Basis of design principles – application to CLT

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Abstract

The design of cross laminated timber (CLT) structures is not regulated in the current version of European structural timber design standards of EN 1995 (Eurocode 5). Due to the increasing importance of CLT, it is one of the main goals of the current version of Eurocode 5 to implement the design of CLT structures. In the present paper some general aspects, relevant for the implementation of CLT in European standards in order to be consistent with the general philosophy of the Eurocodes are summarized and discussed. The differences between standard test specimens and structural components as well as the uncertainties related to the production procedure of CLT and the non-standardized test procedure are discussed. An investigation of 12 different test series from five different producers clearly indicates a large variation between different production series. Based on the investigation from the test series a reliability analysis is performed. The results indicate that same partial safety factor as recommended for GLT is appropriate in order to achieve an acceptable reliability. However, the analysis also indicates the potential for a smaller partial safety factor in the future, in case that the productions of CLT is standardized and appropriate standardized test methods for the individual material properties exist.

Keywords: Cross laminated timber, Structural reliability, Partial safety factor, Variability of the materiel properties

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1. Introduction

A large proportion of the societal wealth is invested in the continuous development and maintenance of the built infrastructure. It is therefore essential that decisions in this regard are made on a rational basis; i.e. to balance expected consequences and the investments into more safety. Structural design codes are therefore calibrated on the basis of associated risks or, simplified, on the basis of associated failure probability. Reliability based code calibration is already implemented in several modern design codes, such as OHBDC (1983), NBCC (1980), or EN 1990 (2002). For background information about reliability based code calibration it is refereed to e.g. Rosenblueth and Esteva (1972); Ravindra and Galambos (1978); Ellingwood et al. (1982).

In the current version of Eurocode 5 (EC 5) the design of cross laminated timber (CLT) structures is not regulated. This large-dimensional plate-like, stand-alone structural timber product can be used as complete wall or floor element as well as girder. Due to the growing importance of CLT in the construction sector, it is one of the major goals of COST Action FP1402 to implement the design of CLT structures in the new version of EC 5.

The timber construction product CLT is relatively new on the market; the first CLT elements where produced in Central Europe 25 years ago. Although meanwhile worldwide CLT productions exist, Central Europe still remains as hot spot with a share in worldwide production volume of 90% (800'000 m^3), produced in nine large CLT productions (more than 20'000 m^3 per year; three of them produce even more than 100'000 m^3 per year) and 23 small and medium sized productions (see Schickhofer et al., 2017). The majority of CLT from Europe has many common parameters, e.g. the most common timber species used is Norway spruce (Picea abies), the base material (lamination) is mainly strength class C24 or T14 according to EN 338 (2016) and the layers are usually bonded at their side-faces but not or only unintendedly at their narrow faces (edges). There is also a strong tendency standardizing the CLT layups and the layer thicknesses to 20, 30 and 40 mm.

In this paper, relevant aspects for the implementation of CLT in European standards are summarized and discussed. Hereby it is particularly focused on issues and challenges that are associated to the formulation of design equations that are consistent with the general philosophy of the Eurocodes as prescribed in EN 1990 (2002). In the first part the differences between standard test specimens and structural components are discussed. Afterwards the representation of material properties for structural design and code calibration are introduced. In Section 4 the variability of the material properties of CLT is investigated and discussed. It is mainly focused on the uncertainties related to the production procedure of CLT and the non-standardized test procedure. Thereafter, the variability of selected material properties and strength related issues are discussed based on the results from other investigations. Using the identified variabilities a simplified reliability based code calibration is performed.

2. CLT – standard test specimen vs. structural components

When modelling timber material properties in a structure, i.e. at any generic point, in time and in space, several issues related to timber grading, size effects and duration of load effects have to be taken into account, see also Köhler (2006). For engineered wood products, such as CLT, the situation is even more complex as the joint behavior of the assembled timber boards, the finger joint connections and the bond lines have to be represented. Furthermore, the production process of engineered wood products might affect the variability and uncertainty of the properties of the product.

In Figure 1 the various aspects that influence the load bearing capacity of CLT at a generic point in the structure are illustrated. The base material for the production of CLT is graded structural timber. Graded structural timber is available in form of strength classes, i.e. classes of structural timber with specified target reference properties as timber density, material modulus of elasticity and resistance for bending or tension. The targets for the reference properties are expressed as fractile or mean values from the corresponding anticipated probability distribution functions; 5% fractile for the density and the MOR and mean values for the MOE. All other material properties of the graded structural timber are estimated based on the classification made based on the reference properties. It has to be considered that the reference properties representing the properties of the entire strength grade, but not necessarily the properties of an individual batch (see also Figure 2). Obviously the variability between the sawn timber batches is related to the quality of the grading device that has been used. Different base material strength classes can be used for the production of CLT and different production techniques exist to produce a classified and specified CLT product, see e.g. Schickhofer et al. (2010); Gagnon and Pirvu (2011); Harris et al. (2013); Brandner et al. (2016).

Classified engineered wood products have assigned values for the strength and stiffness properties associated to different possible failure modes. These failure modes relate to standardized test set ups that are specified in order to imitate the loading and failure modes in real structures as close as possible. Test data from these standardized tests are taken to verify the strength and stiffness properties of the engineered wood product and to quantify the variability, e.g. the coefficient of variation (COV), of the measured properties. For CLT a test standard is missing. Some test setups and recommendations can be found in EN 16351 (2015) and EAD (2015), former CUAP (2005). However, in the recent experimental investigations often, a relatively large amount of the tested specimens show failure modes different to the target ones (see Section 4.2.2).

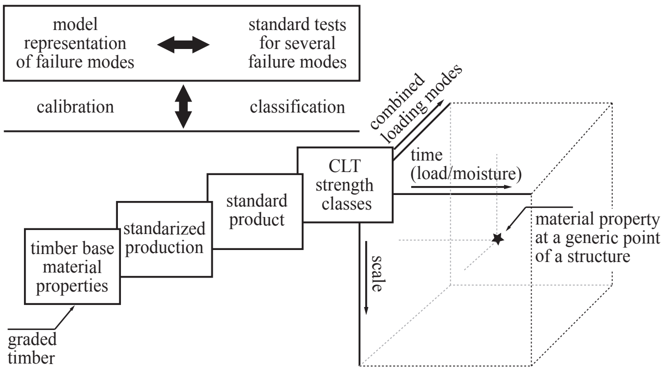

Figure 1: Strength and stiffness related properties are relevant to represent in structural design assessment. However, this includes the consideration of various aspects.

Together with the analysis of model calculations for the corresponding failure modes the entire production and classification process is calibrated and validated. However, the production and classification process is not perfect and under full control, thus, beyond the uncertainty that is associated to the variability of measured test data the uncertainty due to the imperfect production and classification process has to be considered.

