of beams with holes); and finally, (v) stimulate the discussions in the Working Group 11 *Finite Element Based Design* within the European standardisation Sub-Committee CEN/TC250/SC5 *Eurocode 5*.

2 FE analyses in the 2nd generation Eurocodes

The use of FE analyses for structural design is being addressed in the ongoing development of the 2nd generation of the Eurocodes. The European Commission[1] has stated that "long-term confidence in the codes is based on the ability of the structural Eurocodes to evolve in an appropriate manner in order to address the variety of new methods, new materials, new regulatory requirements and new societal needs developing" and that the "structural Eurocodes are appraised so as to identify improvements to the existing suite to reflect the state of the art, and extend harmonisation." In 2019, the Technical Committee CEN/TC 250 of the European Committee for Standardisation, responsible for all Eurocodes, established an ad-hoc group "Numerical methods" to coordinate design guidance related to FE analyses in the 2nd generation Eurocodes.

For the 2nd generation of EN 1990 there is the intention to consider FE analyses in an Informative Annex as part of one of the future amendments of the document. Regarding structural modelling, prEN 1990 (2022) prescribes that models should be "appropriate", consider "relevant variables and relevant boundary conditions", and are "based on well-founded engineering theory and practice". prEN 1990 (2022) also recommends that a structural model "be validated to establish whether the model reproduces the physical phenomena to be investigated with an acceptable level of accuracy". This validation can include experiments and/or comparisons with other structural models that have been already validated.

In current EN 1992-1-1 (2004), specific guidance on numerical modelling is given for calculation of global second order effects. In the latest draft of prEN 1992-1-1 (2023), there are general provisions for non-linear numerical analysis in Clause 7 and Annex F, which reference prEN 1990 (2022). For steel structures, the 1st generation of Eurocode 3 contained information on the use of FE analyses for verifications of plated structures, EN 1993-1-5 (2006) Annex C and EN 1993-1-6 (2007). In the 2nd generation of Eurocode 3, an entire new part of the standard is dedicated to "Design Assisted by Finite Element Analysis" (prEN 1993-1-14, 2022).

For the design of timber structures, current EN 1995-1-1 (2004) provides no guidance regarding FE analyses, whereas the latest draft of the 2nd generation Eurocode 5 (prEN 1995-1-1, 2022) contains a very brief Annex O *Numerical analysis for uni-directional timber elements* dealing explicitly with FE modelling. The Sub-Committe CEN/TC250/SC5, responsible for Eurocode 5, recently created a new working group CEN/TC250/SC5/WG11 *Finite Element Based Design*, which has its first unofficial meeting on 25 August 2023.

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[1] https://eurocodes.jrc.ec.europa.eu/2nd-generation/evolution-en-eurocodes

3 Ongoing survey on the use of FE models in structural timber design

A survey on the use of FE models for the design of timber structures in engineering practice is online since June 2023 [2]. The target audience of the questionnaire are structural engineers involved in the design of timber structures with the objective to get an overview on the use of FE models, namely which models and modelling approaches are being used, and the main difficulties designers face when modelling. The preliminary results presented in this paper are based on 268 answers received until mid-July 2023.

85% of all answers, with Germany and Austria representing 20% each, originate from seven European countries, see Fig. 1. 8% of the answers come from non-European countries (Fig. 1a). More than 40% of the respondents report having more than 15 years of experience designing timber structures and 20% report having less than 5 years of experience (Fig. 1b). In addition to the experience of the respondents, the reported higher focus on the design of timber structures, compared to steel or concrete structures (Fig. 1c), shows that the answers provide a valid overview on the use of FE models in the design of timber structures.

As expected, most designers report using linear-elastic structural models very often, geometrically non-linear 2nd-order models much less often, and models with material non-linearities seem to be used the least (Fig. 1d). Regarding connection models, hinged or rigid connections are reported to be used very often, whereas linear-elastic springs are used to a much lesser extend, and nonlinear springs seem to be rarely used (Fig. 1e).

Various aspects of modelling timber structures, where difficulties are encountered, are illustrated in Fig. 1f. Hybrid structures, i.e. structures with materials with different creep-, moisture-, and temperature-dependent behaviour, as well as fatigue, seem to be difficult for modelling, whereas creep and fire seem less complicated. Regarding the design of timber connections, the main reported problems are related to connection stiffness, combined or complex loading, and load distribution between fasteners (Fig. 1g). The respondents were asked to answer the questions about difficulties in modelling some aspects only, if they had sometimes/often tried to model those aspects.

