Volume Effects in Glued Laminated Timber Beams

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ABSTRACT: This paper discusses several aspects related to volume effects on glued laminated timber (GLT) beams, with focus on the combined effects of height and length on the bending strength. Challenges related to the prediction of the mechanical properties of very large GLT beams using numerical models are discussed. If the exact lay-up of a GLT beam is not known (i.e. if there is no knowledge about local and global timber properties along boards and about finger joints), a large number of test results are needed to ensure a reliable validation of numerical models. A review of experimental research shows that the variability of bending strength and stiffness properties is significantly smaller for larger GLT beams. A simplified study on the effect of reduced material properties on the structural reliability of GLT beams is also presented.

1. INTRODUCTION

Timber is a naturally grown material and the mechanical properties of timber boards are partly characterised by large variation, within and between timber boards (e.g. Isaksson, 1999; Fink and Kohler, 2011; Brandner, 2013). The variation within timber boards results from local defects (typically knots and knot clusters) and the variation between boards results, in addition to knots, also from other anatomical characteristics, and the processing of the logs (e.g. fibre orientation, annual ring width, distance to pith and sawing pattern). To a certain degree, the variation of the mechanical properties is reduced by strength grading, through which boards are classified into strength classes according to certain strength-indicating properties and characteristics. A detailed summary of strength grading principles is given by Ridley-Ellis et al. (2016).

Glued laminated timber (GLT) is an engineered timber product composed out of layers of lengthwise finger-jointed timber boards (laminations) that are glued together on their side faces. GLT beams can be fabricated from timber boards of a single strength class (denoted ’h’ for homogenous) or from timber boards of two to three different strength classes (denoted ’c’ for combined). If timber boards from more than one strength class are used, the timber boards with the highest strength class are located in the outer zones of the elements, where bending stresses are expected to be higher. Compared to structural timber, GLT has several advantages, such as more homogenised properties, better dimensional stability and more geometrical possibilities, i.e. GLT members can be fabricated in larger dimensions. Nowadays, GLT beams with lengths significantly above 20 m and heights up to 3 m are fabricated.

The strength classes of GLT are mostly defined by its bending strength, which is highly related to the tensile strength of local weak areas in the outermost laminations, which are most likely to be under tensile stresses. The likelihood of local weak areas occurring increases with increasing beam dimensions and, therefore, the bending strength decreases with increasing volume on average (Thelandersson et al., 2003). However, it has also been observed that the influence of single local weak areas decreases with increasing beam dimensions, as a result of homogenisation (see e.g. Schickhofer et al., 1995; Fink et al., 2015b). As a naturally grown material, timber shows a larger variability of its material properties compared to other structural materials. In addition, the two above-mentioned opposing volume-related effects, i.e. higher probability of occurrence of weak zones and homogenisation, are particularly relevant for large-dimension GLT beams. Besides the natural variability of the mechanical properties also the material heterogeneity results in a size effect (see e.g. Bažant and Li, 1995). For GLT beams this effect was investigated in Blank et al. (2017), and was identified to be more relevant for smaller dimensions.

Volume effects can be determined experimentally, but the large dimensions of the elements that would have to be tested make this particularly difficult, which adds to the problem of the even larger number of experiments that would be required to assess the variability of the results.

An alternative approach to study volume effects in GLT beams are probabilistic simulation tools. The first model was developed by Foschi and Barrett (1980) and several models have been developed since then (e.g. Fink et al., 2015b; Frese and Blaß, 2016; Sieder and Brandner, 2022; Vida et al., 2022). The principle of all those models is similar: At first, the lay-ups of individual GLT beams are simulated by means of probabilistic models. Afterwards, the mechanical properties of the simulated GLT beams are estimated using mechanical models. The validation of the these models can be done by different approaches: (i) if the exact lay-up of the individual experimentally tested GLT beams is known (e.g. Colling, 1990; Fink et al., 2015a, 2021), a mechanical model that takes into account the mechanical properties of each segment of each lamination can be directly validated against the test results. This approach requires a relatively limited number of test results, but the experiments are significantly more labour-intensive, since the properties of each timber board have to be thoroughly documented; (ii) if only the strength grade and finger joint (FJ) quality of the tested GLT beams is known, as is often the case, a mechanical model that takes into account the mechanical properties of each segment of each lamination cannot be directly validated against the experimental results. Nevertheless, the statistics of the test results (e.g. mean value, coefficient of variation and quantiles) can be used, to some extent, to validate the entire probabilistic-numerical tool (including the model to simulate the timber boards and the numerical model). However, a relatively large number of tests would be required in this case.