Furthermore, it has to be considered that the identified material properties are related to standardized tests and not to the strength and stiffness related properties in a generic point in the structure. Scale effects, duration of load and moisture effects and a possible combination of different loading modes also affect the relevant property (strength and stiffness) here and have to be considered.

Due to similarities between CLT and glued laminated timber (GLT) many of the above mentioned issues might be adaptable. However, for some issues such as the production process or the test procedure significant differences exist and have to be considered. Furthermore, different areas of applications as well as additional failure modes have to be considered. At this point it has to be mentioned that some of the above mentioned issues are not jet solved for GLT; i.e. the assumptions are often based on engineering judgment. However, due to relatively long experience with GLT in structural applications the assumptions made seem to lead in reliable solutions even though they might not be fully optimized jet.

3. Representation of material properties for structural design and code calibration

The objective of structural design is to choose structural dimensions such that the load bearing capacity of components R is larger than the effect of applied loads S with sufficient reliability. When structural design is performed according to a design standard, e.g. the Eurocodes the objective is addressed by deriving a design value for the load bearing capacity r_d and compare this with the corresponding design value for the effect of the applied loads s_d. The design value of the load bearing capacity is computed based on the design value of the relevant material property x_d, e.g. the bending resistance such that the non-exceedance probability of that design value is

$$Pr(X < x_d) = \Phi(\alpha\beta) \tag{1}$$

Here, Φ is the standard normal operator, α_X is the so-called FORM sensitivity factor and β is the target reliability. In the Eurocodes conventional values are suggested, i.e. $\alpha = -0.8$ for the material resistance and $\beta = 3.8$ such that the non-exceedance probability refers to a 50 year reference period. In order to estimate a design value that fullfills the criterion for the non-exeedance probability, the material property at hand has to be represented as a random variable. If it can for example be assumed that the bending resistance can be represented by a lognormal distributed random variable the design value can be formulated as a function of the mean value μ_X,the coefficient of variaton V_X, α_X and β as

$$x_d = \mu_X e^{-\frac{1}{2}\log{(1+V_X^2)}+\alpha_X\beta\sqrt{\log{(1+V_X^2)}}} \tag{2}$$

In the Eurocodes the design value is in general estimated indirectly via the so-called characteristic value x_k and a partial safety factor γ_X with $x_d = x_k/\gamma_X$. Given that the characteristic value of a variable is defined as the p_k-fractile of the corresponding probability distribution function, the characteristic value x_k for a lognormal distributed variable X is defined as

$$x_k = \mu_X e^{-\frac{1}{2}\log{(1+V_X^2)}+\Phi(p_k)\sqrt{\log{(1+V_X^2)}}} \tag{3}$$

Accordingly the partial safety factor γ_X is computed as

$$\gamma_X = e^{(\Phi(p_k)-\alpha_X\beta)\sqrt{\log{(1+V_X^2)}}} \tag{4}$$

As can be seen from Eq. (4), γ_X is dependent on the definition of the characteristic value (p_k), the variation of the resistance property (V_X), the importance of the resistance variable (α_X) and the target reliability level expressed for a 50-year reference period (β). The FORM sensitivity factor α_X is chosen such that it represents the importance of the resistance variable relative to the load variables for typical design situations. For the representation of a strength related material property for structural design and for the quantification of the partial safety factors it is therefore of importance:

- to have a clear and unambiguous definition of the characteristic value, e.g. as the 5 % – fractile of a well defined population.
- to estimate the coefficient of variation of this population.

The definition of a population for CLT is associated with a number of challenges that is discussed in the following section.

4. Variability of the material properties of CLT

4.1. Challenges in Defining the European CLT Population

For the calibration of partial safety factors it is essential to represent the variability of the product properties of CLT. Placing CLT as construction product on the European market requires a CE marking which, since the Construction Product Regulation (CPR) entered in force in mid of 2013, can be achieved by producing CLT according to a harmonized product standard or via a European Technical Assessment (ETA), former European Technical Approval (ETA). In both cases a Declaration of Performance (DoP) on behalf of the CLT producer is mandatory guaranteeing the user the constancy of performance and conformity of CLT with the declared properties. As the European product standard for CLT, EN 16351 (2015), is still not harmonized, so far CE marking via ETAs remains. The process for issuing an ETA for CLT is regulated by the European Assessment Document EAD 130005-00-0304 (EOTA, 2015), former Common Understanding of Assessment Procedure CUAP, OIB-260-001/99-116 (CUAP, 2005), which contains, apart from definition and intended use, detailed information for determining physical (mechanical) properties of CLT elements based on performance testing and regulations to fulfil the requirements declared in CPR. Currently CLT producers still follow their individual approvals, thus the product properties of CLT as well as their variability cannot be described straight forwardly.

The variability of the material properties identified within one individual campaign is representing the overall variability of CLT properties only partially. In addition to the variability of an individual batch also the variability between batches from the same producers and the variability between different producers have to be considered (see Figure 2). Due to the differences of the regulations combined with the rather low experience of at least some CLT producers (the production process of CLT might be less optimized compared to e.g. GLT) between producer variability is expected to be significant.

Being interested in a performance based declaration of a European CLT population with associated mechanical properties, the amount of published test series is limited, even for the main properties of CLT exposed out-of-plane as well as in-plane. Some of these properties are also only regulated in analogy to other structural timber products

