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Article

Cross-Laminated Timber: A Survey on Design Methods and Concepts in Practice

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Abstract: Cross laminated timber (CLT) is becoming increasingly popular in timber construction due to its versatility. However, its structural anistropy requires the application of particular concepts and design methods. The article on hand presents the results of a worldwide survey conducted among engineers working with this product. Thus, it presents the current state of knowledge and practice on CLT construction: an overview of the experience of engineers working with CLT design, the commonly used verification methods, and the implementation of the material properties and different required assumptions in the software. An outlook to design problems in complex design situations relevant for multi-storey buildings and potential research fields is indicated additionally. The general picture is quite heterogeneous, with little consensus on the assumptions, design methods or applied tools. A wide repertoire of different approaches based on a large range of literature is found in practice. This is in part the result of the current lack of standardisation and currently incomplete regulations. Future efforts should focus on these two aspects to increase the applicability of CLT globally and strengthen its competitiveness.

Keywords: design guidelines; multi-storey buildings; questionnaire

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1. Introduction

In addition to the pursuit of more sustainable building culture, several new developments have made timber more and more attractive as a building material over the last decades. Today, the European construction industry accounts for 25% of global greenhouse gas emissions, making it one of the most polluting industries, in general. Most of the emissions are related to the production of construction materials [1]. According to a report by the Intergovernmental Panel on Climate Change (IPCC), cement production alone is responsible for 13% of all greenhouse gases emitted by the industrial sector [2].

The urge to find less carbon-intensive materials and to promote their use in construction is thus evident. Timber not only sequesters carbon from the environment but also requires very little transformation energy to turn the original logs into on-site delivered timber construction products. The switch from an industry that relies mainly on concrete as the predominant building material to one that favours materials such as timber could reduce current carbon emissions by an estimated 14–30% [3]. Such an effect relates to the forest sequestering carbon. Moreover, wood is a renewable material, when obtained from properly managed forests. Current forest certification systems not only ensure environmental aspects such as biodiversity or ecosystem services, but also additional aspects such as worker's rights are protected, local employment, or indigenous rights [4].

In this context, the fairly young product cross laminated timber (CLT), depicted in Figure 1, is particularly worthy of mentioning, as it is becoming increasingly popular in the construction sector. Its production has experienced a boom as shown in Figure 2 [5].

Although until the mid-1990s CLT was still considered a niche material, with the introduction of more technical specifications and published research, the use of CLT in practice grew rapidly.

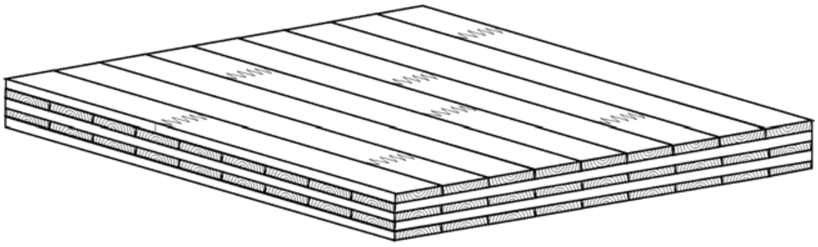

Figure 1. Example of a cross laminated timber panel [6].

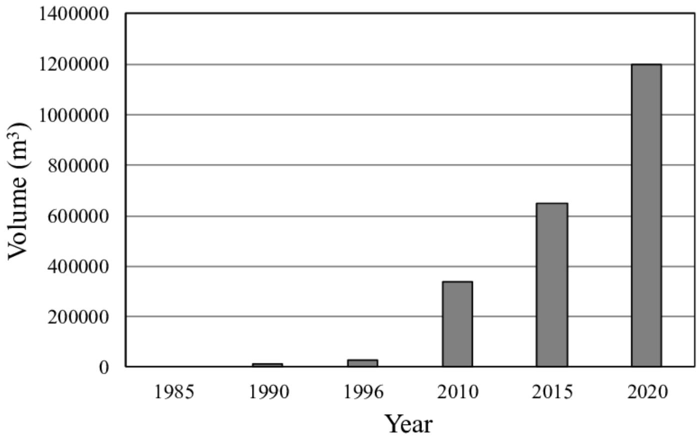

Figure 2. Increase in the volume of cross laminated timber production according to Sandoli et al. [5].

Due to its structure made of orthogonally glued wooden boards, as shown in Figure 1, this relatively rigid and planar product makes the leap from exclusively light and soft constructions, such as timber frame structures, to massive timber elements. As already mentioned by Schickhofer et al. [7], this leads to comparability with established reinforced concrete structures and thus to competitiveness in demanding construction projects, such as those shown in Figure 3.

This article presents the current state of knowledge and practice on CLT construction, based on the results of a worldwide survey, which was motivated within a European research project, InnoCrossLam [8], which aimed "at increasing the competitiveness of cross laminated timber (CLT) as a versatile engineered product, by increasing its predictability in demanding design situations not covered by the guidelines of today, or codes and standards foreseeable in a near future". The obtained answers provide an insight not only into current practice, but also on future development needs.

The paper is structured as follows: Section 2 presents a summary of the current state of the art in CLT, focusing on its main differences in structural response and current implementation in standards. The following Sections present different areas of the questionnaire. Thus, Section 3 presents the framework of the questionnaire, followed by the description of the background of the respondents in Section 4. The design methods, literature, and tools used, as well as actual knowledge of the product, are described in Section 5, while Section 6 focuses on more specialised design situations, such as seismic design. The paper in Section 7 concludes with some recommendations for future research and developments, based on the obtained results.

(**a**) Sensations Strasbourg
(© KOZ Architectes)

(**b**) Z8 Leipzig
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(**c**) 5-storey building
(© ABA Holzbau van Kem-pen)

(**d**) Himmelsstürmer Schwäbisch-Gmünd
(© Schlosser Holzbau GmbH)

(**e**) Hotel Therme
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(**f**) H41 Aachen
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Figure 3. Impressions from projects using cross laminated timber panels.

2. State of the Art

2.1. Particularities of Cross Laminated Plates

The assembled and planar nature of CLT cross-sections shows great versatility in structural terms. CLT elements can bear stresses in and perpendicular to their plane. Typical product characteristics are summarised in Schickhofer et al. [9] and provided by the European product standard [10].

Since CLT consists of longitudinal layers that are rigidly connected to layers of transverse lamellae by an adhesive bond [10], it requires special approaches when calculating its mechanical properties and assessing its structural performance in comparison to typical timber products such as structural timber or glued laminated timber.

The anisotropic material characteristics of wood in combination with the orthogonal arrangement of the layers allow—e.g., when loaded in bending out of plane–for a non-negligible deformation between the single layers (Figure 4). The ratio of the modulus of elasticity parallel $E_{m,0,mean}$ and perpendicular to grain $E_{m,90,mean}$ of the in CLT frequently used spruce classified in C24 according to EN 338:2013 [11] is approximately 30/1. The resulting differential deformations of the CLT cross-section violate the first Bernoulli hypotheses of normal remaining cross-sections and the second Bernoulli hypotheses of planar cross-sections (Figure 4). Thus, the actual structural behaviour does not allow for a straightforward application of the typical bending theory for cross-sections with homogeneous stiffness distribution over the height as outlined for example in Timoshenko and Goodier [12].