4 Methods for finite element based design of timber structures

The 2nd generation of EN 1990 has the intention to include an Informative Annex for FE based design, see Section 2. In order to promote the corresponding developments in timber construction and to address the needs of practice (see Section 3), *Guidelines for Finite Element Based Design of Timber Structures* were developed by *Kuhlmann* et al. (2019-2022). A draft of the guidelines was discussed in March 2023 at a CEN/TC250/SC5

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[2] https://form.jotform.com/223392062220343

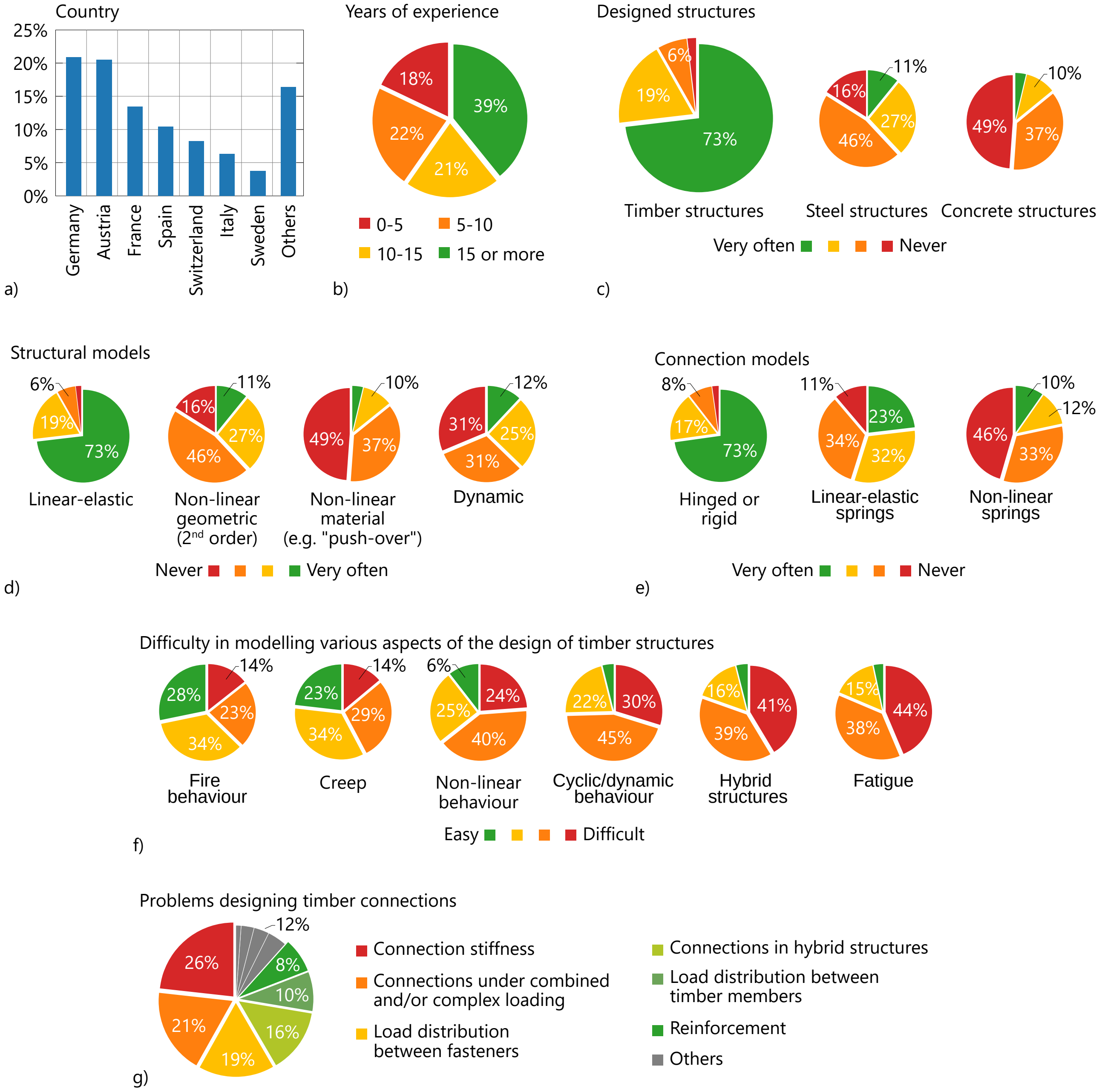

Figure 1. Part of the preliminary results of an ongoing online survey (still available at https://form.jotform.com/223392062220343).

meeting, see CEN document CEN/TC 250/SC 5 N 1693 (2023). For the consistency with the Eurocodes, the draft is based on prEN 1993-1-14 (2022), the structure of which is also reflected in the draft of the planned Informative Annex of EN 1990. An international working group is currently revising and further developing this document.