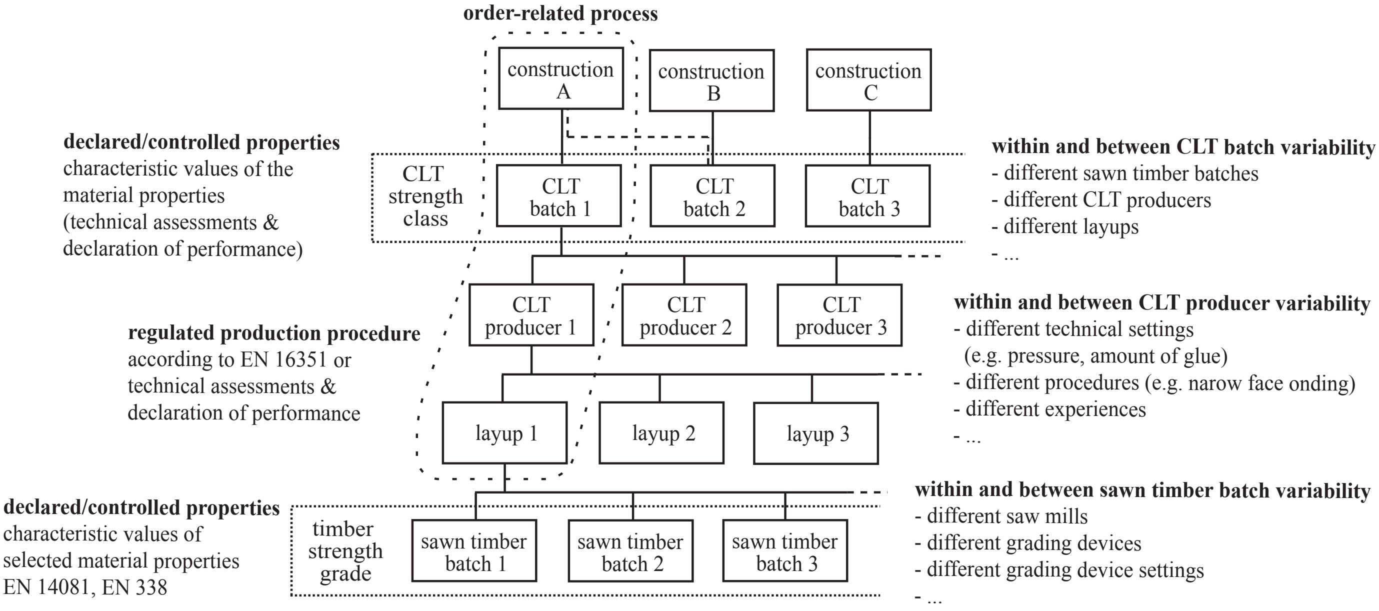

Figure 2: Hierarchical model for the variability of product properties in CLT.

such as GLT, i.e. based on engineering judgement. In the following section test series from certification processes are discussed.

4.2. Case study

In order to discuss the variability between different series and different producers 12 test series performed at Lignum Test Centre of the Institute of Timber Engineering and Wood Technology, Graz University of Technology, are discussed. These data base on CLT elements from five different Central European CLT producers and comprise bending (six series) and rolling shear properties (six series) determined by means of four-point bending tests on CLT loaded out-of-plane. Table 1 & 2 show a compilation of test series and test results. All test series were performed for certification purposes. All timber boards had the same nominal strength class C24, according to EN 338 (2016), thus similar base material properties might be assumed. However, it has to be mentioned that significant differences between the mean densities of the test series are identified. Thus a certain variation of the test results can be expected.

The limitation of this study, for the investigation of the within and between batch variability of CLT are described and the problem of non-standardized tests within this context is illustrated. For both, the out-of-plane bending strength and the out-of-plane rolling shear strength, the variabilities of the test series are anyway investigated and summarized. Due to the limitations of the used data series (see Section 4.2.1) no hierarchical level was developed as it would not reflect the actual variability of CLT.

4.2.1. Limitations of this study

The study presented in this Section has some limitations, in order estimate the variability of CLT:

- The mean densities of all test series were larger compared to the target density defined in EN 338 (2016) for this strength class $\rho_{\text{mean}} = 420$ kg/m^3. This indicates that the base material used for producing the CLT elements is better than declared. It appears that producers in frame of certification processes are in favour delivering better quality material which might not be the case in running productions. The heterogeneity in the base material may lead to variability and thus additional uncertainty larger than commonly expected.
- Producing CLT from base material of quality higher than declared raises the elastic modulus of elasticity of CLT in bending out-of-plane as well as the bending resistance. In respect to rolling shear, base material of higher quality origins usually from the outer part of logs featuring mature wood and flat grain. This affects the rolling shear modulus negatively, however, for rolling shear resistance the influence should be negligible. The positive influence on the bending resistance combined with the small influence on the rolling shear resistance leads to an increase of the probability for rolling shear failures prior to bending failure in case of higher strength grades (see also Section 4.2.3 and Ehrhart et al. (2015)).
- As mentioned all series origin from testing procedures in frame of certification. In five rolling shear series and in four bending series the CLT elements more or less represent the first elements produced by the companies and on the corresponding production line.

Thus prior experience with production line, production process and by the producer are limited. It has to be expected that these productions have improved by meanwhile gained experiences and company internal harmonization processes as well as stabilization of raw material suppliers.

- It is common practice that in case of not too large specimen, one part or even the whole series is taken from one CLT plate (see e.g. Brandner et al., 2017) Consequently, the observed variability in tested properties might be too low, representing rather the variability within a CLT plate than the variability e.g. associated to a batch of CLT plates. Thereby induced bias depends on the specimen and plate dimensions and on how the sampling was made. However, due to relatively large dimensions of common CLT production plates (in length up to 30 m, in width up to 3.5 m) featuring an orthogonal layup and finger jointed laminations, variabilities in lamination properties might be represented to some extend.
- In some series a relative large number of unexpected failures occurred, e.g. rolling shear failure prior bending failure, which might be a result of the non-standardized testing procedure. The related uncertainties are described in more detail in Section 4.2.2.
- Tested series comprise CLT featuring different layups and number of layers. Although the layup is explicitly considered in the evaluation process, differences in the layup might have also some influence on the observed CLT properties not taken into account so far.
- Test series A, B, a, and f are from the same CLT producer and featuring CLT with narrow face (edge) bonding, in contrast to all others featuring no or only unintended narrow face bonding. This might affecting the rolling shear properties (see Ehrhart et al., 2015).
- CLT elements in test series c is made of laminations featuring stress reliefs which again affects the rolling shear properties which are in that series much lower than in the others.
- All test series comprise CLT made of Norway spruce, some CLT producers are allowed to use also other softwood timber species (e.g. pine) for their CLT featuring the same declared properties.

However, in respect to the aimed characterisation of European CLT population properties, the outcomes from tested series have to be differentiated from the properties regulated in individual ETAs and declared individually by the producers within their DoPs. For example, analysing the ETAs from involved CLT producers, bending properties and rolling shear strengths in the range of $f_{\mathrm{m,k}} = 24.0 - 28.8$ MPa (with majority $f_{\mathrm{m,k}} = 26.4$ MPa), $E_{0,\mathrm{mean}} = 11'000 - 12'500$ MPa and $f_{\mathrm{r,k}} = 0.8 - 1.25$ MPa are given featuring a variation which is much lower than in tested samples. Within the currently ongoing revision of EC 5 aiming on implementing the design of CLT, the standardisation of a CLT strength class (system) and associated characteristic properties is required. The current PT SC5.T1 document (2017-12-01), as basis for EC 5, further harmonises the CLT properties, regulating e.g. $f_{\mathrm{m,k}} = 24.0$ MPa, $E_{0,\mathrm{mean}} = 11'600$ MPa and $f_{\mathrm{r,k}} = 1.4$ MPa.