According to Mestek et al. [13], additional shear deformations have to be taken into account for a ratio of the element height h to an element span l of 1/20. In addition, the influence of this so-called structural anisotropy applies not only to plates in bending. When in-plane loaded, three failure mechanisms of the material, which are depicted in Figure 5, generally have to be considered: gross shear failure, net shear failure and shear failure in the crossing areas of the lamellas [14,15]. Gross shear failure only occurs in homogeneous and rigidly bonded cross-sections. Due to the frequent lack of narrow side bonding of the lamellae in the product and the possible occurrence of cracks in the cross-section, this failure mechanism is often of minor relevance. Whereas torsion in the failure of the crossing area of the lamellae is primarily governing, in the case of net shear failure a partial cross-section fails in shear.

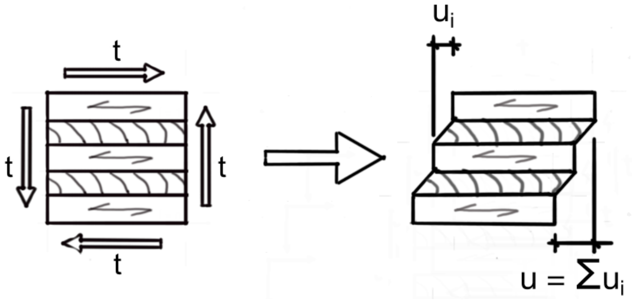
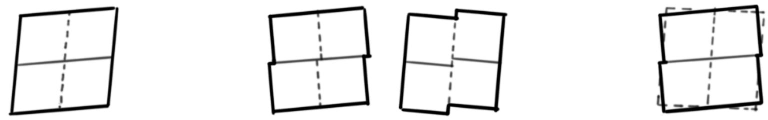


Figure 4. Shear deformations between layers of a cross laminated timber plate cross-section according to Mestek et al. [13], where t are the applied shear forces, u_i the resulting deformation of a transverse layer, and u the total deformation of the plate. Redrawn and adapted by the authors.



(**a**) Gross shear failure (**b**) Net shear failure (**c**) Failure in crossing areas

Figure 5. Failure modes of shear walls according to Danielsson et al. [14]. Redrawn and adapted by the authors.

In the case of compressive actions perpendicular to the grain, cross laminated timber has increased strength and stiffness values in comparison to conventional timber products due to the blocking effect of the transverse layers.

In conclusion, more complex design methods for the layered build-up of the material have to be considered to ensure safety and usability over the service life. The first calculation methods were developed by Kreuzinger [16] and Scholz [17]. For a concise evaluation of different analytical and numerical methods typically applied in practice—such as the so-called γ-method of EN 1995-1-1:2016 [18]—the reader is referred to Bogensperger et al. [19]. A comparison between test results and some of the typically applied calculation methods for CLT is provided in Buka-Vaivade et al. [20].

2.2. Current Cross Laminated Timber Regulation in Standards

CLT is currently regulated by individual technical approvals of respective manufacturers scattered on several European Technical Assessments (ETA) based on European Assessment Documents (EAD)—e.g., EAD 130005-00-0304 [21]. Such ETAs may include individual requirements on material and testing for product characteristics. Even if it is not legally intended, some ETAs contain requirements for the design of a particular producers's products. Brandner et al. [22] provided a comprehensive review of the developments towards harmonised European standards in 2016.

Due to this historically grown, highly diverse market, common design principles and guidelines for CLT are hardly found. Some of the best-known and mostly used literature has been developed by different associations and companies in different regions: Wallner-Novak et al. [23,24] in Austria (published in German language), Börgström and Fröbel [25] in Scandinavia (published in English language), and Karacabeyli and Douglas [26] in North America (published in English language).

In order to reduce the complexity of the market, resulting from a multitude of different ETAs, and thus to increase accessibility and competitiveness, the European Committee for Standardisation (CEN) developed harmonised building standards [27] under the mandate of the European Commission. The CLT design is currently to be included in the revision process of the European building design standards, the structural Eurocodes [28]. Therefore, while cross laminated timber was barely mentioned in the first generation of Eurocodes, the design of fundamental application cases – such as wall and floor elements – is currently being prepared to be included during the revision of a second generation of documents which will be available in 2026 [29].

An overview of the applicability of European design principles to CLT is given in Fink et al. [30]. The COST Action FP1402 (European Cooperation in Science and Technology), in preparation for the above mentioned second Eurocode generation, developed a holistic state of the art and science report on CLT [31]. The document addresses topics such as stability problems (of local members and global systems), contact problems—e.g. as compression perpendicular to the grain–, vibration behaviour, connection modelling and verification and global modelling approaches for, for example seismic behaviour.

3. Description of the Questionnaire

This paper presents the results and conclusions from a questionnaire to (mostly) European practitioners (the region where the CLT is used mostly today) regarding their current practice and knowledge of the CLT structural design. The questions were aimed at those problems in design situations relevant for multi-storey buildings which are not yet part of the current standards, nor of the upcoming second generation of structural Eurocodes. It complements the results obtained by Espinoza et al. [32].

The database was collected by using a digital questionnaire distributed among engineers working in practice around the world. According to quantitative methods of empirical social research [33], a standard questionnaire with 48 (mainly closed) questions was created [34].

The questionnaire was distributed worldwide digitally to those who could process or install CLT (that is, CLT manufacturers, suppliers, engineers in construction companies, structural engineers, and researchers in institutions). The survey started online on 13 January 2020. On the cutoff date, 15 August 2020, 141 engineers from over 20 countries had participated in the survey. A large proportion of the participants came from the main area of the CLT industry, Germany and Austria, as shown in Figure 6. The questions were classified into the following categories: general experience of participants on CLT construction; general design methods for CLT; complex design situations: (a) challenges, (b) problems, and (c) improvements; joints and connections in CLT structures; and seismic design with CLT.

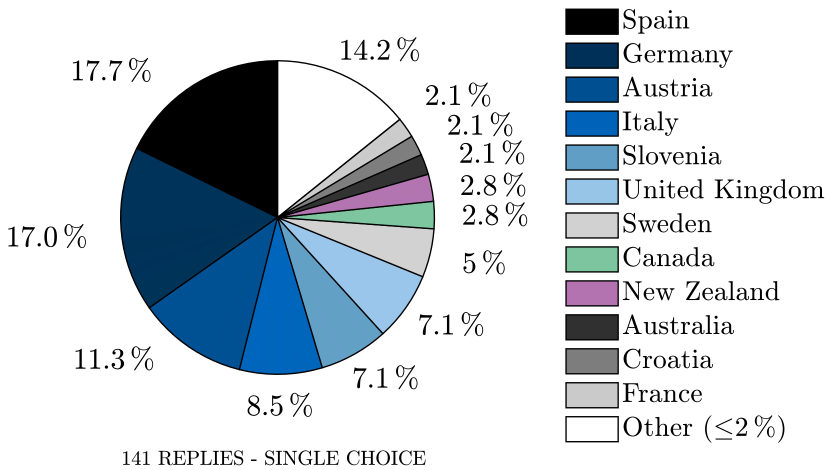


Figure 6. Origin of the respondents.

The most relevant results are presented in the following sections and are discussed from a selection of questions. The paper thus provides an overview of the experience of engineers working with CLT, typical verification methods, common implementation of the material properties and used assumptions.