Simulation models are an efficient tool to study the influence of size effects, but due to the above-mentioned issues, quantitative analyses are still associated with large uncertainties, especially for very large beams, where detailed experimental data is particularly scarce and model validation is very difficult. Therefore, it is not surprising that the different models give different results, even though they all show a reduced strength and a reduced variability for larger GLT beams. These two effects influence the characteristic 5^{th}-percentile value in opposite directions.

Discussions on the influence of volume effects on the strength of GLT beams are often limited to their influence on the 5^{th}-percentile value, which is the standard value for structural design practice. However, the reduced variability influences the structural reliability and should also be considered. This paper focuses on the effects in conjunction with the reduced variability.

2. LITERATURE REVIEW – EXPERIMENTAL RESEARCH

The material properties of GLT have been investigated for many decades and large data sets are available. However, the available data are only comparable to a limited extent, since many parameters are different between the various different studies, which makes it difficult to establish a baseline from which to make comparisons. Examples are:

- *Wood species:* GLT beams produced from different wood species. In Europe, most of the studies were performed on GLT made of Norway spruce (*Picea abies* (L.) H. Karst.).
- *Material source:* GLT beams made from timber boards sourced from different origins and with different quality. This includes different strength grades (results in GLT beams of different strength classes), different growing regions of the boards, different cross-sectional dimensions of the boards, different grading procedures and devices used for the classification, as well as different grading settings.
- *Finger-joint (FJ) quality:* Even though there are specific production requirements for FJs that try to ensure minimum strengths, their actual strength might be different between the individual studies, since the GLT beams were fabricated by different producers and using different equipment. Furthermore, it is reasonable to assume that the quality of FJs has changed over time and the strength of FJs being produced today might be different from that of FJs produced decades ago.
- *Timber board length:* The average length of the timber boards varies, resulting in a different amount of FJs, e.g. per one meter length of lamination. This might be of particular importance for higher strength classes, for which the strength of FJs might become more relevant.
- *GLT layup:* Some studies were performed on GLT beams with homogeneous and others with combined symmetric / asymmetric layup.
- *Dimensions & test setup:* GLT beams with different dimensions have been investigated. Most studies have been performed according to the European Standard EN 408 (2003), i.e. via a four-point bending test setup, resulting in similar length l to height h ratios and similar lengths under a constant maximal bending moment (area between the loading points).
- *Sample size:* The number of tested beams also varies significantly between the studies.

It has also to be considered that experimental investigations are performed to answer specific questions and the corresponding studied parameters sometimes do not allow for the results to be quantitatively compared to other studies. E.g. Ehlbeck and Colling (1987) tested 52 GLT beams with different dimensions and, in most of those beams, there were no FJs in the central zone under constant maximal bending moment; Gehri (1992) also tested beams without FJs (no strength values were available). It also has to be considered that, especially in older studies, the test results, test setup, grading procedure, etc. are often not or only partly documented (e.g. Gehri, 1995; Kolb and Frech, 1977).

Therefore, the studies presented in Table 1 are limited to experimental investigations on:

- GLT beams fabricated from graded timber boards;
- GLT beams made from Norway spruce (*Picea abies* (L.) H. Karst.);
- GLT beams where the bending strength and bending stiffness are documented; and
- GLT beams tested in edgewise bending with similar test setups, i.e. beams shapes and loading configuration.

Considering the diversity of input parameters (e.g. strength class) a comparison of the absolute values is not possible here without any data modification. Anyhow, in the present study, the focus was on the variation. Figure 1 shows the coefficients of variation (COVs; calculated according to Eq. 1) of the experimental investigations summarised in Table 1.

$$COV = \frac{\sigma}{\mu} \quad \text{with} \quad \sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2} \tag{1}$$

where μ and σ are the estimated mean value and the standard deviation of the investigated material property $\mathbf{X}$ (here f_m and E_m). X_i is the measured value, $\bar{X}$ is the mean value of a test series and n is the sample size of the test series. It has to be noted that some of the data sets containing large

Table 1: Overview of experimental data considered in this study.