The FE guidelines aim at providing guidance on the use of numerical methods in daily engineering practice and in expert engineering applications. Major benefits of the implementation of such rules are a reduction of modelling errors and introducing the possibilities of expert application of FE analyses for cases that go beyond the standard design cases of the Eurocodes. Additionally, clear requirements on the verification and capabilities of FE models are necessary in order to check the suitability of software solutions, in case of external verification of FE results, and (legal) disputes. Furthermore,

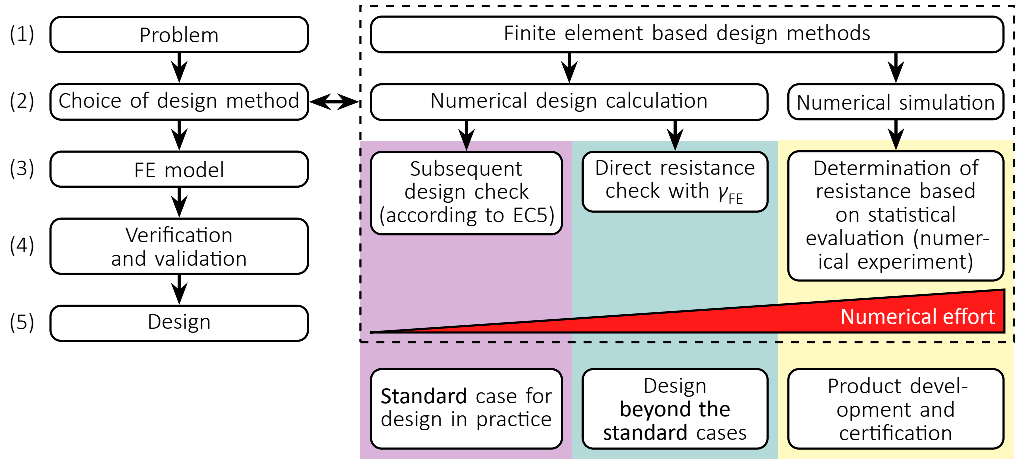

Figure 2. Proposed procedure for the FE based design, Töpler & Kuhlmann *(2022).*

such rules contribute to an improved trustworthiness and acceptance of numerical models. Finally, the guidelines aim at promoting the transfer of knowledge into practice.

The structure of the FE guidelines, see (CEN/TC 250/SC 5 N 1693, 2023), resembles the one of the Eurocodes with Sections 0 to 3 being the *Introduction*, *Scope*, *Normative references* and *Terms, definitions and symbols*. The main parts of the document, Sections 4 to 8, are described below. Section 9 deals with the documentation of FE analyses. Finally, the annexes provide further detailed modelling information including singularities, material modelling, CLT and benchmark cases. This structure results in a concise main part, and allows for the subsequent addition of annexes on specific topics, such as modelling of fire design, that are only briefly covered in the main part.

Fig. 2 gives an overview of the proposed procedure for the FE based design. In step (1), the problem to be investigated is defined. In step (2), the appropriate design method is chosen. Three design methods are described in Section 4 of the FE guidelines, depending on the purpose and the complexity level of the numerical calculations.

In daily engineering practice, FE analyses are usually used to calculate internal forces, deformations and eigenvalues and to evaluate the load-bearing behaviour of complex three-dimensional structures where the design check follows the rules of standards such as EC5. In this case the design method *numerical design requiring a subsequent design check* can be used, where the guidelines provide (i) information on modelling, e.g. creep, stiffness of joints and connections, (ii) methods for evaluation of the quality of FE results, e.g. mesh density, singularities, (iii) minimum requirements for software when modelling certain problems, (iv) benchmarks for comparison of calculation results. Here, input values of the numerical models are nominal values of the geometry and representative material parameters (characteristic or mean values) according to EN 1995 (all parts), relevant product standards, or technical approvals. The results are internal forces, stresses, strains, deformations and eigenvalues (effects of actions, also referred to as system response quantities, SRQs). Design verifications are carried out according to the design formulas in the current standards. Hereby, the partial factor γ_M covers uncertainties of the model, material properties and geometries.

The possibility of an expert engineering application of FE analyses beyond the standard cases defined in the Eurocodes is enabled with the design method *numerical design with direct resistance check*. Examples for such models are given in Sections 5.1 and 5.2. This method allows to exploit the full potential of numerical analyses and to compute not only the effects of actions but also the resistances numerically. Taking into account the model uncertainties, the load-bearing capacity can thus be directly verified without relying on the analytical/empirical formulae of the Eurocodes. Input values are also nominal and representative values. Characteristic resistances, R_k, can be determined by dividing numerically determined resistances by the partial factor for modelling, γ_FE. The partial factor for modelling, γ_FE, covers the uncertainties of the numerical model and the type of analysis considering the differences between the numerical model and physical reality, and can be computed as

$$\gamma_\mathrm{FE} = \frac{1}{m_\mathrm{x} \cdot (1 - k_\mathrm{n} \cdot V_\mathrm{x})} \geq 1.0 \quad , \tag{1}$$

where m_x is the mean value of the ratio of the measured (or known) and the computed results for n samples; k_n is the characteristic fractile factor according to EN 1990, Annex D; V_x is the coefficient of variation of the ratio of the measured (or known) and the computed results for n samples. Design resistances, R_d, can be obtained by applying the standard partial factors according to EN 1990 and EN 1995 (all parts). This method introduces the possibility of a complete numerical design within the semi-probabilistic safety concept of the Eurocodes.

