GLUED LAMINATED TIMBER IN BENDING: THOUGHTS, EXPERIMENTS, MODELS AND VERIFICATION

Reinhard Brandner[1], Gerhard Schickhofer[2]

ABSTRACT: The paper concentrates on the "bearing model for glued laminated timber (glulam, GLT) in bending. Starting with a general overview concerning the derivation of essential model parameters, the necessity of a new model for the characterisation of the bending capacity of GLT as a system based on the characteristics of the system elements board and finger joint as well as the adhesive is pointed out. The herein derived model consists of simple stochastic considerations which are manifested by a huge amount and intensive examination of test samples on boards and finger joints in tension as well as hence build up GLT-beams in bending. The verification of the derived model(s) is accomplished by practical test samples and additional by a comparison with so far internationally published bearing models for GLT in bending, collected during an intensive literature study. As a conclusion, the paper clearly demonstrates the necessity of consideration of stochastics and especially on the main describing characteristics like the representative distribution model and its parameters, the expected value as well as a measurement concerning the deviation (dispersion) of strength and other characteristics of interest.

KEYWORDS: glued laminated timber, glulam, bearing model for GLT in bending, stochastics, representative distribution model, expectable distribution parameters

1 INTRODUCTION

Glued laminated timber (GLT, glulam) is probably the best known engineered wood product (EWP) and as linear structural member wide applied in timber engineering. First applications started in the 18th and 19th century and upturned immediately with the development of heavy-duty adhesives for interior and exterior dispositions. GLT, nearly exclusive made of Norway Spruce or SPF (spruce-pine-fir), reached wide establishment and encouraged producers, engineers and researchers to establish international standardisation regarding its physical potential, production requirements and its design. For the characterisation of the physical-mechanical potential of GLT, solely on the knowledge of the potential of the components boards and finger joints, modelling of relationships between the components and the system properties became necessary.

Over the last decades codles of researchers put in their energy and thoughts to establish straight-forward and engineer-capable models, mainly the "bearing model for GLT in bending" (BMB-GLT). Up to now, as present in the revision process of the European Standard prEN 14080 for GLT, numerous models and sub-models of researchers and much more thoughts are given, but a final decision is still lacking.

The aim of this work and the contribution by this paper emphasises on a large research project consisting of intensive literature study concerning the BMB-GLT and an investigation of so far internally available test results of about 2,000 tension tests on boards, few hundred tension tests on finger joints and about 300 bending tests on GLT-beams. The aim of the first step is to make a comparison of all models and test results available. The second step covers the establishment of a straight-forward "bearing model for GLT in bending", based on the knowledge of the expectable stochastic parameter field gained from external and internal tests on boards, finger joints and hence build up GLT. The new bearing model for GLT in bending is thereby split up in two sub-models, first describing the relationship between the tensile strength of the boards with the bending strength of hence build up GLT, and second regarding regulations as minimum requirements concerning the finger joint tensile strength in relation to tensile strength of the jointed boards. The conclusive third step deals with the verification of the models by comparison with present and past models and by confrontation with new test series conducted during the research project. Finally, a proposal for standardisation is presented.

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[1] Reinhard Brandner, Institute for Timber Engineering and Wood Technology, Graz University of Technology | Competence Centre holz.bau forschungs gmbh Graz, Inffeldgasse 24/I, 8010 Graz, Austria. Email: reinhard.brandner@tugraz.at

[2] Gerhard Schickhofer, Institute for Timber Engineering and Wood Technology, Graz University of Technology | Competence Centre holz.bau forschungs gmbh Graz, Inffeldgasse 24/I, 8010 Graz, Austria. Email: gerhard.schickhofer@tugraz.at

2 DERIVATION OF MODELLING PARAMETERS – SOME GENERAL THOUGHTS AND REFERENCES

The "bearing model for GLT in bending" (BMB-GLT) is the prime model for the characterisation of GLT on the basis of the characteristic properties of the base material. The model serves for the determination of the characteristic bending strength of GLT under edgewise loading ($f_{m,g,k}$) which corresponds to a beam in bending as the main loading situation. Based on the fact that the GLT-beam in bending predominantly fails in the flexural tensile zone (before or even after a possible failure in the flexural compression zone; shear failures are not considered) the characteristic tensile strength of the GLT-lamella in grain direction ($f_{t,0,lam}$) is the most decisive parameter for the bearing model for GLT in bending. Thereby, the GLT-lamellas themselves form a serial sub-system, consisting of board-segments and finger joints as elements of the system structure GLT. Due to the statically indetermined internal structure and the stochastics of the local stiffness and strength values the interaction of the elements in the rigid composite system structure GLT enforces, amongst other characteristic properties, homogenisation effects in the strengths. In the frame of the BMB-GLT these homogenisation effects are generally named as "laminating effect" and defined by $\lambda = f_{m,g} / f_{t,0,l}$ which can be defined on the mean- (λ_{mean}), 5 %-quantile- (λ_{05}) or other statistical levels. The main reasons for the activation of these compensation effects are described amongst others in [1] and will be amended and discussed briefly:

- compensation, due to a lower tensile bearing capacity in case of testing a single board in comparison to a board embedded in the rigid composite of a GLT-beam, as a result of moment-axial-force-interaction initiated by eccentricities (because of local stiffness variations within the cross sections) in the "un-guided" tensile test in contrast to the "guided" loading of the board within the moment-tensile-zone of the GLT-beam tested in bending;
- compensation, due to the reinforcement of local growth characteristics by adjacent clear wood board segments and / or stiffer elements with expected higher strength capacities (→ system effect / group effect) of boards in the rigid composite GLT;
- compensation with increasing system size, due to the decreasing probability of the occurrence of board segments with a low strength potential in the highly stressed moment-tensile-zone of the GLT-beam.

While the first sub-effect can be traced back to the variability of stiffness and strength characteristics within the elements, the variability between the elements is decisive for the contribution to the laminating effect resulting from the last two listed sub-effects. All three sub-effects depend on the dispersion and / or the relation between the stiffness and the strength properties, and increase with increasing variability within and / or between the elements. Due to that, a higher laminating effect can be expected in case of GLT built up of ungraded board material, material graded in only one or few strength classes (exclusive reject) (→ expectable high to middle variability between the boards) or board material of lower strength classes (→ expectable high variability within the boards) than it can be expected for GLT build up of selectively classified board material or boards of the highest strength classes (→ almost free of growth characteristics (clear wood)). As a consequence, the representative distribution models (RSDMs), the variability, the dispersion of strength and stiffness within and between boards as well as the relationships between them, expressed in auto-correlation and cross-correlation coefficients respectively, are essential and define important model parameters for virtual representation of the laminating effect behaviour.

Due to lack of sufficient own test results and scarce literature for clarifying the internal variability of the tensile strength and stiffness within the boards (some input available in [2-6]) a full stochastic process including all above input parameters can not be presented now but is still in progress. Nevertheless, the herein discussed model bases on high sophisticated statistical evaluation of a huge amount of confirmed internal and external data sets and includes all necessary statistics for representing the RSDMs, the expectable dispersions as well as the relationships between the tensile strength of the lamella (boards + finger joints) and the bending strength of the hence build up GLT.
First of all, the state of the art till 2007 of so far investigated internationally BMB-GLT are discussed before as second step, internal and external data sets concerning the tensile strength of boards and hence build up GLT-beams tested in bending are listed and prepared for the further statistical evaluations.

2.1 STATE OF THE ART OF BMB-GLT

As part of the research project all so far available internationally published BMB-GLT till 2007 were investigated. For comparability and in reference to the current European GLT-standard EN 1194 all these models were, if necessary, transformed to the reference dimensions of the boards (w_l = 150 mm, t_l = 40 mm, l_l = 2,000 mm) and GLT-beams (d_g = 600 mm, w_g = 150 mm) by means of the equations (1-2). As a consequence, all further test results for the derivation and verification of the new BMB-GLT are transformed in respect to this reference dimensions.

$$k_{size,l} = \left(\frac{w}{150}\right)^{0.10} \cdot \left(\frac{l}{2{,}000}\right)^{0.10} \tag{1}$$

$$k_{size,g} = \left(\frac{w}{150}\right)^{0.05} \cdot \left(\frac{d}{600}\right)^{0.10} \tag{2}$$

The investigated nationally and internationally published BMB-GLT with focus on the relationship of the board tensile strength vs. the bending strength of GLT are given in Figure 1 (for further details see [7]). The diagram illustrates the range and diversity of these models. For clarification: according to the investigated models, GLT of strength class GL24h and GL32h (acc. EN 1194) can be theoretically build up with boards of a characteristic tensile strength in the range of $f_{t,0,l,05}$ = [11 ÷ 18] N/mm² and $f_{t,0,l,05}$ = [17 ÷ 26] N/mm², respectively. The answer of the question which may cause these remarkable deviations within the models still remains. Nevertheless, the deviations indicate the necessity of further parameters to describe the relationship $f_{m,g}$ vs. $f_{t,0,l}$ which have not been considered up to now.

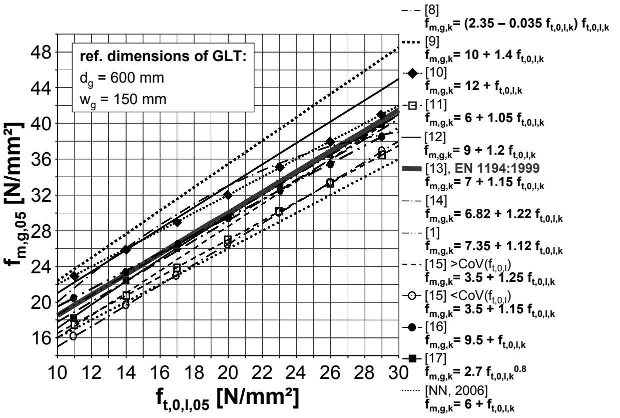

Figure 1: *Investigated BMB-GLT in regard the relationship of the tensile strength of the boards vs. the bending strength of GLT*