4. General Experience on Cross Laminated Timber Construction

4.1. Background and Experience

In addition to technical questions, the survey started with general questions about the background of the participants, whose results are given in Tables 1 and 2. In general, most of the respondents have many years of work experience in large companies whose main focus is the wood industry. This background suggests a competent population and provides additional validity to the subsequent survey results. Moreover, due to the wide spectrum of respondents, conclusions may be drawn about the general situation of CLT in construction practice, and the associated problems and challenges.

Table 1. Profile of the participants (single choice).

(a) Professional Sector						
Design company	Construction company	Supplier/ Manufacturer	Researcher at company	University/ Research institute	Software developer	Other
47.4%	20.8%	4.0%	5.2%	18.5%	1.2%	2.9%
(b) Work Experience						
<3 years	3 to 10 years	11 to 20 years	>20 years			
13.5%	34.0%	34.8%	17.7%			

Table 2. Data of the companies of the participants.

(a) Size based on the number of employees (single choice).					
<5	5 to 10	11 to 30	>30		
19.2%	9.9%	17.7%	53.2%		
(b) Percentage of timber structures (or research projects) in the volume order (single choice).					
<10%	10–40%	41–70%	>70%		
21.3%	23.4%	12.1%	43.3%		
(c) Percentage of cross laminated timber structures (or research projects) in the order volume (single choice).					
<10%	10–40%	41–70%	>70%		
44.0%	27.0%	15.6%	13.5%		
(d) Type of cross laminated timber buildings that are designed/built by the respondents (multiple choice).					
Single/double family houses	Apartment buildings (1–3 storeys)	Multi-storey buildings (4+ storeys)	Industry buildings	Public buildings/ buildings for assemblies	Special constructions
70.2%	62.4%	60.3%	36.2%	59.6%	28.3%

More than 70% of the respondents are involved in practice (Table 1a), belonging either to a design company or to a construction company. Researchers accounted for around 20% of the participants, being this a comparable percentage to construction companies.

In terms of work experience, see Table 1b, those who have worked for more than 11 years constitute the majority (52.5%), while only 13.5% of the respondents have very limited work experience, that is, less than 3 years.

More than half of the participants work in companies with more than 30 employees, while less than a third work in small companies with a size of 10 or fewer employees (Table 2a). The contacted population worked mostly on companies specialized on timber construction, as demonstrated by the fact that almost half of the respondents state that more than 70% of the order volume in their origin companies consists of timber constructions (Table 2b). Nevertheless, for almost a quarter of them, timber constructions comprise less than 10% of the volume.

4.2. Cross Laminated Timber Knowledge

Participants in the questionnaire were asked to assess their own knowledge and experience with cross laminated timber constructions. However, while approximately half of the respondents indicated that more than 70% of their order volume is wood construction (Table 2b), only 13.5% of the total accounts for the construction of CLT, as given in Table 2c. The current share of CLT constructions is still quite scarce in most of the companies: 44.0% answered that CLT is ordered in less than one-tenth of the overall company's projects. Additionally considering that for 27.0% of the respondents the share is 10–40%, in 70% of the cases, CLT construction constitutes less than half of their current construction volume. This may indicate the fact that the knowledge of CLT construction is currently concentrated in a few specialised companies and is not yet common.

Furthermore, participants indicated which type of CLT-based buildings they had already planned and built. Most of them, 70.2%, were already in contact with CLT when building single-family or double houses. However, these low-rise residential buildings are closely followed by multi-family houses, multi-storey buildings and public buildings, as shown in Table 2d.

When asked about their familiarity with the product, as shown in Table 3a. Most of them 85% of the 141 engineers questioned assume to be in proper contact with cross laminated timber structures, though in most cases their experience may be limited to a few reduced experiences. Participants were asked if they consider the concepts of existing design guidelines appropriate. Table 3b shows that no one is completely dissatisfied with the current situation. However, only 13.5% consider the existing design concepts to be appropriate without restrictions. The majority, 86.5%, are in between, implying that the majority of respondents are basically comfortable with the existing design provisions.

Table 3. Participants knowledge on cross laminated timber, CLT (single choice).

(a) Are you familiar with the CLT construction?				
Not familiar ●○○○○	●●○○○	●●●○○	●●●●○	Very familiar ●●●●●
0.7%	1.4%	10.6%	34.0%	53.2%
(b) Are you confident that the current CLT design concepts are adequate?				
Not at all				Yes
0%	9.2%	38.3%	39.0%	13.5%

5. Design Methods for Cross Laminated Timber in Practise

5.1. General

As explained above, CLT elements require quite different design and analysis models in comparison to conventional timber products (e.g., structural timber, or glued laminated timber). The basic differences are briefly described in Section 2. Therefore, the questionnaire asked also about the current knowledge of these particular design models accounting for CLT peculiarities.

Based on the different population and due to the possible importance of different backgrounds and professional experience, the data were first cleaned by excluding participants who appeared less qualified from the evaluation ("<3 years" in Table 1b and "not familiar" in Table 3a). Based on the statements, the three professional branches "design", "construction" and "research" were filtered (Table 1a). For the comparison of the results of a in this way differentiated analysis with the total population, the results of all participants are provided unfiltered additionally.

5.2. Reference Literature

When asked about the literature used, a multitude of sources were mentioned (Figure 7). Only 23.9% of the indicated works are normative standards EN 1995-1-1:2016 [18], EOTA [21], CSA O86:19. [35], which are marked blue in Figure 7. As explained previously, CLT has not yet been included in detail in current standards. As a consequence of the lack of normative literature, most of the respondents refer to various published manuals on the design of cross laminated timber Wallner-Novak et al. [23,24], Börgström and Fröbel [25], Karacabeyli and Douglas [26], Tra [36], Herzog et al. [37], Bogensperger et al. [38].

For material parameters on the other hand, as shown in Figure 8, respondents refer to the product standard for structural timber [11] and glued laminated timber EN 14080:2013. [39] or the European Technical Assessments (based on EOTA [21], e.g., ETA 14-0349 [40], ETA 12-0347 [41]). The official documents for material properties of CLT are highlighted in blue, e.g., [42]. Therefore, while the material parameters are uniformly applied to a certain extent, the approach to the design is very heterogeneously documented.

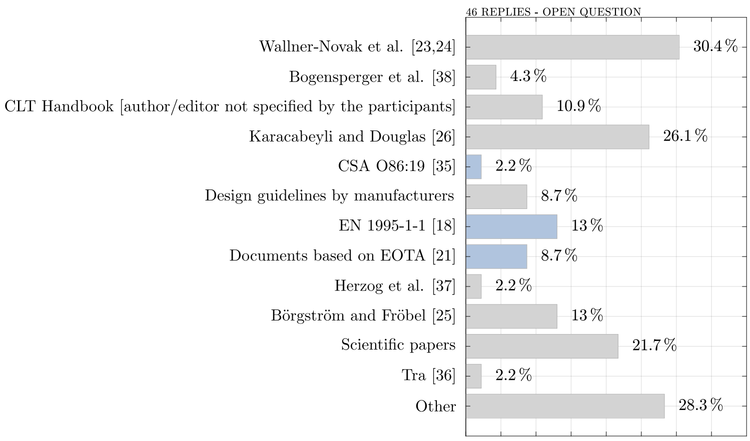


Figure 7. Used literature for design.