Numerical simulations can be applied in product development and certification and in research for complementing and extending the scope of physical experiments. On the highest level, stochastic input values for geometrical and material properties may be used and a statistical evaluation according to EN 1990 may be performed for determining the test-based resistance (including the actual partial factor).

It is essential to ensure sufficient accuracy of the FE analyses results, hence step (4). For this reason, the terms verification and validation were defined in prEN 1993-1-14 (2022). Verification demonstrates that the numerical model and analysis are properly implemented, understood and applied. Additionally, that the used numerical solution is a good approximation of exact mathematical solutions, mechanical models, or benchmarks. Validation proves that the model correctly or conservatively captures the physical phenomena to be modelled by comparing numerical results with known accurate solutions (benchmarks). Within the validation the uncertainty of the model can be quantified by evaluation of the differences of numerical results and benchmarks, e.g. by calculation of γ_FE, see Eq. (1). Verification and validation can be partially or fully overlapping.

The design verification, step (5), differs for the three design methods. In the case of *numerical design calculations requiring a subsequent design check*, the numerically determined SRQs are used directly for design verification according to EN 1995 (all parts).

For *numerical design calculations with direct resistance check* and *numerical simulations* in ULS design, the structural resistance is determined by taking the lowest resistance from following three criteria: (i) ultimate stress; (ii) maximum load level of the computed load-deformation path; (iii) largest tolerable deformation (or strain). Characteristic resistances R_k may be determined by dividing numerical resistances R_FE by the partial factor for modelling γ_FE or based on statistical evaluation according to EN 1990.

It has to be highlighted, that FE analyses should not bring significant resistance increases or decreases of SRQs compared to other well-established design methods, unless shown to be reasonable through an extensive verification and validation.

5 Examples of FE based structural design

5.1 Beam-on-Foundation (BoF) model to predict connection properties

5.1.1 Capability and applicability of BoF

The beam-on-foundation (BoF) modelling approach is able to predict stiffness as well as the non-linear load-displacement behaviour of reinforced dowel-type steel-to-timber and timber-to-timber connections (e.g. *Lemaitre* et al., 2021). Combined with a kinematic model of a connection, BoF models of single fasteners also allow predicting the load distribution between fasteners. In addition to timber-to-timber and steel-to-timber connections, layered engineered wood products like CLT, connections with gaps or soft inter-layers, connections with multiple-shear planes (*Lemaitre* et al., 2018) and combination of materials like timber-concrete composite connections (*Gikonyo* et al., 2023) can be modelled. BoF models can also be used to handle timber connections under complex loading such as fire loading (*Cachim* & *Franssen*, 2009) or cyclic loading (*Sauvat*, 2001). BoF models also allow predicting the behaviour of connections with counteracting in-plane loading (e.g. example no. 3 in Fig. 3) and spatial loading situations (e.g. example no. 4 in Fig. 3).

In BoF models, the fastener is represented by a beam element supported by springs describing the embedment behaviour in the surrounding timber matrix. Depending on the modelling purpose, different material models and types of analysis can be used. Simplified linear-elastic models allow for predicting stiffness, rigid-ideal plastic models allow for strength prediction (cf. *Johansen*, 1949), while bi-linear elastic approaches are able to predict stiffness and strength (cf. *Sawata* & *Yasumura*, 2003; *Cachim* & *Franssen*, 2009), and other nonlinear models are adequate for more complex numerical simulations (e.g. *Lemaitre* et al., 2018; *Schweigler* et al., 2021; *De Santis* & *Fragiacomo*, 2021). For example, prediction of the nonlinear load-displacement behaviour, and therefore of the stiffness and ductile capacity of the connection, requires an elasto-plastic material model for the steel fastener and multi-linear/non-linear spring elements for the wood embedment behaviour. For more advanced calculations, considering either the rope effect in connections or hysteresis, geometrically nonlinear analyses are required. In any case, for these models to be valid, brittle failure modes must be prevented, namely through reinforcement, e.g. with self-tapping screws, which highlights the need to be aware of model limitations and what they imply in practice. For connections without reinforcement, additional checks for brittle failure are required.

For engineering practice, the capabilities of the BoF model are limited by the availability of modelling features in engineering design software and standardized model input parameters. To overcome the latter barrier, *Schweigler* et al. (2019) presented a database of parameters for description of the non-linear embedment stress-displacement curves. For description of the elasto-plastic steel fastener behaviour the approach from EC 3 (prEN 1993-1-14, 2022) can be used as proposed in *ADIVbois* (2022).

Based on the modelling complexity and the software, the following classification of BoF model types can be done:

- 2D simple: linear-elastic material and spring models; geometrically linear calculation
- 2D standard: plastic material model for steel and multi-linear/non-linear spring models; geometric non-linear calculation
- 3D advanced: plastic material model for steel and multi-linear/non-linear spring models; coupling or rotation of springs; geometric non-linear calculation.