One kind of these potential parameters is seen in the dispersion of the strength values, especially in the dispersion of the base material which corresponds – as briefly discussed above – with the homogenisation potential due to the rigid composite action. The further research on this topic concentrates on the derivation of influences of the primal dispersion on the expectable characteristic bending potential of GLT. This appears logical and trivial at the same time due to the fact that the 5 %-quantile of a variate is calculated by means of parameters of the location (e.g. expected value) and the shape (e.g. dispersion value like the coefficient of variation $CoV(X)$) and a distribution dependent factor k_{05} (e.g. k_{05} = 1.645 in case of a ND-variate) as given in (3-5).

$$X_{05} = \mu - k_{05} \cdot \sigma = \mu \cdot \left(1 - k_{05} \cdot CoV(X)\right) \tag{3}$$

with

$$P\left(x \le X_{05}\right) \ge 5\% \tag{4}$$

and

$$\sigma = \mu \cdot CoV(X). \tag{5}$$

On the basis of internal and external data presented hereafter expectable coefficients of variation for the tensile strength of boards and finger joints, $CoV(f_{t,0,l})$ and $CoV(f_{t,j})$ respectively, and the bending strength of GLT, $CoV(f_{m,g})$, are investigated. Further more, relationships between the characteristics are analysed by means of regression analysis, under consideration of boarder conditions and inclusion of experiences.

2.2 DATA BASIS: INTERNAL AND EXTERNAL DATA SETS

First of all and for clarification: all internal data sets were performed on boards and GLT-beams of Norway Spruce (*Picea abies Karst.*) and in accordance with the regulations given in EN 408 and EN 1194.

Table 1: *Internal data of boards tested in tension*

project no. [--]	**dimensions** l / w / t [mm/mm/mm]	**nominal grade(s)** (acc. DIN 4074) [--]	**sample size** [--]
p_1#-I [18]	4,000 / 160 / 32	MS10, MS13, MS17	120 #
p_1#-II [18]	4,000 / 170 / 36	MS7, MS10, MS13, MS17	217 #
p_2# [19]	4,000 / 155 / 37	MS10, MS13, MS17	144 #
p_3# [20a-c]	4,000 / 108 / 43	MS10, MS13, MS17	385 #
p_4# [21]	4,000 / 150 / 26	MS7, MS10, MS13	60 #
p_5# [22]	3,000 / 175 / 40	3 rigidity grades	90 #
p_6# [23]	3,000 / 170 / 43	MS10, MS13, MS17	392 #
	total (boards)		**1,408 #**

Table 2: *Internal data of GLT-beams tested in bending*

project no. [--]	**dim.** w / d [mm]	**nominal grade(s)** (acc. DIN 4074) [--]	**sample size** GLT / boards [--]
p_1#-01 [18]	160 / 300	MS10	21 # / 71 #
p_1#-02 [18]	160 / 300	MS13	27 # / 64 #
p_1#-03 [18]	160 / 300	MS17	14 # / 69 #
p_1#-04 [18]	160 / 300	MS13 / MS10	20 # / 64 #
p_1#-05 [18]	160 / 300	MS17 / MS13	16 # / 69 #
p_1#-06 [18]	160 / 600	MS10	10 # / 71 #
p_1#-07 [18]	160 / 600	MS17	14 # / 69 #
p_2# [19]	150 / 300	MS17	15 # / 68 #
p_3#-01 [20a-c]	90 / 300	MS17 / MS13 / MS10	16 # / 40 #
p_3#-02 [20a-c]	45 / 300	MS17 / MS13 / MS10	24 # / 40 #
	total (GLT-beams)		**177 #**
	average quantity of tested boards per GLT-series		62 #

Table 1 and Table 2 list the internal data of tensile tests on boards and bending tests on GLT investigated in the further statistical analysis. Approximately 1,400 boards of seven series of six different projects tested between 1994 and 2006, with an average weighted cross section of $w / t = 150 / 39$ mm and an average weighted free testing length of $l_0 = 3{,}000$ mm are considered. All boards were strength or stiffness machine graded. Concerning the GLT-beams, approximately 180 beams of three projects and in total six sub-series, only considering GLT-beams without a failure initiated by a finger joint, with the background-knowledge of the tensile capacity of the board material are included in the further studies. The average weighted coefficient of variation of the boards' tensile strength and the bending strength of the GLT-beams was $CoV(f_{t,0,l}) = 27.2$ % and $CoV(f_{m,g}) = 14.6$ %, respectively. Additionally, external data from [10,11,24] referenced in [1], were taken into account.