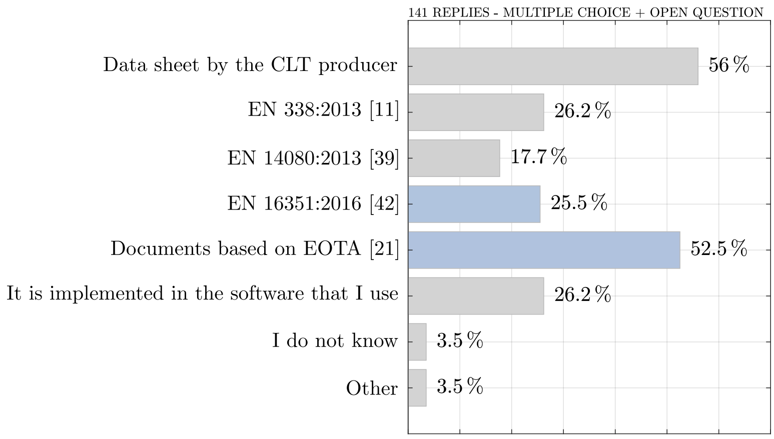


Figure 8. Used literature for product parameters.

5.3. Used Background Theories

Questions on the actual knowledge of the required theoretical background were part of the survey. As shown in Table 4a, the γ- method is preferred in the three profession sectors analysed. The use of alternative theories depends widely on the occupational field. As a result, no clear picture emerges on the used model.

When modelling the material (Table 4b), the answers are divided quite equally between the two given possibilities, namely effective properties or a layered section. Therefore, there is no prevailing opinion on building practice on how the material should be implemented.

It may be seen (Table 4) how many people do not actually know what theory lies behind the software they are using. Although only those considered experienced are included in this part, about 10–20% of the respondents do not know how the material is implemented in their calculations. The number decreases from 20% for designers, to 15% for construction, and up to 12% for researchers. This may be partly due to the fact of CLT being a novel material, which was not part of the typical timber engineering curriculum until recently. This result may raise doubts about the adequacy of some of the resulting designs and the corresponding safety level.

In some application cases, e.g., point supported floors or cantilevered elements, the torsional stiffness of the material has a major influence on the load-bearing behaviour of the plate. Thus, participants were asked how they usually considered torsional stiffness in their models when required (Figure 9). Only a quarter of respondents, 24.8%, include torsion in their calculations. In the following questions on the background of the calculations, whose results are not shown here, it can be seen overall that the deeper the actual knowledge is examined, the greater the proportion of those who cannot answer the question is found, which is consistent with the previously observed high percentage of people who did not know the used material model (Table 4a).

Table 4. Assumptions used for structural modelling of material and plates in bending (multiple choice).

(a) Structural modelling of plates in bending

Modelling of plates in bending	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
γ-method	**57.1**%	**48.5**%	**50.0**%	**43.3**%
Shear analogy	39.7%	27.3%	42.3%	27.0%
Beam theory	27.0%	39.4%	26.9%	20.6%
Theory of plates	22.2%	42.4%	26.9%	22.7%
I do not know	19.0%	15.2%	11.5%	27.0%
Other	1.6%	0.0%	0.0%	5.0%

(b) Structural modelling of the material

Modelling of the material	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
Homogeneous cross-section with effective properties	**49.2**%	39.4%	**57.7**%	42.6%
Non-homogeneous cross-section with layer properties	46.0%	**51.5**%	53.8%	**43.3**%
I do not know	17.5%	18.2%	11.5%	22.0%

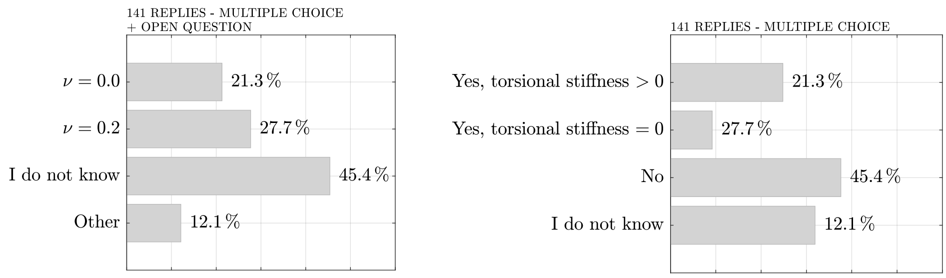


Figure 9. Applied Poisson's ratio (**left**) and torsional stiffness (**right**).

5.4. Used Tools and Design Verification

Table 5 shows the answers given to the question of what type of software or tool was used for CLT verification. It was a multiple-choice question since more than one tool may be used in different stages of the design or for different design situations. In all cases, practice-orientated finite element (FEM) software was used mainly, especially in the case of designers and constructors in practice (around 70%). CLT orientated software is also mostly used, especially in the construction sector. Half of the respondents use different additional possibilities related to self-developed tools, which means that in most cases designers need to rely on their own tools for certain analyses and verifications. There is no uniform best-practice solution. Instead, a variety of different approaches is used even for individuals. Each respondent gave an average of two to three answers to this question.

Table 5. Approach for cross laminated timber (CLT) verification (multiple choice). Legend: [a] Binderholz (DC/Wallner-Mild), KLH Designer, StoraEnso Calculatis, etc.; [b] CLTdesigner, TimberTech, etc.; [c] Dlubal , SAP 2000, SOFiSTiK, etc.; [d] Abaqus, Ansys, etc.; [e] MatLab, MS Excel, etc.

Cross Laminated Timber (CLT) verification	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
By hand calculation	42.9%	51.5%	46.2%	40.4%
Software provided by a CLT producer [a]	50.8%	72.7%	46.2%	50.4%
CLT oriented software [b]	54.0%	69.7%	46.2%	50.4%
Practice oriented FEM software [c]	**69.8**%	**72.7**%	**53.8**%	**61.7**%
Advanced FEM software [d]	3.2%	6.1%	15.4%	8.5%
Own solutions [e]	42.9%	57.6%	46.2%	49.6%

A similar conclusion can be drawn from the results shown in Figure 10, which relates to the related level of satisfaction of the existing software. The panorama is again quite heterogeneous, with no prevailing solution among the respondents. Many software solutions are mentioned and even "Other" solutions which were not included in the questionnaire are the majority. Satisfaction is highest for own-developed solutions, closely followed by practice-orientated FEM software, software provided by a producer and CLT-orientated software. Only the advanced FEM software is used by a few (and mostly in the research field), who happen to also be those least satisfied.

As can be seen in Figure 11, 80.9% of the participants additionally check the results of the software. Approximately half of them, 48.3%, use a hand calculation for this task, while a third check by developing an alternative calculation as a comparison. Consistently with the results given in Figure 5 the typical workflow may be described as a software-based solution, to be complemented by the verification of some particular results.