In Fig. 3, the capability of the different BoF model types for predicting strength, stiffness and load distribution along the fastener is demonstrated by common connection examples. In addition, the BoF model capabilities are compared with the capability of analytical approaches from Eurocode 5 and literature. Furthermore, the most common engineering design software, according to the survey results presented in Section 3, are added to the corresponding BoF model types based on the available software features. The consequent software supported use of the BoF model would replace several sets of analytical formulae according to the EYM and therefore also simplify engineering design.

5.1.2 Prediction of connection stiffness using a BoF model

To illustrate one of the possible applications of the BoF model, a comparison of connection stiffness predicted from BoF and observed from experiments is highlighted. The experiments chosen for the comparison are part of those presented in *ADIVbois* (2022), which is briefly described below. Further information is available in *ADIVbois* (2022).

In *ADIVbois* (2022), three different connection configurations were studied: (i) one slotted-in steel plate, (ii) two outer steel plates and (iii) two slotted-in steel plates. For

		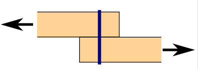			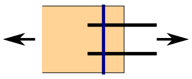			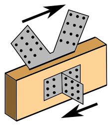			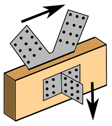			* Most used FE program (according to the survey results presented in Section 3)
		F_R	K	$f(u)$	F_R	K	$f(u)$	F_R	K	$f(u)$	F_R	K	$f(u)$	Example of suitable software packages*
Analytical	EC5	✓	≈	✗	✓	≈	✗	✗	✗	✗	✗	✗	✗	
	Literature	✓	≈	✗	✓	≈	✗	✗	✗	✗	✗	✗	✗	
BoF-model	2D simple	✗	✓	≈	✗	≈	≈	✗	✗	✗	✗	✗	✗	RFEM, RSTAB, ACORD
	2D standard	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	≈	✗	RFEM, RSTAB, ACORD
	3D advanced	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Abaqus

Figure 3. Capability of different types of BoF models compared to analytical approaches predicting the ductile capacity F_R, the stiffness K, and the load distribution along the fastener $f(u)$, for common design examples.

each connection configuration, two different dowel diameters (12 and 16 mm) and different timber member thicknesses were investigated. All connections were composed of 2 rows of 4 dowels and were axially loaded in tension to failure. This experimental campaign therefore included 18 test series with 5 repetitions per series. The experimental connection stiffness was defined as the slope of the load-slip curve from range of 10% and 40% of the average load-carrying capacity of one test configuration series. To reduce the impact of manufacturing on the mechanical behaviour of the tested connections, precautions were taken with regard to drilling and positioning tolerances. Parallel-to-grain embedment tests and 3-point bending tests of steel dowel were also carried out using the same timber members and dowel sets as for the connection tests.

The mechanical response of each test series was numerically simulated with the same BoF model as described in *Lemaitre* et al. (2021) (corresponding to BoF model type *3D advanced* in Subsection 5.1.1). The embedment test and 3-point bending test results were used as input for the BoF model to respectively describe the non-linear spring elements for the wood embedment behaviour and the elasto-plastic behaviour of the steel fastener. A second series of simulations were conducted with a linear elastic BoF model.

A comparison between the observed and predicted connection stiffness with elastic and non-linear BoF model approaches are presented in Fig. 4. Stiffness prediction from Eurocode 5 is also added to the comparison. A better prediction of connection stiffness is observed with both elastic and non-linear BoF model approaches than Eurocode 5. This can be explained by the absence in Eurocode 5 design equation of: (i) timber member and steel plate thicknesses; non-linear effects of (ii) number of fasteners and (iii) diameter; and (iv) distinction between connection configurations (in Eurocode 5, there is no distinction on slip modulus between steel-to-timber connections with slotted-in steel plate or outer steel plates). This example shows that BoF is a general method which can encompass most connection geometries and configurations to predict connection stiffness with high accuracy. The BoF model may be used to establish new design equations