In the following the values declared in individual ETAs and DoPs as well as the proposal of PT SC5.T1 are used as a starting point for analysing the partial safety factor, together with the uncertainty included in estimating the variabilities for properties determined from presented individual test series.

4.2.2. Standardized tests

As already mentioned for CLT so far a test standard is missing. However, it is widespread to perform testing in accordance to EN 408 (2003). Nevertheless, the tested specimen often show failure modes different from the target ones. The amount of such unexpected failures varies significantly between the investigations. A typical example are bending tests intended for investigating bending properties were a rolling shear failure occurs before the specimen fails in bending. From these tests, it is only known that the bending strength is at least the bending stress that corresponds to the load applied on the specimens when the rolling shear failure occurred.

In the six test series (Section 4.2.3), conducted to identify the bending strength altogether 15 (out of 88) specimens failed in rolling shear. Only one series had no rolling shear failure, in one series even more than half of the specimens failed different to bending. In particular in that series, the reason therefore was a base material quality which significantly exceeded the nominal strength class, which is apparent considering mean density and mean MOE.

In order to estimate the bending strength, of data sets considering so-called censored data, usually the maximum likelihood method (MLM) is used (e.g. Benjamin and Cornell, 1970; Faber, 2012). The principle of the MLM is to find the parameter, in order that the selected distribution function most likely reflect the data sample. The parameters of the distribution function are estimated by solving the optimisation problem:

$$L(\boldsymbol{\theta}|\hat{\mathbf{x}}) = \prod_{i=0}^{n} L_i(\boldsymbol{\theta}|\hat{x}_i) \qquad \min_{\boldsymbol{\theta}} \left(-L(\boldsymbol{\theta}|\hat{\mathbf{x}})\right) \tag{5}$$

$L(\boldsymbol{\theta}|\hat{\mathbf{x}})$ is the Likelihood of the observed data , $\boldsymbol{\theta}$ represents the parameter vector, and $\hat{\mathbf{x}}$ are the measured values (here the out-of plane bending strength f_{m} or the out-of-plane rolling shear strength f_{r}, respectively).

If the tested specimen fails as expected, the quantity of interest is measured directly and the Likelihood of the observed data $\hat{x}_i$ is equal to the realisation of the density function $f_X(\hat{x}_i|\boldsymbol{\theta})$:

$$L_i(\boldsymbol{\theta}|\hat{x}_i) = f_X(\hat{x}_i|\boldsymbol{\theta}) \tag{6}$$

If the tested specimen shows a failure mode different from the target ones, the measured value does not describe the quantity of interest, but can be used as censored information. For censored observations (denoted $\hat{x}_{i,\mathrm{c}}$), the Likelihood can be calculated with the realisation of the cumulative distribution function $F_X(\hat{x}_{i,\mathrm{c}}|\boldsymbol{\theta})$ according to:

$$L_i(\boldsymbol{\theta}|\hat{x}_{i,\mathrm{c}}) = 1 - F_X(\hat{x}_{i,\mathrm{c}}|\boldsymbol{\theta}) \tag{7}$$

One advantage of the MLM is that the uncertainties of the MLM estimators can be estimated. In general, the uncertainty of the estimated parameter increases with increasing number of censored data and thus more test results are needed for reliable predictions. Within the framework of this investigation the uncertainties of the MLM estimators are, however, not considered; i.e. they are assumed to be correct. Under consideration of the large expected differences between the batch properties and the 'real' properties this assumption seems to be appropriate.

One practical problem when the tested specimen show failure modes different from the target ones, is that censored data might not have been considered in the analysis of studies found in the literature. In such cases the actual material properties are underestimated and a direct comparison to other investigations might not be possible. In this respect it is of particular importance that standardized test procedures for CLT will be developed were the investigated failure mode can be achieved with high probability.

Another example for a non-standardized experimental test is the in-plane shear test. Over the last years numerous of different testing arrangements have been developed in order to find the actual material properties. Examples for different experimental setups are Jöbstl et al. (2008), Brandner et al. (2013), and more recent Brandner et al. (2017). Even though the test arrangements were selected for different purposes (e.g. shear resistance of single lamellas or entire structural elements), it indicated the difficulties in getting information needed for a reliability analysis.

4.2.3. Out-of-plane bending strength

Six test series (from five different producers) were performed and investigated to find the out-of plane bending strength based on four-point bending tests. Every test series had different layups, the sample size varied from 12 to 22 test specimens.

In Figure 3 the measured out-of-plane bending strength (or the corresponding bending stresses, in case of a out-of-plane rolling shear strength) as well as the estimated distribution functions of all individual test series (assuming a lognormal distribution) are illustrated. The COV's of the individual series are between 0.046 and 0.152. Considering all test results the variability (further denoted as overall variability) is COV = 0.208 (black line in Figure 3).

In principle the variability of CLT can be described by three hierarchical levels:

- Variability between the CLT producers
- Variability between the individual batches from the same producer
- Variability within individual batches

Due to limited number of test series and the limitations described in Section 4.2.1 a reliable estimation of the three hierarchical levels can not be made (e.g. only two test series for the out-of-plane bending strength were produced by the same producer). However, the between batch variability and the within batch variability are investigated.

The out-of-plane bending strength of the individual batches can be assumed lognormal distributed. From Figure 3 a large variability between the batches can be observed. The between batch variability can be expressed by the variability of the mean bending strength $f_{\mathrm{m,mean}}$ of the six batches. The expected value and the variability are $E[f_{\mathrm{m,mean}}] = 41.4$ MPa and $\sigma[f_{\mathrm{m,mean}}] = 8.24$ MPa (assuming a lognormal distribution). Accordingly the variability between $f_{\mathrm{m,mean}}$ is even larger than for the individual batches (COV ≈ 0.20). The large variability between the batches clearly indicates the needs for a more standardized product and production. At this point it has to be mentioned that for common constructions usually one CLT producers is delivering the entire material. Only for very large constructions more than one CLT producers are common (see Figure 2).

In addition to the mean bending strength $f_{\mathrm{m,mean}}$ also the variabilities of the individual batches $\sigma(f_{\mathrm{m}})$ are different: $E[\sigma(f_{\mathrm{m}})] = 4.79$ MPa and $\sigma[\sigma(f_{\mathrm{m}})] = 2.71$ MPa (assuming a lognormal distribution). The within batch variability might be also effected by the rather small experience of the producers, at the time when the samples were produced. However, as already mentioned it has to be expected that these productions have meanwhile improved and thus the variability within the individual test series might be smaller.