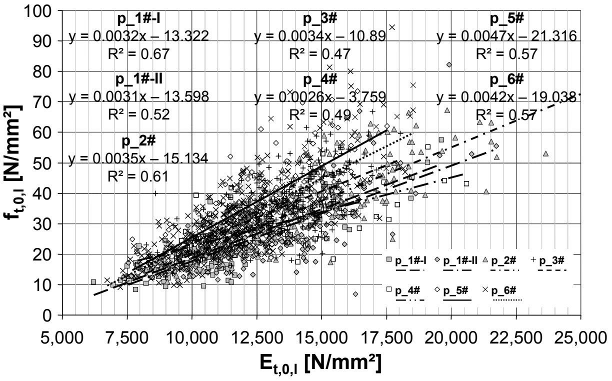

Figure 2: *$f_{t,0,l}$ vs. $E_{t,0,l}$: internal data, 7 series of 6 projects*

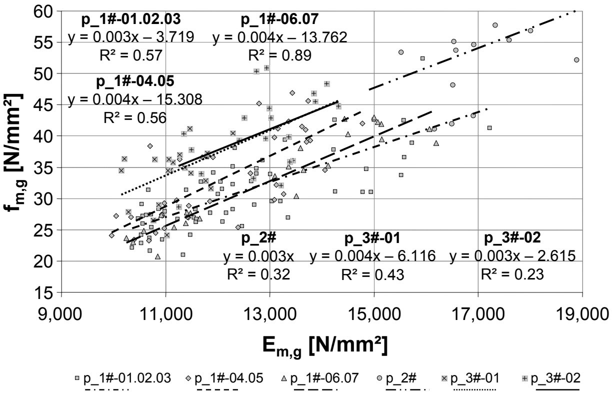

Figure 3: *$f_{m,g}$ vs. $E_{m,g}$: internal data, 6 series of 3 projects*

Figure 2 and Figure 3 show the relationships between strength and stiffness of the data pairs $f_{t,0,l}$ vs. $E_{t,0,l}$ and $f_{m,g}$ vs. $E_{m,g}$. As one outcome of the statistical analysis the tensile E-modulus and the tensile strength of the boards can be well presented by means of a two-parametric lognormal distribution (2pLND) as RSDM whereas the bending strength of GLT can be modelled by means of the normal distribution (ND). As a consequence of the skewed distributions of the tensile properties Figure 2 shows a more funnel-shaped scatter for the data pairs of $f_{t,0,l}$ vs. $E_{t,0,l}$ whereas Figure 3 illustrates the more or less uniform distribution and the nearly parallel linear regression lines of the various data sets of the relationship $f_{m,g}$ vs. $E_{m,g}$ resulting from the averaging effects due to the rigid composite action within the GLT-beam. This essential information will be applied in the further considerations.

3 DERIVATION OF A NEW "BEARING MODEL FOR GLT IN BENDING"

As already discussed in chapter 2 the laminating effect, as parameter for the expression of the homogenisation potential of the board material and lamellas bonded in the rigid composite structure GLT, primarily depends on the interaction within the lamellas, boards and board segments and hence on the dispersion within and between the system components. As a consequence, the laminating effect can be seen as an interaction of serial and parallel system effects, as a combination of effects in relation to dimensional changes (k_{size}, etc.) and group effects (e.g. k_{sys}). As for example: someone may wonder itself about the mentioned homogenisation potential by comparing the characteristic bending strength of boards and that of GLT build up of the same class of boards, e.g. boards of C24 acc. EN 338 with $f_{m,l,k} = 24$ N/mm² and hence build up GLT-beams of GL24h acc. EN 1194 with $f_{m,g,k} = 24$ N/mm². Here, the associated reference dimensions have to be taken into account! To clarify the above statements concerning the laminating effect satisfactorily further investigations are necessary concerning the sufficient clarification of serial and parallel system actions and related effects in the system structure GLT under bending stress. In the meantime a statistical analysis by means of RSDMs, regression analysis and further statistical tools, under consideration of boarder conditions, was performed.

Within the further discussions, the BMB-GLT is examined by splitting it up into two sub-models. The first model regards the "requirements for the board material" and the second model regards the "minimum requirements for the finger joints" necessary in order to achieve GLT of a specified strength class. Under consideration of external test series (e.g. [1]) RSDMs and expectable ranges of the distribution parameters – especially the coefficients of variation of the strength values ($CoV(f_{t,0,l})$, $CoV(f_{t,j})$ and $CoV(f_{m,g})$) – were determined. According the above findings the 2pLND was identified as RSDM for characterising the tensile strength parallel to grain of the board material and the tensile strength of the finger joints, whereas, due to the homogenisation effects, the ND was selected as representative model describing the distribution of the bending strength of GLT-beams tested edgewise.