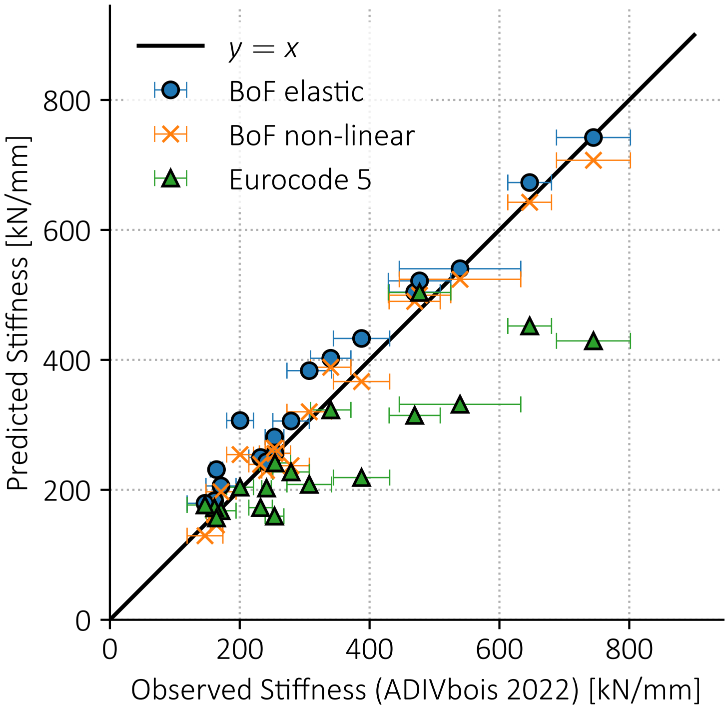

Figure 4. Comparison of connection stiffness prediction from BoF models and Eurocode 5 and observed stiffness from experiments in ADIVbois *(2022). Horizontal error bars represent the standard deviation of the mean connection stiffness observed for each test series (18 in total).*

to predict connection stiffness thanks to a parametric study. Furthermore, it can also be used directly to numerically predict the stiffness of more complex connections, e.g. complex loading, moment resisting connection.

5.2 FE based design of beams with holes

Holes in timber beams are a frequent requirement for the passing-through of infrastructure services in buildings. However, no provisions were included in the first generation of EN 1995-1-1 (2004), leaving this to National Annexes, such as DIN EN 1995-1-1/NA (2013). This issue has been tackled in the new version of EC 5 (prEN 1995-1-1, 2022), where an analytical design model was incorporated. The document defines restrictions on hole shape, size and location within the beam, which are known to be safely covered by the design method. Although a great effort was made to consider a wide range of configurations, it is almost impossible for a simplified analytical design approach to cover all possible cases that may be of interest in practice. Examples would be shapes that deviate from the defined circular and rectangular geometries or groups of holes that might be penalized too strongly by the current design rules.

An FE based approach to design holes in beams can incorporate the same theoretical background as used in the standardized procedure, namely the Weibull Theory (*Weibull*, 1951), but would allow more freedom in the selection of shapes (including corner radii in the case of rectangular holes) and placement. Furthermore, the design of stresses on the reduced cross-section becomes trivial. The implementation of such an analysis is simple enough to integrate in FE software used for the engineering practice, but clear guidance is needed to ensure a safe application of this method.

In the following, a concept similar to that presented by *Aicher* et al. (2007) is implemented in a simple parametric FE model, and is then used to design hole configurations for which experimental results are available. For the design concept the main idea is to consider the computation of the so-called Weibull stress, σ_{wei}, as

$$\sigma_{\text{wei}} = \left(\frac{1}{\Omega_0} \int_{\Omega} \sigma_{\text{t,90}}^{m} d\Omega \right)^{1/m} \approx \left(\frac{1}{\Omega_0} \sum_{i=1}^{N} \sigma_{\text{t,90},i}^{m} \Omega_i \right)^{1/m} \quad , \tag{2}$$

where $\sigma_{\text{t,90}}$ are the stresses perpendicular to the grain, m is the Weibull modulus, taken as $m = 5$ in *Aicher* et al. (2007), and $\Omega_0 = 0.01\,\text{m}^3$ is the reference stressed volume. The integral of Eq. (2) should only consider the region with tensile (positive) stresses, represented here by the Ω volume. In the context of FE computations, this equation is simply discretized as shown on the rightmost side of Eq. (2). By comparing σ_{wei} to the strength $f_{\text{t,90,k}} = 0.5$ MPa, the maximum capacity of the configuration can be estimated.

The method was implemented in *Abaqus v2022* (2022) using the available Python API and the standard solver. A linear model was defined using four-node, plane-stress linear elements with reduced integration of type CPS4R. The mesh in the immediate proximity of the hole was discretized with elements of size 2 mm and grew up to 20 mm at the ends of the beam. The post-processing consists of extracting the results corresponding to the stresses perpendicular to the fiber in the first and third quadrants (see Fig. 5a) of the hole region and then proceed to apply Eq. (2) on each region independently. The maximum capacity is then obtained as $V_{\text{max}} = (f_{\text{t,90,k}}/\sigma_{\text{wei}} \cdot V)$, where V is the load applied in the FE model. The implementation is available as Python code in the DaRUS repository (*Tapia*, 2023). As mentioned above, the method is simple enough to be programmed in different FE software, including commonly used commercial software and open-source solutions.