The investigated samples might not be optimal for a reliable prediction of the characteristic out-of-plane bending strength. It has to be considered that as long as the CLT production is only regulated by ETAs the corresponding strength properties on characteristic level have to be assumed appropriate, at least when performing code calibration. However, the variability of the strength properties is not regulated, but essential for the estimation of the partial safety factors (see Section 3). Even though each sample had a different layup the variability between the different samples clearly indicates the variation between the different producers and production series.

As already outlined the number of specimens which failed in rolling shear prior to bending varies between the series. A comparison between the mean modulus of elasticity in bending $E_{\mathrm{m,loc,12,mean}}$ and the number of unexpected out-of-plane rolling shear failure (see Table 1) clearly indicates the high correlation; i.e. CLT plates with a high $E_{\mathrm{m,loc,12,mean}}$ (indication for a high quality of the raw material) have a higher probability of a rolling shear failure.

Table 1: Compilation of test results of different test series for determining out-of-plane bending properties.

Series	Unit	A	B	C	D	E	F
Number of tests	[-]	15	22	15	12	12	12
Bending failure	[-]	14	21	6	11	12	9
$\rho_{12,\mathrm{mean}}$	[kg/m^3]	466	457	464	438	433	488
$E_{\mathrm{m,loc,12,mean}}$	[MPa]	12'923	12'736	13'530	11'709	10'315	13'511
$COV[E_{\mathrm{m,loc,12}}]$	[-]	0.062	0.045	0.062	0.091	0.086	0.057
$f_{\mathrm{m,12,mean}}$	[MPa]	46.6	37.3	54.4	38.7	30.6	40.2
$COV[f_{\mathrm{m,12}}]$	[-]	0.098	0.046	0.152	0.096	0.125	0.142

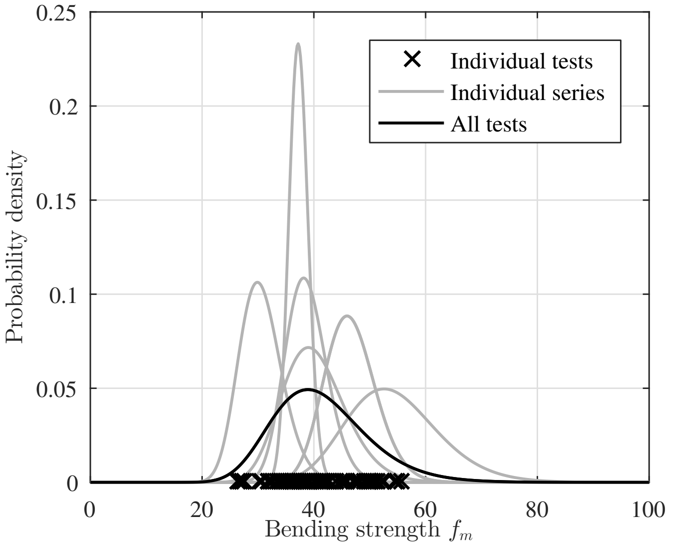

Figure 3: Probability densities of six test series tested in out-of plane bending.

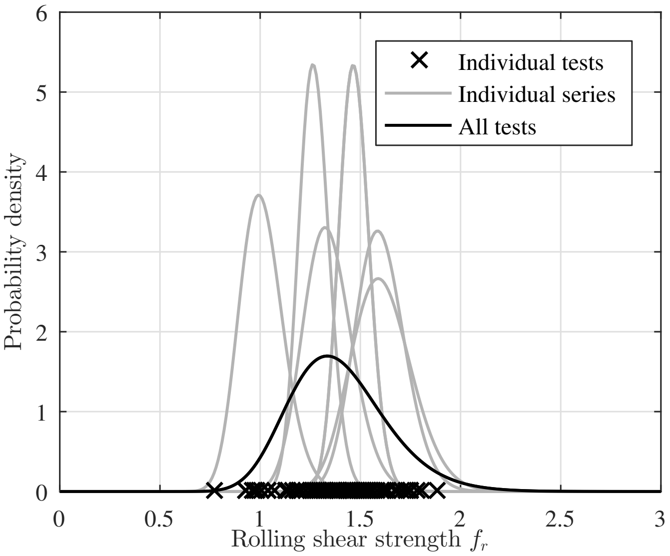

Figure 4: Probability densities of seven test series tested in in rolling shear by means of out-of-plane bending tests.

4.2.4. Out-of-plane rolling shear strength

The rolling shear strength of CLT elements was investigated in out-of-plane four-point bending tests on six test series (from five different producers, six different layups). The sample size varied from 11 to 22 test specimens. In four test series only rolling shear failures were observed. However, in two series one specimen failed in bending.

In Figure 4 the test results and the estimated lognormal distribution functions of all individual test series are illustrated. Overall the variability of the individual test series seems to be smaller compared to those from the out-of-plane bending strength: COV $\in [0.051, 0.108]$. However, the mean values are significantly different.

The out-of-plane rolling shear strength was assumed to be lognormal distributed. The between batch variability is expressed by the variability of the mean rolling shear strength $f_{\mathrm{r,mean}}$ of the six batches. The expected value and the variability are $E[f_{\mathrm{r,mean}}] = 1.388$ MPa and $\sigma[f_{\mathrm{m,mean}}] = 0.246$ MPa. Accordingly the variability between $f_{\mathrm{r,mean}}$ is significantly larger than for the individual batches (COV $\approx$ 0.18), but slightly smaller as for out-of-plane bending strength. The estimated parameter of the variabilities of the individual batches $\sigma(f_{\mathrm{r}})$ are: $E[\sigma(f_{\mathrm{r}})] = 0.110$ MPa and $\sigma[\sigma(f_{\mathrm{r}})] = 0.0322$ MPa. As for bending, the large variability between the batches clearly indicates the needs for a more standardized product and production.

Due to the large number of rolling shear failure (prior to bending failure) from test series C, this series was also used to investigate the out-of-plane rolling shear strength (nine specimens failed in out-of-plane rolling shear). Series C indicates an average out-of-plane rolling shear strength and a relatively small variability, compared to the six reference series. However, from $E_{\mathrm{m,loc,12,mean}}$ and $\rho_{12,\mathrm{mean}}$ it becomes obvious that the raw material are highly over average (highest $E_{\mathrm{m,loc,12,mean}}$, see Table 1). This confirms that the bending strength is significantly larger influenced by the properties of the raw material than the rolling shear strength.

4.3. Other studies

The large variability between different producers was also indicated in Brandner et al. (2015b,a, 2017) presenting data from in-plane shear tests. In this study, samples of

Table 2: Compilation of test results of different test series for out-of-plane rolling shear.