Study	Number of beams	Span [mm]	Beam height [mm]	Strength class[a]
Falk et al. (1992)	104	5400	300	-
	96	5400	300	-
	112	5400	300	-
Schickhofer et al. (1995)	23	5310	297	1010
	30	5310	297	1313
	20	5310	297	1717
	20	5310	297	1310
	22	5310	297	1713
	10	9504	594	1010
	18	9504	594	1717
Aasheim and Solli (1995)	24	5400	300	-
	20	10800	600	-
Brandner et al. (2008)[b]	25	9000	600	GL36h
	5	9000	600	GL36c
Frese and Blaß (2009)[c]	7	9000	600	GL32c
	7	9000	600	GL32c+
	5	9000	600	GL32c
	7	9000	600	GL36c
	7	9000	600	GL36c+
	5	9000	600	GL36c
Brandner and Schickhofer (2010)	24	2880	160	GL24h
	25	5760	320	GL24h
	25	5760	320	GL24h
	25	5760	320	GL28h
Frese et al. (2010)[b]	20	10800	600	GL32c
	20	10800	600	GL36c
Fink et al. (2015a)	12	5680	320	GL24h
	12	5680	320	GL36h
Kandler et al. (2018)	10	2340	132	-
	10	2340	132	-
	10	4140	231	-
	10	5200	330	-
	10	5200	330	-
Fink et al. (2021)	4	10960	600	GL24h
	2	18160	1000	GL24h
	4	10960	600	GL32h
	2	18160	1000	GL32h

[a] As given by each specific study.
[b] 5 of the GLT beams failed in shear.
[c] Values taken from Blaß et al. (2009).

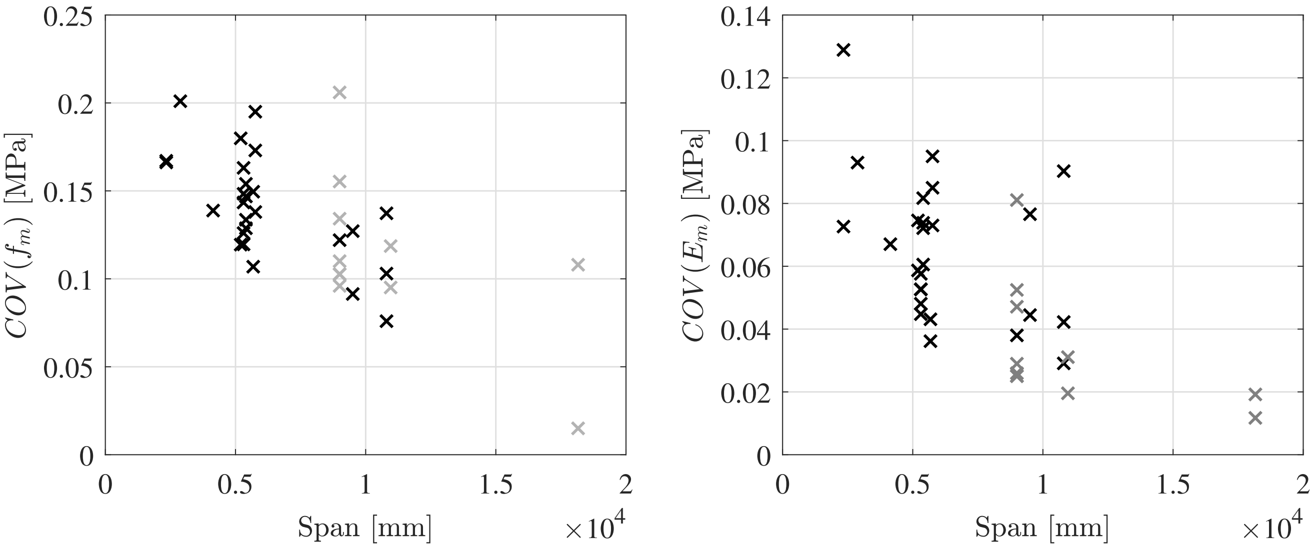

Figure 1: Coefficient of variation of the bending strength and bending modulus of elasticity of edgewise loaded GLT beams of each configuration presented in Table 1. Grey crosses represent configurations for which the sample size is $n < 10$.

GLT beams are very small and, therefore, the variation might be slightly underestimated. Also different variations between strength classes (resulting from the different variation of the timber board properties) might be expected, which are not represented here. However, the reduction of the COV with increasing beam dimensions, i.e. span and height, which are both coupled by the definition of the test configuration, is clear, for both the bending strength f_m and the bending modulus of elasticity E_m. Even though only a very limited number of experimental investigations for larger GLT beams exist, it seems to be likely that the variation will become even smaller for very large GLT beams. At this point, it has to be mentioned that the variation presented in this study presents only the variation of individual test batches. In practice, however, additional variation such as, e.g., the variation between batches from one single producer or the variation between different producers needs to be considered (for more details it is refered to (Fink et al., 2018).