Figure 5a presents the used 2D FE model with the dimensions and stress field for σ_{90}. A detailed view of the first quadrant (Q-I) is shown in Fig. 5b, where the corresponding stressed volume required in Eq. (2) is shown. Computing the σ_{wei} according to Eq. (2) and comparing this value to $f_{\text{t,90,k}}$ yields a maximum capacity of $V_{\text{max,FE}} = 39.2$ kN. This is 20% conservative with respect to the corresponding experimental characteristic value of $V_{\text{exp,k}} = 49.1$ kN (*Aicher* et al., 2007), and slightly more progressive than the result obtained with prEN 1995-1-1 (2022) of $V_{\text{max,EC5}} = 36.6$ kN.

The FE based design may also be applied to rectangular holes. Figure 5c shows the $\sigma_{\text{t,90}}$ stresses at the corner of such a hole according to a configuration described in *Danielsson* (2008). In this case the FE based method yields $V_{\text{max,FE}} = 31.4$ kN, whilst $V_{\text{exp,k}} = 40.6$ kN, thus the FE solution is about 22% on the safe side. A result according to prEN 1995-1-1 (2022) cannot be obtained since the corner radius $r = 25$ mm is not

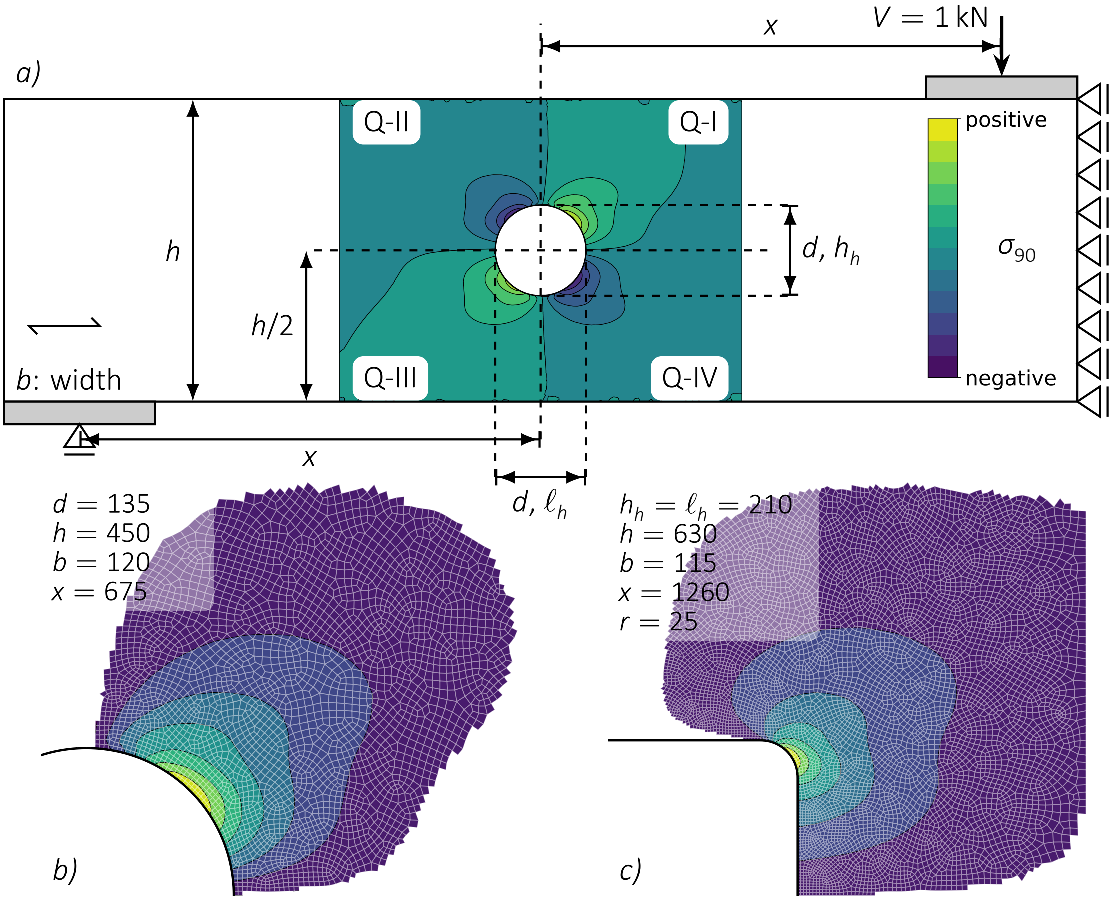

Figure 5. (a) Definition of geometry and boundary conditions of the FE model, and stress field of σ_{90} in the region of the hole; detailed view of the stressed volume and FE mesh for a circular (b) and for a rectangular hole (c). Stresses were filtered so that $\sigma_{90} > 0$ are shown. (All dimensions in mm.)

allowed. However, it has to be noted that this method neglects the effect of shear stresses, which can be taken into consideration under the same theoretical background, e.g. as proposed by *Danielsson* & *Gustafsson* (2010). A further FE based approach to design rectangular holes was presented by *Hochreiner* et al. (2020). Although originally developed for notches, the mechanical similarities with the design of holes should allow a direct application of this method for rectangular holes, too.