Series	Unit	a	b	c[a]	d	e	f[b]
Number of tests	[-]	22	15	13	11	12	14
Rolling shear failure	[-]	22	15	13	10	11	14
ρ_{mean}	[kg/m^3]	454	461	430	442	492	486
$f_{\mathrm{r,12,mean}}$	[MPa]	1.47	1.61	1.01	1.34	1.60	1.27
$COV[f_{\mathrm{r,12}}]$	[-]	0.051	0.094	0.108	0.091	0.077	0.059

[a] Width to thickness ratio, $w_l/t_l < 4$

[b] Originally intended for determining the bending strength

CLT elements from three different producers indicate significant different mean densities although CLT with equal base material of nominal strength class C24 was requested. As tested shear properties are influenced by product parameters others than density a comparable conclusion for these properties cannot be made. However it is apparent that the variability of in-plane shear properties as well as densities seems not to be significantly influenced by the producer.

5. Material properties of CLT for different failure scenarios (ULS)

In this chapter current different material properties of CLT for different failure scenarios (ultimate limit state) are illustrated and discussed; it is referenced to the example presented in the BSPhandbuch (Schickhofer et al., 2010). It is only focused on selected material properties of CLT elements in respect to ultimate limit state design as well as on fire resistance and duration of load effects. Aspects regarding stability, connections, serviceability and so on are not considered.

5.1. Bending strength

One possible approach for estimating the characteristic value of the out-of-plane bending capacity of CLT is by using the analogies to GLT. As the bending strength of GLT and CLT are both related to the tensile strength parallel to grain of the laminations in the outermost layer(s) in the bending-tension zone.

For structures loaded in parallel, a so-called system strength factor k_{sys}, commonly defined as the ratio between quantiles of system and element load bearing capacity, is allowed according to EC 5 (2004). The reason therefore is that a very low realization of the capacity of a single element will not automatically lead to failure of the structure, as the weak element acts together with the adjacent elements; i.e. the stronger elements, which are typically also stiffer, take a higher load proportion. The effects of reinforcing due to mutual action between adjacent lamellas lead to a decrease of the variability of the system properties compared to that of the single elements. The most appropriate approach to consider the additional safety due to a reduced variability would be the reduction of the partial safety factor. However, a similar effect can be achieved by increasing the design value with $k_{\mathrm{sys}} \geq 1.00$. At this point it has to be mentioned that, to be consistent with solid timber and other engineered wood products such as GLT, CLT elements should be treated as individual structural components. Thus it is of particular importance to identify the actual variability of the material properties, here of the out-of-plane bending strength.

Looking at the experimental investigations performed by Jöbstl et al. (2006) and the studies introduced in Section 2 it seems that the variability of bending capacity of individual production series is about $COV[f_{\mathrm{m,CLT}}] = 0.05$ to 0.16, thus overall lower than for GLT; $E[COV[f_{\mathrm{m,GLT}}]] \approx 0.15$ (JCSS, 2006).

5.2. Shear strength

The shear strength is needed either for the design of floor elements (CLT plates loaded primary perpendicular to the plane direction, i.e. out-of-plane) and for wall elements, i.e. CLT plates loaded primary in-plane direction. In CLT elements exposed to shear in-plane three different failure scenarios have to be distinguished: gross-shear, net-shear and torsion failure; see e.g. Bogensperger et al. (2007, 2010); Flaig and Blaß (2013); Brandner et al. (2013). Consequently, five different shear properties are required:

- Shear for CLT out-of-plane
- Rolling shear for CLT out-of-plane
- Gross-shear for CLT in-plane
- Net-shear for CLT in-plane
- Torsion for CLT in-plane

According to Schickhofer et al. (2010), for floor elements a characteristic shear strength $f_{\mathrm{v,CLT,k}} = 3.0$ MPa is recommended. More recently, in Brandner et al. (2016) a value of $f_{\mathrm{v,CLT,k}} = 3.5$ MPa, in-line with regulations for GLT according to EN 14080 (2013), is proposed.

For CLT elements loaded in-plane differentiation in products featuring narrow-face (edge) bonded lamellas within layers and without narrow-face bonding is made. Corresponding values are $f_{\mathrm{v,gross,k}} = 3.5$ MPa (in case of narrow-face bonded CLT), taking into account the gross cross-section, and $f_{\mathrm{v,net,k,ref}} = 5.5$ MPa (in case of CLT without narrow face bonding), considering the layers only in the weak plane direction. In the latter case, verification of a potential torsion failure in the gluing interfaces between the layers has to be made; a value of $f_{\mathrm{t,node,k}} = 2.5$ MPa is proposed; see e.g. (Brandner et al., 2015b, 2016, 2017).

Following the experimental investigations in Brandner et al. (2015b) for net-shear, shear modulus and density variability band-widths of $\mathrm{COV}[f_{\mathrm{v,net}}] = 0.02$ to 0.08 were found by testing six to seven specimen taken from the same CLT element at each parameter setting (additional details are provided in Brandner et al., 2017).

5.3. Rolling shear

The rolling shear properties were investigated e.g. in Ehrhart et al. (2015) by testing board sections of Norway spruce and other wood species. The results indicate a large influence of the width to thickness ratio, w_l/t_l. In particular for timber boards with a small ratio very low rolling shear properties were identified, which consequence from the increasing tension perpendicular to grain stresses at the free edges, i.e. increasing stress peaks with decreasing ratio w_l/t_l. However, performing standard tests according to EN 408 (2003) the characteristic strength value is about $f_{\mathrm{r,CLT,k}} = 1.4$ MPa with $\mathrm{COV}[f_{\mathrm{r,CLT}}] = 0.13$ to 0.22. In comparison to the variability in rolling shear strength as observed by testing CLT elements out-of-plane in bending, these values are significantly higher, which underlines also the homogenization and system action as present in CLT elements.

5.4. Compression strength perpendicular to grain

In Bogensperger et al. (2011) an experimental investigation for compression perpendicular to grain is presented. The test campaign included the investigation of the location of the applied load (e.g. center or edge) as well as the gauge length. The outcome of the investigation was a recommendation of a characteristic value 2.85 MPa as basic material property, thus about 14% larger as for GLT. More recently, Brandner and Schickhofer (2014) report on a comprehensive test campaign conducted by Ciampitti (2013). Considering these and previous test results on CLT elements found in literature, in comparison to GLT overall 30% higher strength and modulus of elasticity in compression perpendicular to grain were concluded and a characteristic value of $f_{\mathrm{c,90,CLT,k}} = 3.0$ MPa together with $COV[f_{\mathrm{c,90,CLT}}] = 0.08$ for the basic value is proposed.