3.1 TENSILE STRENGTH REQUIREMENTS ON THE BASE MATERIAL BOARD

On the basis of the conclusions gained so far, the relationship between the bending strength of GLT ($f_{m,g,mean}$) and the tensile strength of the board material ($f_{t,0,l,mean}$) was analysed by means of the regression analysis on the statistical more stable mean level. For support of the decision process concerning which regression model should be applied to represent the relationship best following boarder conditions and constraints were taken into consideration:

- if the board tensile strength on the mean level tends to zero the same holds true for the corresponding GLT bending strength

$$f_{t,0,l,mean} = 0 \rightarrow f_{m,g,mean} = 0\,, \qquad (6)$$

- if the board tensile strength on the mean level tends to infinity the same is assumed for the corresponding GLT bending strength

$$f_{t,0,l,mean} = \infty \rightarrow f_{m,g,mean} = \infty\,, \qquad (7)$$

- due to with increasing strength class higher homogenisation in the base material the relationship between GLT bending strength and tensile strength of the boards, the laminating effect, decreases.

As a consequence, the model expressing the requirements on the tensile strength on the board material to satisfy a certain bending strength of the corresponding GLT is modelled as a function of the RSDMs, the means and the dispersion of the strengths, $CoV(f_{t,0,l})$ and $CoV(f_{m,g})$.

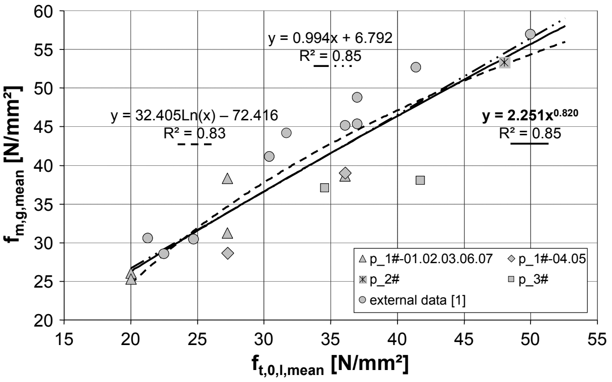

Figure 4: *$f_{m,g,mean}$ vs. $f_{t,0,l,mean}$ considering internal and external data sets; various regression models*

In a further step of the modelling process the relationship $f_{m,g,mean}$ vs. $f_{t,0,l,mean}$ was examined by means of a linear, a logarithmic and a power regression model (Figure 4). Due to the above constraints and boarder conditions the power regression model as given in (8) was preferred for the further examinations, which is in addition in principle in line with the work of [17].

$$f_{m,g,mean} = 2.251 \cdot f_{t,0,l,mean}^{\;0.82} \qquad (8)$$

The chosen power model was in addition supported by an applied section wise regression analysis and is in general an already wide applied model type for the description of size effects or the relationship ($f_{t,0,k}$ / $f_{m,k}$) vs. $f_{m,k}$ acc. to [25], both contributing to the laminating effect.

The next step was to analyse the dependency of $CoV(f_{m,g})$ vs. $CoV(f_{t,0,l})$ as shown in Figure 5. On the basis of internal data sets no significant relationship can be demonstrated. As a consequence and in line with the expectations, the higher the dispersion of the board's tensile strength, the higher the homogenisation potential and the influence on the laminating effect due to the activated rigid composite action. Consequently, the dispersions of $f_{m,g}$ and $f_{t,0,l}$, $CoV(f_{t,0,l})$ and $CoV(f_{m,g})$ respectively, can be treated as independent of each other.

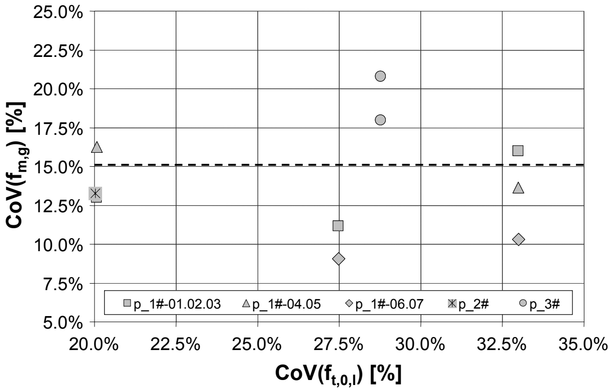

Figure 5: *$CoV(f_{m,g})$ vs. $CoV(f_{t,0,l})$, internal data*

In a further step the expectable ranges of the dispersions $CoV(f_{t,0,l})$ and $CoV(f_{m,g})$ were examined and investigated under consideration of available publications. Based on internal data sets and on the publications of [26] as well as of [27] the expectable $CoV(f_{t,0,l})$ for visual or machine graded board material lies in between $CoV(f_{t,0,l}) = (30 \pm 10(15))$ %. Visual graded boards can be – due to lack of sensitivity of limited grading parameters – classified in the range of $CoV(f_{t,0,l}) = (35 \pm 5)$ %. This range has to be additionally assumed for in only one to two classes machine graded boards (reject disregarded). In case of in more than one or two classes machine graded material the dispersion can be assumed in the range of $CoV(f_{t,0,l}) = (25 \pm 5)$ %. Due to markedly selection similar can be assumed for board material of the highest strength classes. For comparison, the dispersion of the bending strength of GLT-beams in reference dimensions is given with $CoV(f_{m,g}) = (15 \pm 5)$ %.