6 Discussion

The preliminary results of the survey in Section 3 generally highlight the widespread use of simple FE models for structural design, as well as some of the main difficulties faced by structural designers in practice. Even though adequate software is available to designers, the *translation of a real-world structure into a structural model* is often a minor part of their education. Given the increasing complexity of architectural solutions, adequate structural modelling is a valuable option to overcome the limitations of analytical and empirical formulas (which are also models) and to avoid the use of multiple component-specific software (often preferred due to their simplicity), but sometimes neglecting mechanical consistency. As an example, addressing stability issues with 2$^{\mathrm{nd}}$ order theory in FE analyses instead of member-based methods or the consideration of semi-rigid behaviour of joints for complex three-dimensional models are still exceptions in practice. Furthermore, material models for timber and wood-based products and failure criteria for arbitrary stress states are still not available in many software. Finally, the need for model validation, e.g. through benchmarking, is of paramount importance. Software capable of dealing with arbitrary timber structures and engineers educated in modelling complex structures are key conditions of a reliable and economic application of FE analyses for structural design.

In the 2nd generation Eurocodes, the challenge of integrating FE analyses into the design process is being addressed. However, this is not done consistently by the various Eurocodes. Whereas for steel structures, a whole new part prEN 1993-1-14 (2022) dealing with FE based design was developed, for Eurocode 0 *Basis of design*, the work on an Informative Annex dealing with FE models has just started. For designing timber structures, the use of FE analyses is currently limited to the calculation of internal forces, deformations and eigenvalues, while the possibilities of numerical calculation of resistances and a fully FE based design are not provided. However, first efforts, in the form of a proposal of guidelines and methods for FE based design verification of timber structures (*Töpler* & *Kuhlmann*, 2022), are being pursued.

Promising possibilities of using FE models for design cases of timber structures were presented in two examples, Sections 5.1 and 5.2. BoF models are able to predict stiffness and non-linear load-displacement behaviour of reinforced dowel-type connections, which is crucial for modelling complex three-dimensional structures. Geometries of holes and notches in beams are currently limited by the corresponding application limits of the analytical and empirical design formulas in Eurocode 5, but FE analyses can be utilised for designing alternative geometries. Both these methods are ready for implementation in commercial software.

At this point, the question of “How much prominence should FE based design of timber structures be given in standardization in the coming decades?” should be asked. Or “Is it imaginable that with ongoing technical development, some of the analytical and empirical design equations in Eurocode 5 could be extended, or even replaced, by mechanically consistent failure criteria for FE analyses?”. On the other hand, non-verifiable black box results should be avoided at all costs, as the reliability of such a FE based design is of paramount priority. In fact, if adequate modelling guidance and verifications methods are not available, the already very heterogeneous quality of FE analyses in design practice might increasingly be at risk. Therefore, it is crucial that the use of FE analyses for structural design is addressed by standardisation committees, such as the newly formed CEN/TC250/SC5/WG11.

In this context, three important aspects need to be discussed, including: (i) technical possibilities and limitations; (ii) education of practitioners; and (iii) reliable design methods for standardization. For a general applicability of FE analyses, various material-specific *technical limitations* must be overcome, foremost mechanically consistent material formulations for strength and failure criteria at all relevant stress interactions, including material characteristics like the size effect (see Section 5.2), long-term behaviour and many more. The modelling of stiffness and strength of connections is currently only possible to a limited extent, whereby mechanical models such as BoF models, see Section 5.1, offer practice-ready proposals for simplified modelling. Fatigue, hybrid structures, and dynamic behaviour present further design challenges. For the technical implementation of these aspects in numerical models for a FE based structural design, skilled designers also need powerful software solutions.

In *engineering education*, there is a need for teaching how to create adequate models, namely levels of simplification and methods of validation based on mechanical principles. Hereby, examples and benchmarks are very valuable as a supplement to standards and to support education. For this purpose, available modelling guides, e.g. *Chen* et al. (2022) or *Bader* & *Ormarsson* (2023) amongst others, present a rich collection of examples of modelling and modelling recommendations which could be adopted as a basis for background documents in WG11.

Regarding *standardisation*, and given the legal status of standards in many countries, the question arises which types of FE analyses can be accepted for which design situations. This is linked to the reliability of FE based design. The discussed guidelines for a finite element based design of timber structures, Section 4, describe three methods for ensuring reliability depending on the complexity level and design purpose. Such normative rules also offer the possibility for engineers to set verifiable minimum standards for the modelling of certain design situations, even in software implementation.

7 Conclusions

Based on the survey results, recent developments in other parts of the Eurocodes, and the shown examples, it has become clear that numerical methods should be integrated more into the design concepts for timber structures in Eurocode 5. We propose to develop a first draft of corresponding rules based on the FE guidelines in WG 11 by the end of 2023.

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