When considering compression strength perpendicular to grain (test according to EN 408 (2003)) it has to be mentioned that the failure criteria is usually not an ULS; in most design situations it is only an exceedance of a defined deformation. In this respect the calibration of the partial safety factors cannot be performed with a standardized procedure as e.g. introduced in this paper. For this an additional parameter has to be considered: The probability of a structural failure given that the deformation exceeds or not exceeds the threshold of the deformation. In any case, the consequences of exceeding the deformation limit are in general less harmful than for other strength properties.

5.5. Fire resistance

For the design of structural timber members at normal temperature the 5% fractile values are used for the material properties (e.g. strength properties); according to EC 5 (2004). In contrast, for the fire design of structural timber members, EC 5 – part 2 (2004) gives conversion factors to enable design with 20% fractile values. That reflects the results of traditional fire codes in Europe (for a detailed description see König (1993, 2005)).

The approach for fire design of structural timber members is different to other materials; e.g. concrete still use 5% fractile values in the fire situation. This contradiction has been recognized in the scientific community. Motivated by this, a research project titled 'reliability based design of timber in fire', with the objective to analyze the current approach for the fire design of timber members based on EC 5 and the determination of the required safety factors in case of fire based on reliability analysis, is currently performed at ETH Zurich. For the implementation of CLT for fire design into the new version of EC 5 this issue should be covered first before optimizing design solutions for fire exposure.

5.6. Duration of load – Modification factor k_{mod}

One of the distinctive characteristics of timber is that its strength is influenced by the intensity and the duration of the applied stresses; strength degradation in timber is observed even under static (permanent) loading. This effect is referred to as the duration of load (DOL) effect. Numerous experimental programs have focused on the investigation of the DOL effects in clear wood specimen and later on also in full size timber components, and a variety of different models have been proposed to describe the phenomenon. Hereby, it has been mainly focused on the duration of load effect of bending specimen. Some of the proposed models have a physical hypothesis of the phenomena as a basis; however, they all consist of variable model parameters which can be calibrated to observed experimental data. The domain of experimental evidence is thus rather limited and it is always the question of proper extrapolation to other applications in timber engineering.

In absence of experimental investigations of the DOL effect for CLT it seems appropriate to assume a rather similar behavior for bending and tension (as it is generally done for GLT). However, this might be not true for other failure modes where also the long-term stress-strain behavior of the glue line is relevant. One example of possible long-term effected aspects might be the influence of narrow face bonded CLT diaphragms. As discussed in Chapter 5.2, narrow face bonded boards usually fail in gross-shear. However, due to long-term effects such as e.g. moisture

Table 3: Compilation of selected material properties' COVs of CLT for individual production series.

Material property	COV
Bending strength out-of-plane	0.05 – 0.16
In-plane net-shear strength	0.02 – 0.08
Rolling shear strength	0.05 – 0.11

induced stresses the positive effect might be reduced, see also Brandner et al. (2017).

In the present code formats the DOL effect together with moisture effects are represented by a modification factor k_{mod}. In Eurocode 5 k_{mod} can be chosen depending on the classification of characteristic climate and the characteristic load duration conditions of the structural component relevant in the design situation.

6. Reliability based code calibration – Example

In this section a simplified example for reliability based code calibration of CLT is presented; before the procedure is introduced briefly.

6.1. Simplified procedure

In this simplified procedure for reliability based code calibration only one variable load Q, the permanent load G and the resistance R are considered. The partial factor design equation is given in Eq. (8). Here, R_{k} is the 5% fractile value of a lognormal distributed resistance, G_{k} is the 50% fractile value (mean value) of the Normal distributed load (constant in time), and Q_{k} is the 98% fractile value of the Gumbel distributed yearly maxima of the load (variable in time). γ_{m}, γ_{G} and γ_{Q} are the corresponding partial safety factors. z is the so-called design variable, which is defined by the chosen dimensions of the structural component.

$$z\frac{R_{\mathrm{k}}}{\gamma_{\mathrm{m}}} - \gamma_{\mathrm{G}}G_{\mathrm{k}} - \gamma_{\mathrm{Q}}Q_{\mathrm{k}} = 0 \tag{8}$$

The corresponding partial safety factors can be calibrated to provide a design solutions (z) with an acceptable failure probability P_f (Eq. (9)). R, G, and Q are resistance and loads represented as random variables, $z^* = z(\gamma_{\mathrm{m}}, \gamma_{\mathrm{G}}, \gamma_{\mathrm{Q}})$ is the design solution identified with Eq. (8) as a function of the selected partial safety factors, and X is the model uncertainty.

$$\begin{aligned} &P_f = P\{g(X,R,G,Q) < 0\} \\ \text{with} \quad &g(X,R,G,Q) = z^*XR - G - Q = 0 \end{aligned} \tag{9}$$

As an alternative to the failure probability P_f, structural reliability can be expressed with the so-called reliability index β (Eq. (10)). A common value for the yearly target reliability index is $\beta \approx 4.2$ which corresponds to a yearly probability of failure $P_f \approx 10^{-5}$ (JCSS (2001)). (Note that EN 1990 prescribes a yearly target reliability index of 4.7, design solutions according to existing codes, however, generally do not reach that high reliability).

$$\beta = -\Phi^{-1}(P_f) \tag{10}$$

In order to calibrate the partial safety factor, in general different design situations (different ratios between G and Q) are relevant. This can be considered using a modification of Eqs. (8)-(9) into Eqs. (11)-(12). a_i might take values between 0 and 1, representing different ratios of G and Q. $\hat{R}$, $\hat{G}$, and $\hat{Q}$ are normalized to a mean value of 1. For the calibration of the partial safety factors a range of $a = [0.1, 0.2, ...0.8]$ is typical, in order to exclude the rather unrealistic design situations with very small or large proportion of permanent load (less than 10% and more than 80%) from the optimization. For each a_i one design equations exist, thus altogether n different design equations are considered.

$$z_i\frac{\hat{R}_{\mathrm{k}}}{\gamma_{\mathrm{m}}} - \gamma_{\mathrm{G}}a_i\hat{G}_{\mathrm{k}} - \gamma_{\mathrm{Q}}(1-a_i)\hat{Q}_{\mathrm{k}} = 0 \tag{11}$$

$$g_i(X,\hat{R},\hat{G},\hat{Q}) = z_i^*X\hat{R} - a_i\hat{G} - (1-a_i)\hat{Q} = 0 \tag{12}$$

The partial safety factors ($\gamma_{\mathrm{m}}, \gamma_{\mathrm{G}}$, and γ_{Q}) can be calibrated by solving the optimisation problem given in Eq. (13).

$$\min_{\gamma}\left[\sum_{j=1}^{n}\left(\beta_{\mathrm{target}} - \beta_j\right)^2\right] \tag{13}$$

In this Section a simplified approach for reliability based code calibration is briefly introduced. Please find more information, e.g. in JCSS (2001) and Faber and Sørensen (2003). For timber specific examples see Kohler and Fink (2012, 2015a).