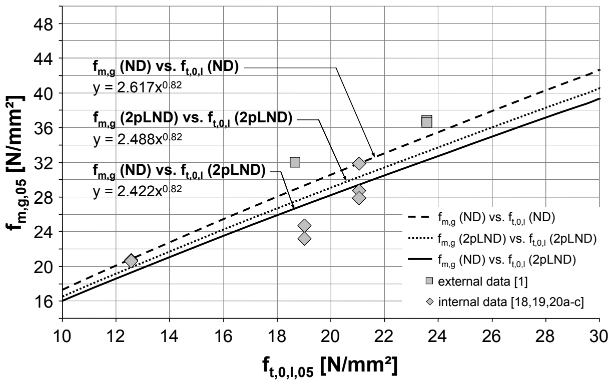

Figure 6: *$f_{m,g,05}$ vs. $f_{t,0,l,05}$ with $CoV(f_{m,g})$ = 15 % and $CoV(f_{t,0,l})$ = 25 %: influence of RSDM; comparison with internal and external data*

Under consideration of the expectable ranges of dispersions of both strengths, $CoV(f_{m,g})$ and $CoV(f_{t,0,l})$, and the corresponding RSDMs for $f_{m,g}$ and $f_{t,0,l}$ the mean-power-function-model $f_{\mathrm{m,g,mean}}$ vs. $f_{\mathrm{t,0,l,mean}}$ was transferred to the 5 %-quantile-level, $f_{\mathrm{m,g,05}}$ vs. $f_{\mathrm{t,0,l,05}}$. Further more, the influence of the RSDM on the transformation process was studied and is shown in Figure 6. The expectable RSDMs for the bending strength of GLT and the tensile strength of the boards, ND and 2pLND respectively, are in line with the results of the statistical analysis and additionally in comparison to the other RSDM-combinations on the safe side. The main results for the model $f_{\mathrm{m,g,05}}$ vs. $f_{\mathrm{t,0,l,05}}$ are given in (9-11).

$$f_{m,g,05} = m \cdot f_{t,0,l,05}{}^{0.82}, \tag{9}$$

with

$$m = 1.67 \cdot \exp\left(1.48 \cdot CoV\left(f_{t,0,l}\right)\right) \tag{10}$$

and

$$CoV\left(f_{m,g}\right) = 15\%. \tag{11}$$

A comparison of the investigated bearing models with the new model, as a first verification of this sub-model, with the expectable dispersions $CoV(f_{\mathrm{t,0,l}}) = (30 \pm 10)$ % and $CoV(f_{\mathrm{m,g}}) = (15 \pm 5)$ % provides one possible explanation for the diversity of the investigated models. Nearly all “bearing models for GLT in bending” investigated are already covered by the new model when a $CoV(f_{\mathrm{t,0,l}}) = (30 \pm 10)$ % and $CoV(f_{\mathrm{m,g}}) = 15$ % are considered (see Figure 7).

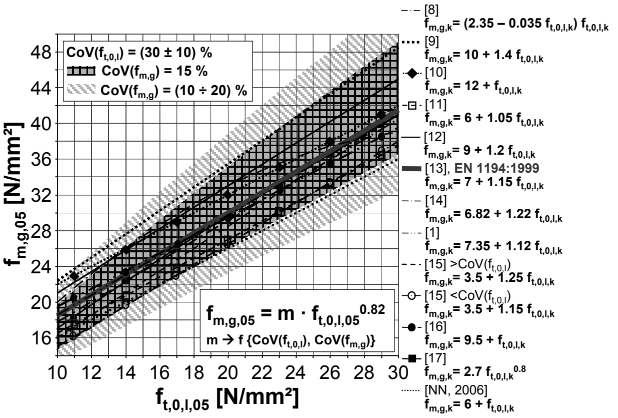

***Figure 7:** Comparison of the new “bearing model for GLT in bending” with internationally investigated bearing models under consideration of stochastics (see [7])*

3.2 MINIMUM TENSILE STRENGTH REQUIREMENTS ON THE FINGER JOINTS

The performance of finger joints under tensile load parallel to grain is primarily dependent on the performance of the jointed components, the adhesive and the production quality. The potential of the finger joints in dependency of the jointed components is according to the “weakest link theory” in particular constrained by the performance of the weaker jointed component. As a consequence, the finger joint connection itself represents a serial system with $n = 2$ #. Furthermore, the production quality is generally governed by a complex of production process parameters and consequently in close relation to the performance of the individual manufacturer. In this respect it is proposed to define minimum requirements for the finger joint tensile strength, coupled with the GLT-strength class system, which is already in line with the standards e.g. EN 1194.