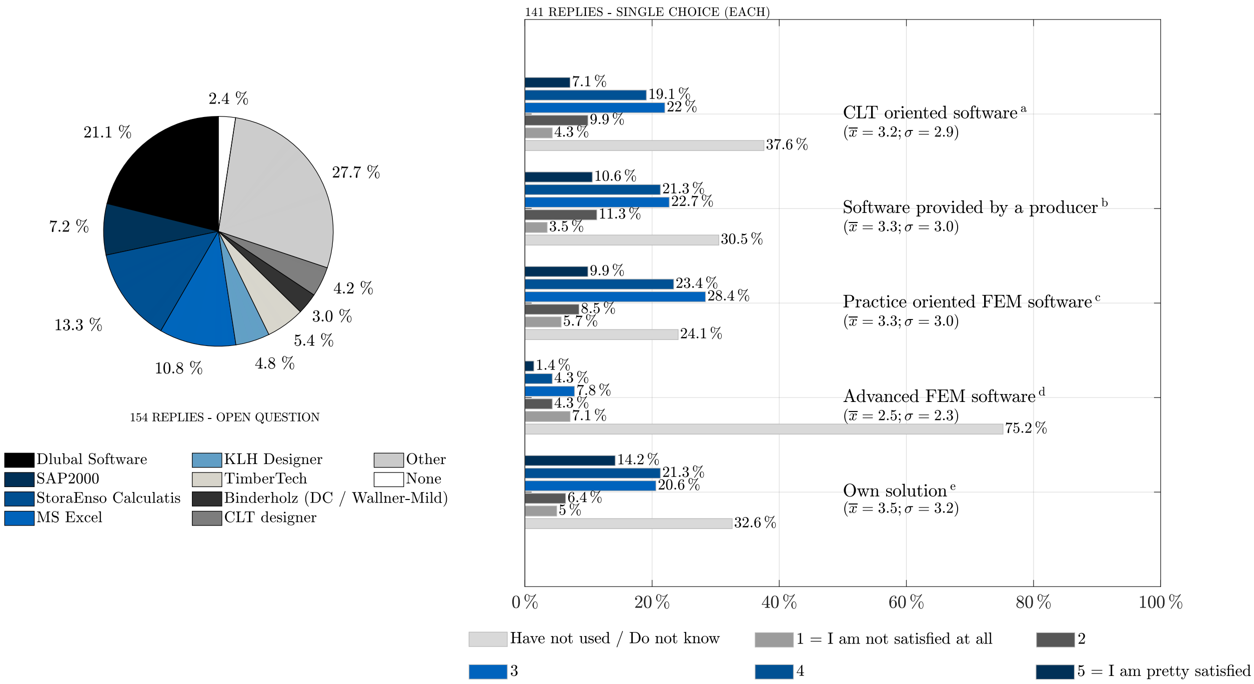


Figure 10. Software used for cross laminated timber (CLT) design (**left**), and satisfaction with available software solutions (**right**). Legend: [a] CLTdesigner, TimberTech, etc.; [b] Binderholz (DC/Wallner-Mild), KLH Designer, StoraEnso Calculatis, etc.; [c] Dlubal , SAP 2000, SOFiSTiK, etc; [d] Abaqus, Ansys, etc.; [e] MatLab, MS Excel, etc.

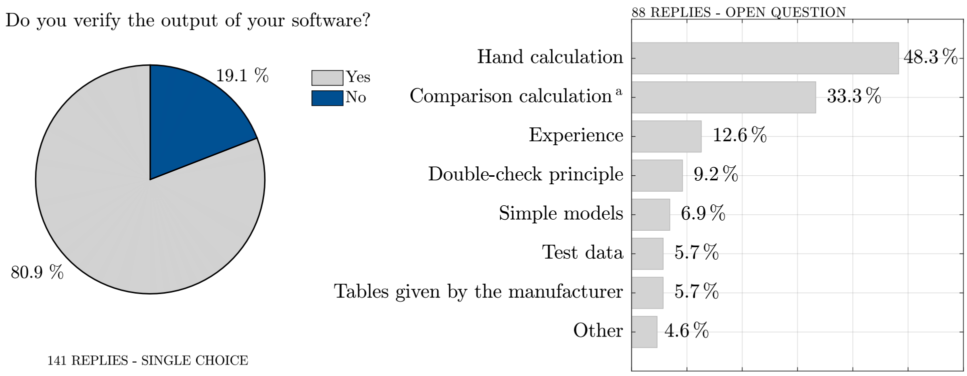


Figure 11. Verification methods. Legend: [a] This includes the application of alternative finite element software and own software solutions i.e., Matlab, MS Excel, etc.

5.5. Joints and Connections

Connections are always a critical element of timber structures, and cross laminated structures are not an exception. The survey, therefore, asked about the different modelling assumptions and the properties used for them in practice.

When asked how connections and joints are typically assumed and modelled, the majority assume a spring model for the connection, followed by a rigid assumption. The relative amount of different assumptions is quite constant among the different possible situations, as shown in Table 6a. Springs are used in 41.1% of the cases in a CLT wall to CLT wall connections, and in 46.8% for a slab-wall connection.

Table 6. Questions related to design of connections (single choice).

(a) Applied connection stiffness				
Applied connection stiffness	Rigid	Spring	Hinge	None
CLT Wall ↔ CLT Wall CLT Floor ↔ CLT Floor	29.1%	**41.1%**	22.7%	7.1%
CLT Floor ↔ CLT Wall CLT Wall ↔ CLT Floor	31.9%	**46.8%**	17.7%	3.5%
CLT ↔ Concrete	31.2%	**41.1%**	19.9%	7.8%
(b) Reference of the assumed stiffness of the connections				
Reference for connection stiffness	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
Documentation from CLT producer	19.4%	21.3%	19.0%	23.4%
Documentation from fastener/connector producer	**32.6%**	**36.1%**	**35.7%**	**32.3%**
Engineering judgement based on experience	22.5%	21.3%	14.3%	21.0%
γ-method	3.9%	1.6%	4.8%	3.6%
Relevant literature	20.9%	16.4%	26.2%	18.5%
Other	0.8%	3.3%	0%	1.2%

The spring model requires the input of stiffness of the connection. To define the used stiffness value, most rely on the documentation of the connection manufacturers (32.3%), followed by the documentation of the CLT manufacturers (23.4%) (Table 6b). When answering "relevant literature", which accounted for around 20% of the answers, the participants were asked to enter their own reference. Most of the participants use the current Eurocode 5 [18] (78.5%). The manuals from Wallner-Novak et al. [23,24] and Karacabeyli and Douglas [26] are quite similarly used (36.4% and 30.6 %, respectively). Other specialised references are mentioned but rarely used: scientific papers (6.6%), European Technical Assessements (ETA) (4.1%), Börgström and Fröbel [25] (2.5%), Kreuzinger [16] (0.8%), and CSA O86:19 [35] (0.8%).

The respondents are not satisfied with the current situation of the design of the joints. They see the greatest potential for improvement in the implementation of FEM software or in the stiffness specification already examined (Figure 12).

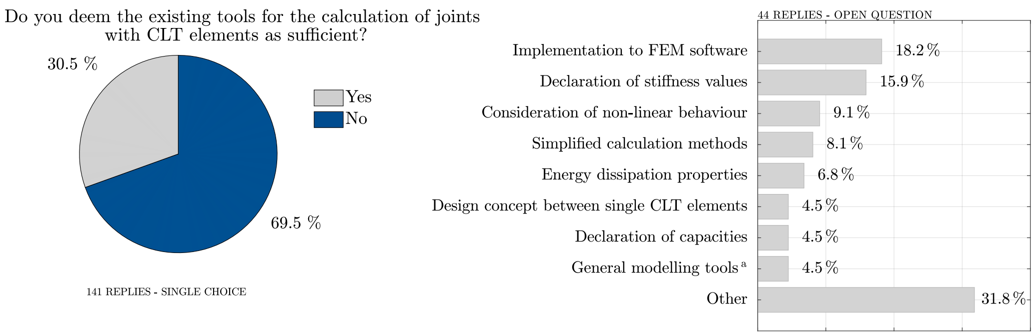


Figure 12. Potential improvements for cross laminated timber (CLT) connection design.