3. STRUCTURAL RELIABILITY – BASED ON THE EUROCODE'S SAFETY CONCEPT

According to FprEN 1990 (2022) (Annex C), a direct correspondence between the design value and the reliability requirements may be established for simple cases. The design value y_d for a Log-Normal distributed variable is

$$y_\mathrm{d} = \mu_\mathrm{Y} \cdot \mathrm{e}^{\left(-\frac{1}{2}\ln\left(1+COV_\mathrm{Y}^2\right) - \alpha_Y \beta_t \sqrt{\ln\left(1+COV_\mathrm{Y}^2\right)}\right)} \quad (2)$$

which for $V_\mathrm{Y} < 0.2$ can be simplified as[1]

$$y_\mathrm{d} \approx \mu_\mathrm{Y} \cdot \mathrm{e}^{(-\alpha_\mathrm{Y} \cdot \beta_\mathrm{t} \cdot COV_\mathrm{Y})} \quad (3)$$

where μ_Y is the mean value, COV_Y is the coefficient of variation, α_Y is the sensitivity factor indicating the importance of Y in the reliability estimation, and β_t is the target value for the reliability index specifying the reliability requirement.

Figure 2 shows the design value of y_d as a function of μ_Y and COV, assuming a sensitivity factor $\alpha = 0.8$, which is a valid approximation for a 50-year reference period under certain conditions (FprEN 1990:2022, Annex C) and a target reliability for a building in *consequence class* CC2 and 50-year reference period $\beta_{50\text{-year}} = 3.8$ (FprEN 1990 (2022), Annex C).

A lower mean strength results in a lower design value, whereas a reduced variability results in a higher one. In the following the reference case $y_\mathrm{d,ref}$ is defined with $h = 600$ mm and $COV = 0.15$. It

[1] which is also expressed in EN 1990 (2002) (Annex C)

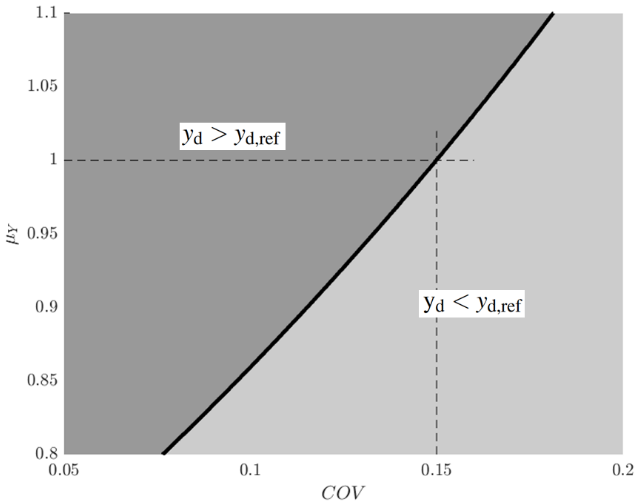

Figure 2: Design value y_d as a function of μ_Y and COV.

has to be noted that if $y_d \geq y_{d,ref}$ (dark grey area in Figure 2) the design would be conservative even without considering a height effect, or a combined length and height effect as identified in this study. Otherwise if $y_d < y_{d,ref}$ a height effect would be required. The Figure shows that GLT beams with a smaller variation of the bending strength can result in a similar or even higher reliability even if the mean value of the bending strength is smaller. However, it has to be considered that the presented approach is very simplified.

It should also be noted that very large GLT beams are often realised in structures that are associated to large consequences in case of a failure and for which a higher target reliability is proposed. This is also reflected in Eurocodes via consequence classes, e.g. by multiplying the loads by a factor k_F=1.1. In those cases, the positive effect of the reduced variability might be even more pronounced.

4. CONCLUSIONS

In this paper the focus is on the influence of the volume effect on the structural reliability. This paper addresses the difficulties regarding the validation of the mechanical properties for very large GLT beams: Experimentally, reliable validations are not possible due to the large number of influencing parameters. But also with probabilistic-numerical simulation models, the effect can only be illustrated with large uncertainties, mainly due to the complexity of the model validation for larger beams.

A review of experimental studies shows that the variability of both bending strength and stiffness is significantly reduced for larger, i.e. longer and higher GLT beams. Even though, only a very limited number of experimental investigations on larger GLT beams exists, it seems to be likely that the variability might be even smaller for very large GLT beams.

The paper concludes with a short simplified study on the effect of reduced material properties on the structural reliability, showing that the effect of reduced mean strength properties can be compensated by a smaller variability. For detailed conclusions, however, further aspects need to be considered.

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