For the optimisation of the performance, the finger joints shall be placed in the “clear wood” section of the jointed components. In order to optimise the strength potential of the GLT-lamella the “mean” finger joint strength needs to be at least equal to the “mean” strength potential of the board-elements which is represented – through the transformation to the 2pLND – by the equation $f_{\mathrm{t,0,l,med}} = f_{\mathrm{t,j,med}}$ corresponding to equal medians. In Central Europe, the expected distance between the finger joints in one GLT-lamella is stated with $l_{\mathrm{exp,mean}} = [2.0 \div 2.5]$ m (see e.g. [28]). This expectable average distance is in conformance with the reference length of boards tested in tension according to EN 1194. In average, one finger joint connection has to be considered within one reference board, respectively one reference GLT-lamella. The formulation regarding the minimum requirements on the finger joint tensile strength on the 5 %-quantile level is given as a relationship between both tensile strengths, $f_{\mathrm{t,0,l,05}}$ and $f_{\mathrm{t,j,05}}$. Under consideration of minor dispersion of the finger joint tensile strength compared to that of the boards in the expectable range of $CoV(f_{\mathrm{t,j}}) = (15 \pm 5)$ %, e.g. due to the placement within the „clear wood“-like sections of the board-segments and the serial action between both jointed components, the ratio between both characteristic tensile strength properties can be formulated according to (12-14).

$$f_{t,j,05} \geq \xi \cdot f_{t,0,l,05}, \tag{12}$$

with

$$\xi \approx 0.78 \cdot \exp\left(1.65 \cdot CoV\left(f_{t,0,l}\right)\right) \tag{13}$$

and

$$CoV\left(f_{t,j}\right) = 15\%. \tag{14}$$

The influence of the bearing behaviour of a soft element (e.g. knot) on an adjacent finger joint in the moment-tensile-zone of a GLT-beam in bending, due to the load distribution in proportion to the stiffness, is not taken into account in (12). Colling [28] examined the influence of knottiness, expressed by the knot-area-ratio factor KAR with a value of KAR = 0.3, in the lamella beside a finger joint in the outermost moment-tensile-zone by means of Monte-Carlo simulations and determined a loss of the characteristic bending strength capacity of GLT of approximately 9 %. Due to the expectable distance between the finger joints and the heavily right-skewed distribution of the knot sizes, the authors judge the probability of occurrence of the examined configuration as marginally important and neglect it in a first approximation.

4 PROPOSAL AND VERIFICATION

On the basis of the foregoing examinations the "bearing model for GLT in bending" in Table 3 and the corresponding strength class system in Table 4 are proposed for the revision of EN 14080 (see e.g. [29,30]). The rounding of the power from 0.82 to 0.80 in (15) and Table 3 respectively, leads after adapting the coefficient *m* in (15) in the practically relevant range of $f_{t,0,l,05} = [10 \div 30]$ N/mm² to a reduction of approximately $(1 \div 6)$ % (around 6 % in case of $CoV(f_{t,0,l}) = 35$ %) of the computed characteristic bending strengths of GLT.

$$m_{power=0.80} \approx 1.88 \cdot \exp\left(1.14 \cdot CoV\left(f_{t,0,l}\right)\right), \tag{15}$$

with

$$CoV\left(f_{m,g}\right) = 15\% . \tag{16}$$

***Table 3:** New BMB-GLT: proposal for EN 14080 applicable for softwood GLT tested acc. EN 408 (straight beam, edgewise, four-point-bending), $d_{g,ref}$ = 600 mm (= 15 laminations, $t_{l,ref}$ = 40 mm), nominal strength class between GL20h and GL36h acc. to EN 1194*

$f_{m,g,k}$	$= 2.5\ f_{t,0,l,k}^{0.8}$	$f_{t,j,k} \geq 1.2\ f_{t,0,l,k}$	for $CoV(f_{t,0,l})$=(25±5)%
	$= 2.8\ f_{t,0,l,k}^{0.8}$	$f_{t,j,k} \geq 1.4\ f_{t,0,l,k}$	for $CoV(f_{t,0,l})$=(35±5)%

***Table 4:** Proposed strength class system and corresponding strength requirements on boards and finger joints acc. the BMB-GLT given in Table 3*

$CoV(f_{t,0,l})$ [%]	strength classes GLT	board[1]	$f_{t,0,l,k}$ [N/mm²]	$f_{t,j,k}$ [N/mm²]
(35±5)%	GL24h	**T**15.0 **E**11.0 +	15.0	20.5
	GL28h	**T**18.0 **E**12.0 +	18.0	25.0
(25±5)%	GL24h	**T**17.0 **E**11.0	17.0	20.5
	GL28h	**T**20.5 **E**12.0	20.5	25.0
	GL32h	**T**24.0 **E**13.5	24.0	29.0
	GL36h	**T**28.0 **E**14.5	28.0	34.0

[1] T … characteristic tensile strength parallel to grain
E … mean tensile E-Modulus parallel to grain
\+ … expectable $CoV(f_{t,0,l}) \geq 30$ %