6. Design Methods in Special Cases

6.1. Complex Design Situations: Challenges, Problems and Improvements

In the current European standard for structural design EN 1995-1-1 [6], cross laminated timber is not explicitly mentioned. As described in Kleinhenz et al. [28], the general design assumptions for CLT will become part of the second generation of the document, expected in 2025. However, in practice, more complex design situations than those to be incuded in the future standard may arise and should be considered. The most representative are shown in Figure 13.

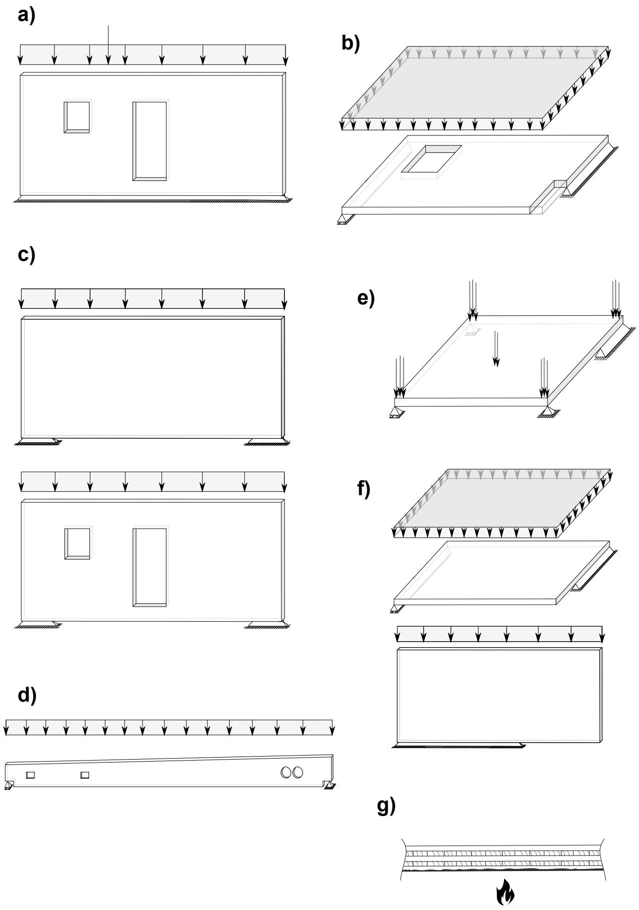


Figure 13. Challenging design situations for cross laminated timber (CLT): (**a**) openings in walls, (**b**) openings in floors, (**c**) deep CLT beams (with openings), (**d**) CLT beams (with openings), (**e**) point supports and concentrated loads, (**f**) cantilevers, (**g**) asymmetrical lay-ups.

Engineers in practice need to face these situations as well, and therefore have been asked about the most challenging from those described in Figure 13. The obtained results are shown in Table 7a, where openings in walls/floors (18.4% and 14.9%) and point supports and concentrated loads (22.7%) are listed most. However, the main concerns widely differ depending on the sector. While constructors and researchers agreed on the challenge posed by openings in walls, designers were more concerned about point supports. Surprisingly, the second most challenging aspect for researchers, cantilevers, was of little concern for practitioners.

When asked why these situations were found to be so difficult, the majority stated the lack of design concepts as the main reason, a position shared between the various professional fields, as shown in Table 7b.

In addition to the situations already listed, more challenging problems are given in Figure 14. Connections (which was analysed in more detail above), vibrations, and fire measurements are most often considered difficult. Here again, the lack of existing design regulations is named the main reason.

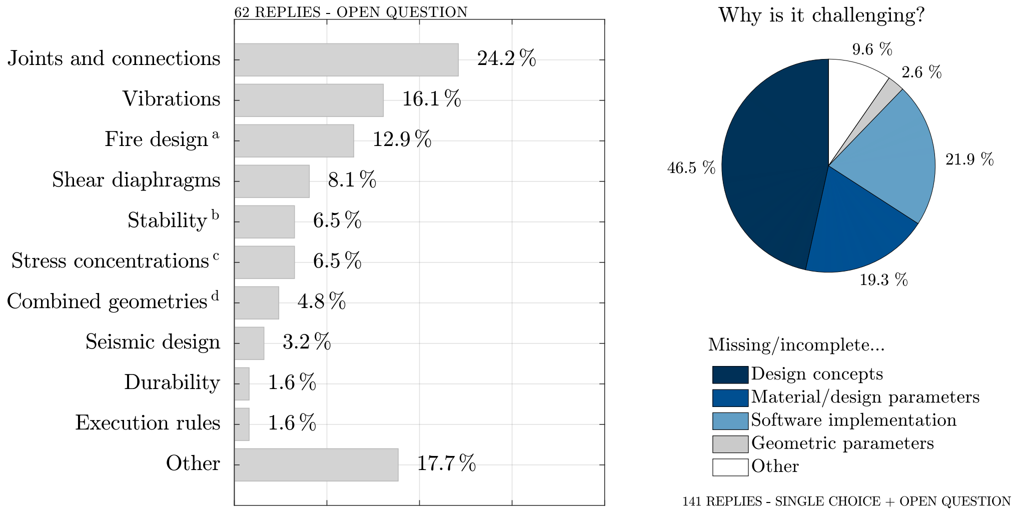


Figure 14. Other challenging situations. Given reasons: [a] resistance and compartmentalization; [b] member and global system; [c] e.g., at connections, openings, etc.; [d] e.g., ribbed plates, etc.

Table 7. Design issues (single choice).

(a) Most challenging design issues				
Challenging design issues	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
Openings in walls	20.6%	**24.2%**	**26.9%**	18.4%
Openings in floors	15.0%	15.2%	11.5%	14.9%
Deep CLT beams	6.3%	12.1%	7.7%	7.8%
Holes in CLT beams	6.3%	9.1%	7.7%	9.9%
Point supports/concentrated loads	**28.6%**	18.2%	11.5%	**22.7%**
Cantilevers	4.8%	0.0%	23.1%	7.1%
Asymmetrical CLT lay-ups	9.5%	9.1%	7.7%	9.9%
I have not encountered any of the above	7.9%	12.1%	3.8%	9.2%
(b) Reasons for the difficulties on solving the complex design situations				
Missing / incomplete...	Designer [63 replies]	Constructor [33 replies]	Researcher [26 replies]	Total [141 replies]
Design concepts	**54.0%**	**42.3%**	**52.2%**	**46.5%**
Material / design parameters	16.0%	19.2%	17.4%	19.3%
Software implementation	24.0%	23.1%	17.4%	21.9%
Geometric parameters	0%	7.7%	0%	2.6%
Other	6.0%	7.7%	13.0%	9.6%

When questioned about their possible qualification on solving these special topics, 43.4% of the engineers think they can solve all the problems (Figure 15). On the contrary, this would mean that more than half encounter problems in practice, and find no satisfactory solution for these topics. Point supports or loads (10.3%), followed by holes in CLT beams (8.8%) and asymmetrical CLT lay-up (7.4%), are described as the most difficult topics. To facilitate design for engineers in practice, the state of knowledge in these areas should be expanded through further research and made accessible to practitioners with the help of design standards.