According to the philosophy of the Eurocodes the partial safety factors for the loads are material independent, thus the optimization is only subjected to γ_{m}.

In the current version of EC 5 one partial safety factor γ_{m} for each material property is given. However, it is well established, that the variability as well as the distribution function of the different failure scenarios are rather different (see e.g. JCSS (2006); Köhler (2006) and Section 5). For solid timber the influence was already investigated by Kohler and Fink (2015b,a) and indicates a significant over- and underestimation for different failure scenarios. However, following the principle of the Eurocode a target reliability has to be met for every individual failure mode.

6.2. Example

In the following the probability of failure P_f and the corresponding reliability index β (for bending) are presented following the simplified procedure introduced in Section 6.1. The out-of-plane bending strength is choosen as corresponding COV's are largest in comparison to other CLT strength properties as summarized in Table 3. Following the concept of Eurocodes partial safety factors sufficient for bending strength can be seen as conservative partial safety factor for all other investigated CLT strength properties. Due to similarities between CLT and GLT the same partial safety factor as proposed for GLT is assumed with $\gamma_{\mathrm{m}} = 1.25$. Furthermore, $\gamma_{\mathrm{G}} = 1.35$ and $\gamma_{\mathrm{Q}} = 1.5$ are applied.

As already indicated the variation of the material properties of the basic population of CLT can not be estimated precisely, as long as it is not a fully standardized product; including requirements for the production e.g. (EN 16351, 2015) and standardized test methods for the individual material properties.

In Figure 5 the results of the reliability analysis are illustrated for different COV's. Here the black dashed line illustrates the target reliability index $\beta = 4.2$.

The black line illustrates the reliability index for COV = 0.208, thus the overall variability of the six test series including the variability between different production series as described in Section 4.2.3. As already mentioned before this value might not represent the variability of the basic population of CLT (see Section 4.2.1). However, it might be seen as an upper bound. On average $\beta = 4.17$ is found which corresponds to a probability of failure $P_f = 1.5 \cdot 10^{-5}$, thus slightly above the target one. Using the simplified procedure introduced in Section 6.1 the optimized partial safety factor would be $\gamma_{\mathrm{m}} = 1.26$.

The solid gray line illustrates the reliability index in case of a smaller variablity COV = 0.15. Looking at the variabilities of the individual test series combined with the issues discussed in Section 4.2.1, such a variability seems to be realistic in case that the production of CLT is more standardized. From the line it becomes obvious that the reliability would be significantly overestimated. The optimized partial safety factor would be $\gamma_{\mathrm{m}} = 1.20$. The corresponding reliability for different load scenarios is illustrated in Figure 5 (gray dashed line). In this respect a smaller partial safety factor (e.g. $\gamma_{\mathrm{m}} = 1.20$) could be applied in the future, assuming the productions of CLT is more standardized and appropriate standardized test methods for the individual material properties exist.

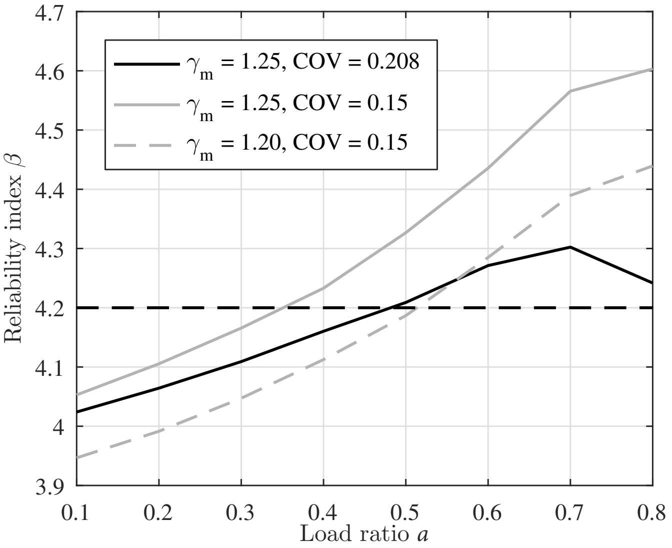

Figure 5: Reliability index β for different design situations α.

7. Conclusions & Outlook

The design of cross laminated timber structures (CLT) is not regulated in the current version of Eurocode 5. Due to the increasing importance of this large-dimensional plate-like, stand-alone structural timber product, in particular for the application in multi-story buildings, it is one of the main goals of Eurocode 5 to implement the design of CLT structures. In this present paper some general aspects, relevant for the implementation of CLT in European standards in order to be consistent with the general philosophy of the Eurocodes as prescribed in EN 1990 (2002) were summarized and discussed.

Although the production of CLT is meanwhile regulated on European level (EN 16351, 2015) current CLT producers still follow their individual approvals, thus the material properties of CLT as well as their variability cannot be described uniformly. In order to discuss the variability between different series and different producers 12 test series performed at Lignum Test Centre of the Institute of Timber Engineering and Wood Technology, Graz University of Technology, were investigated. The results clearly indicates a large variation between the different producers and production series.

For CLT a test standard is missing. Consequently, in the recent experimental investigations often, a relatively large amount of the tested specimens show failure modes different to the target ones. In this respect it is of particular importance that standardized test procedures for CLT will be developed were the investigated failure mode can be achieved with high probability.

As long as the CLT production is regulated by European technical assessments the variability of the basic population is rather large. Especially due to the large differences between the individual production series. However, assuming the overall variability identified for the out-of-plane bending strength a reliability analysis was performed. The results indicate that the same partial safety factor as recommended for glued laminated timber (GLT) $\gamma_{\mathrm{m}} = 1.25$ is appropriate in order to achieve an acceptable reliability. Furthermore, the analysis indicates that a smaller partial safety factor $\gamma_{\mathrm{m}} = 1.20$ could be applied in the future, assuming the productions of CLT is more standardized and appropriate standardized test methods for the individual material properties exist.

The investigation also indicates significant differences between the material properties of the individual test series. Furthermore, the mean densities of all test series were significantly larger compared to the target density defined in EN 338 (2016), which might be a result of the quality of the timber boards. This significant higher quality of the timber boards indicates that the laminations used for producing CLT can be associated with a higher strength class than declared by the producers. In order to identify the overall variability more realistically, additional investigations on randomly selected test series are needed. The same applies for the identification of the characteristic values of the respective material properties.

In absence of experimental investigations of the DOL effect for CLT it seems appropriate to assume a rather similar behavior for bending and tension as for GLT. However, this might be not true for other failure modes where also the long-term stress-strain behavior of the glue line is relevant.

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