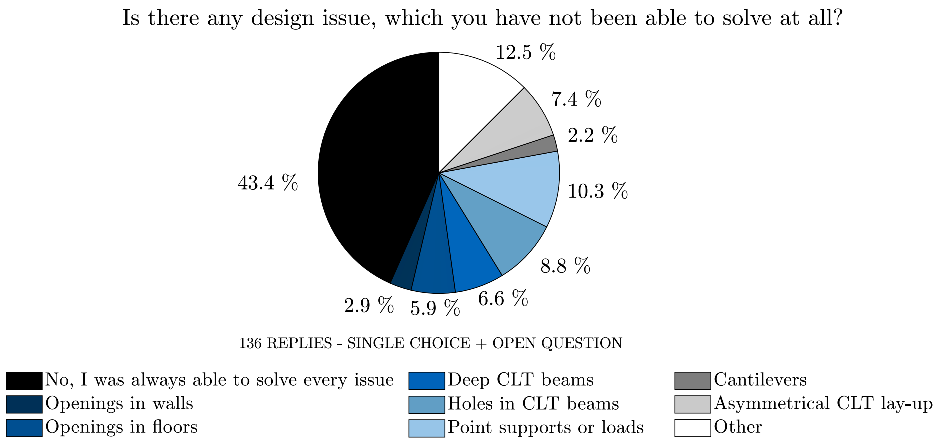


Figure 15. Missing topics in practice.

6.2. Seismic Design

In addition to the complex design situations and the design of the connections, the design in seismic areas was also examined in more detail. However, due to the specialised situation, these questions were only answered by those who have already planned in seismic areas, and skipped by the rest of the participants.

Slightly less than half of the participants (58, 41.1%) stated that they had planned constructions in seismically active regions and answered the corresponding questions. In contrast to Figure 16, these engineers come mainly from southern European countries, such as Italy (20.7%) or Slovenia (13.8%). The proportion of designers rose slightly in this case (47.4% + 6.1% = 53.5%) compared to the general sections. However, the number of researchers declined (23.7% − 6.8% = 16.9%).

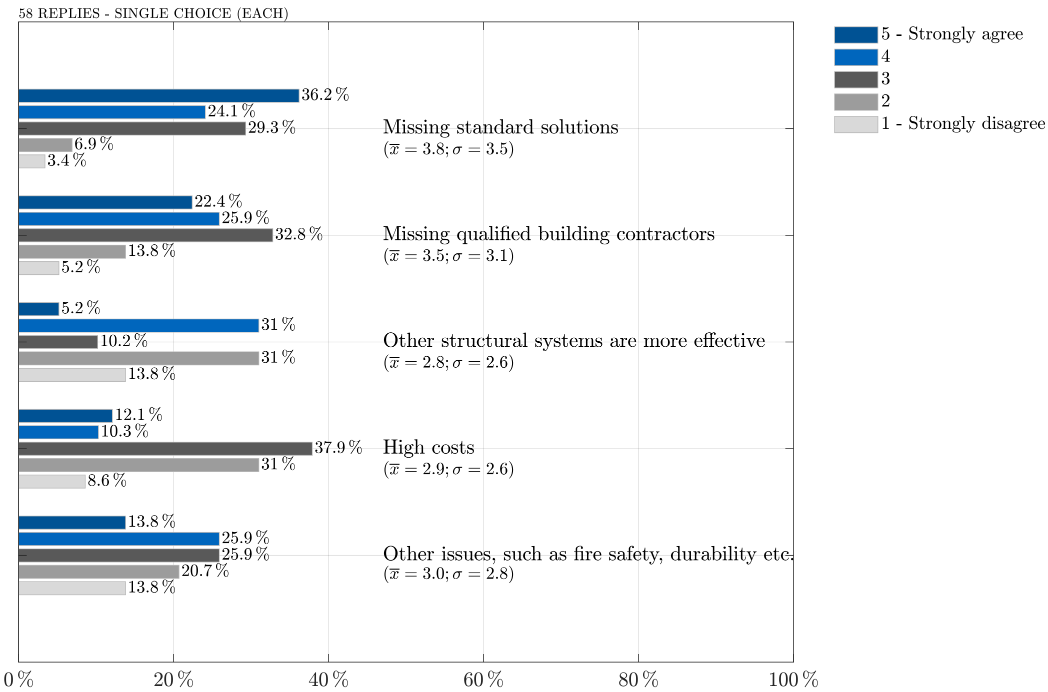


Figure 16. Reasons why CLT or hybrid (CLT-concrete) structures are not commonly used for high-rise buildings in seismically active regions.

As shown in Figure 17, most engineers design massive CLT structures in seismic areas, where the CLT elements are responsible for the bracing effect. CLT wall structures are used mainly (84.5%) for this task. However, just under half of the respondents also plan to use structures such as a light timber frame plus CLT wall/slab elements (46.6%) or concrete cores plus CLT wall/slab elements (48.3%).

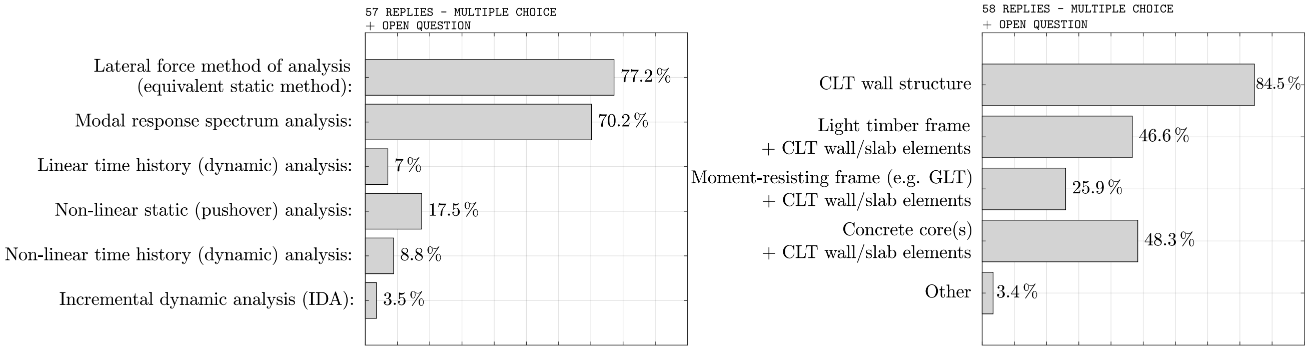


Figure 17. Seismic design with cross laminated timber (CLT). Type of analysis used for seismic design (**left**) and structural systems used in combination with CLT (**right**).

Seismic design requires the use of specialised design models. The two linear calculation methods were ticked by about three-quarters of the respondents, the lateral force method by 77.2% and the modal response spectrum analysis by 70.2%. A similar percentage consider non-linear methods for more complex CLT constructions to take into account the nonlinearity of the material, as shown in Figure 18.

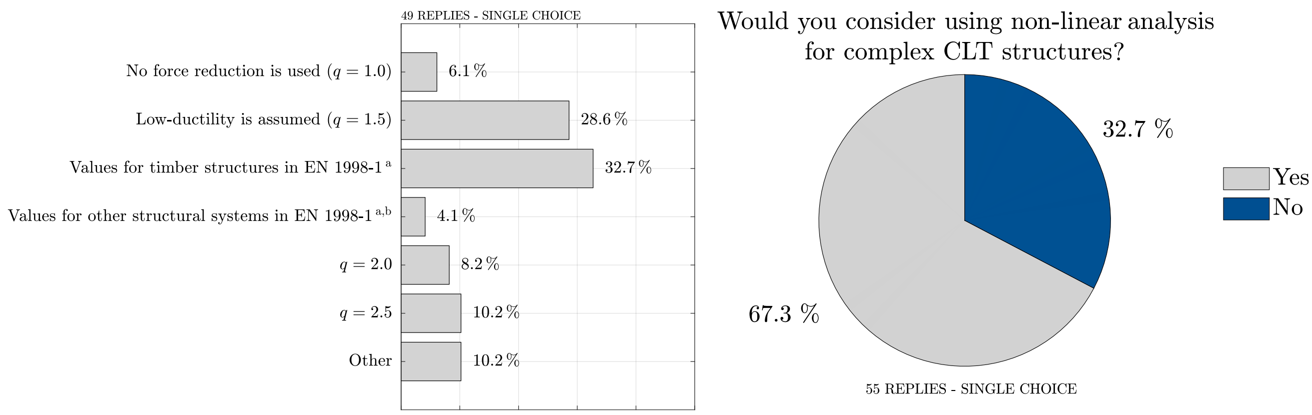


Figure 18. Applied behaviour factors (**left**) and willingness to apply non-linear analysis (**right**).

Different approaches (Figure 18) are taken for the required behaviour factor (q factor), as defined in EN 1998-1:2004 [43] . About one third of the respondents applies the values from Eurocode 8 for timber constructions. Another third applies a low ductility with a q-factor of 1.5. However, other values such as the q factor of 2.0 or 2.5 are also cited. According to the respondents, these latter values come from the national standard of Italy *"Norme tecniche per le Costruzioni 2018"* [44] for a medium ductility class ($q = 2.5$) and based on the current Eurocode 8 draft proposal ($q = 2.0$), CEN/TC 250/SC 8. [45].

The reason why CLT constructions are rarely used for high-rise buildings in seismic areas is not based on the idea that other systems or products are better suited or that CLT costs are too high, but rather on missing design standards or qualified construction companies (Figure 19).

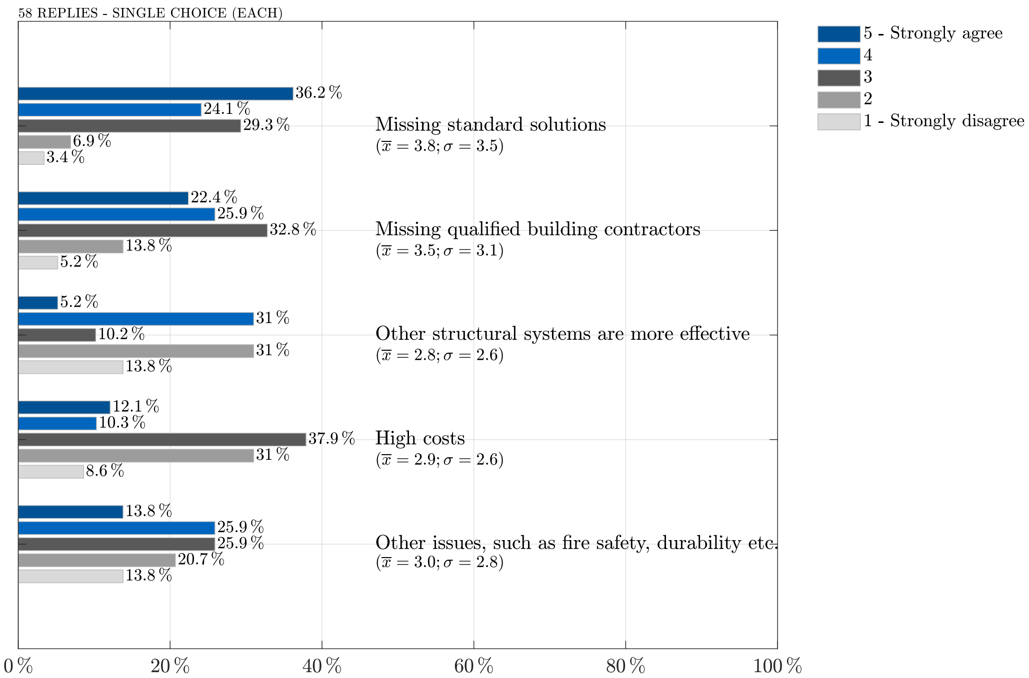


Figure 19. Reasons why CLT or hybrid (CLT-concrete) structures are not commonly used for high-rise buildings in seismically active regions.

7. Final Considerations

The paper presented the results of a worlwide survey to practitioners regarding CLT structures. This document not only provides an overview of the experience of engineers working with CLT, typical verification methods of today, and their common implementation in design software, but it provides a clear picture on the current level of satisfaction and knowledge. As a result, it emphasises the need for further research and developments on CLT.

Though more than half of the respondents describe themselves as being very familiar with CLT construction, The obtained results show how the average level of knowledge differs widely. Some of the participants are very deeply involved with the cross laminated material and are familiar with the required theories.

However, another wide group has dealt with the topic of cross laminated timber rather superficially and knows the most important and basic key points, typically from the guidelines of the CLT manufacturers. They know about the basic theories such as the γ-method. Further more, some of them did not have a sound knowledge of the product, as proved by the fact that 10–20% of them did not know the background theories used for verification in the tools they used.

The survey evaluation also indicated that a wide range of different literature is used for the design in building practice, as cross laminated timber has not yet been included in the standardisation. No uniformly used background document can be identified. Most of the respondents refer to various published manuals on the design of cross laminated timber. Taking into account the recent introduction of CLT in practice and the experience of the surveyed population, it can be inferred that most of the respondents are self-taught about CLT design. For purely time reasons, there is a lack of formal education on CLT in practice.

This idea becomes clearer when considering the questions regarding the tools and design methods used. Again, for the general calculation, the respondents are broadly positioned. Most of them seem to have a wide repertoire of different approaches based on a wide range of literature. The majority of the respondents are satisfied with the software available or used, although the whole picture shows the use of too many different solutions from various providers. Different tools, based on different background theories and with different levels of accuracy may lead to quite diverging results. It is questionable whether this heterogeneity can produce a uniform high level of security.

In contrast, for material parameters, most respondents refer to the product standard for cross laminated timber or the European Technical Assessments, which are all official documents for the material properties of CLT.

Thus, while the material parameters are uniformly applied to some extent, the approach to design is very heterogeneously structured. Again the picture is coherent with the previous conclusions on the need of experience and education.

In the survey, it was found that the actual share of CLT structures was quite low in comparison to other timber products. The question may arise as to why this is so low. The analysis of the survey shows that the reason might not be related to the product itself, since most of the respondents are quite satisfied with the performance of the material, even in demanding situations such as high-rise buildings in earthquake areas.

The results of the survey mainly point to the lack of standardisation and incomplete regulations. Most designers require more information or improved documentation for their design tasks. The lack of a uniform design specification for CLT could result in a more difficult competitive situation. However, the question also arises as to whether a uniformly high safety level can be ensured when a whole diversity of unconsistent references is used. This unclear situation leads to the fact that the construction of a structure in solid timber construction requires a experience and further qualification and can therefore only be carried out by some engineers.

Therefore, the focus needs to be less on research to improve the material's properties, but on developing adequate tools and models for the product. The evaluation of the survey shows that simple design rules are needed. In particular, generally applicable approaches for more complex design problems should be developed. As a further step, work should be done on the implementation of more complex design problems in software solutions. Further research should increase the applicability of CLT globally and strengthen its competitiveness with other building materials.

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