***Table 5:** Coefficients m and ζ in dependency of $CoV(f_{t,0,l})$*

$CoV(f_{t,0,l})$ [%]	$m_{power = 0.80}$ $CoV(f_{m,g})$ = 15 % [--]	ζ $CoV(f_{t,j})$ = 15 % [--]
(**20** ± 2.5) %	2.36	1.08
(**25** ± 2.5) %	**2.50**	**1.18**
(**30** ± 2.5) %	2.65	1.28
(**35** ± 2.5) %	**2.80**	**1.39**
(**40** ± 2.5) %	2.97	1.51

The influence of $CoV(f_{t,0,l})$ on the coefficients *m* and *ζ* is shown in Table 5 and reflects clearly the mutual interrelationship between both parameters: the higher the $CoV(f_{t,0,l})$ the higher the expectable laminating effect but the higher the requirements on the finger joint tensile strength in relation to the characteristic tensile strength of the boards. This is logical from the point of view that a high $CoV(f_{t,0,l})$ by constant $f_{t,0,l,mean}$ corresponds to a very low value for $f_{t,0,l,05}$ whereas the mean material capacity is more or less proportional to the mean finger joint potential and at the end with the mean strength capacity of the GLT.

For further verification of the proposed model in Table 3 composed of two sub-models $f_{m,g,05}$ vs. $f_{t,0,l,05}$ and $f_{t,j,05}$ vs. $f_{t,0,l,05}$ further test series were accomplished. The focus of the additional tests was:

- first, to verify the model for visual graded board material with expectable higher dispersions in the tensile strength, and
- second, to verify the model by testing the highest GLT-strength class GL36 acc. to EN 1194.

The material of the internal tests was Norway Spruce (*Picea abies Karst.*) with provenience Central Europe. Table 6 and Table 7 give an overview of the dimensions and sample sizes of the additional accomplished test series, tensile tests on the board material and finger joints as well as on GLT-beams of the base material. Table 8 and Table 9 show the statistics of the strength data of boards, finger joints and GLT-beams.

***Table 6:** Add. int. tests: boards & finger joints; tension*

project no. [--]	dimensions l / w / t [mm/mm/mm]	nominal grade (acc. DIN 4074) [--]	sample size [--]
pv_1#-I	4,000 / 150 / 40	S10 (vis.)	100 #
pv_1#-II	4,000 / 150 / 40	S10+ (vis.)	100 #
pv_1#-III	4,000 / 150 / 40	S13 (vis.)	100 #
pv_2#-I	4,000 / 170 / 45	T28 E14.5 [1] (mach.)	100 #
	total (boards)		**400 #**
pv_1#-I	150 / 40	S10 (vis.)	50 #
pv_1#-II	150 / 40	S10+ (vis.)	50 #
pv_1#-III	150 / 40	S13 (vis.)	50 #
pv_2#-I	170 / 45	T28 E14.5 [1] (mach.)	30 #
	total (finger joints)		**180 #**

[1] required board strength class with T = $f_{t,0,l,k}$ and E = $E_{t,0,l,mean}$ acc. to the proposal in Table 3 and Table 4

***Table 7:** Additionally internal tests: GLT-beams; bending*

project no. [--]	dimensions w / d [mm]	nominal grade (acc. DIN 4074) [--]	sample size [--]
pv_1#-Ia	150/160	S10	25 #
pv_1#-Ib	150/320	S10	25 #
pv_1#-II	150/320	S10+	25 #
pv_1#-III	150/320	S13	25 #
pv_2#-I	160/600	T28 E14.5 [1]	25 #
	total (GLT-beams)		**125 #**

[1] required board strength class with T = $f_{t,0,l,k}$ and E = $E_{t,0,l,mean}$ acc. to the proposal in Table 3 and Table 4

In addition to the internal tests current accomplished external test series are taken into account including research projects of the Nordic countries published in [31] and a German research project with data given in [32-36]. The selected statistics of these data sets are given in Table 10 and Table 11.

Table 8: *Statistics of boards & finger joints; tension*

	pv_1#-I		**pv_1#-II**		**pv_1#-III**		**pv_2#-I**	
[N/mm²]	$f_{t,0,l}$	$f_{t,j}$	$f_{t,0,l}$	$f_{t,j}$	$f_{t,0,l}$	$f_{t,j}$	$f_{t,0,l}$	$f_{t,j}$
n#	100	49	100	42	100	48	98	30
mean	27.3	26.5	34.4	27.2	41.2	29.3	45.6	52.0
CoV [%]	**39.5**	**18.6**	**38.1**	**16.6**	**30.4**	**14.3**	**26.9**	**18.1**
$\mathbf{x_{05,2pLND}}$	14.0	19.1	16.1	20.4	23.2	22.8	27.6	32.6 1)
$\mathbf{k_{size,EN1194}}$	0.98	1.00	0.98	1.00	0.98	1.00	1.07	1.00
$\mathbf{x_{k,EN14358}}$	**13.1**	**18.5**	**15.0**	**19.8**	**22.0**	**22.2**	**28.6**	**31.1** 1)

1) 2pWD as RSDM because of significant deviations of empD from 2pLND acc. EN 14358

Table 9: *Statistics of GLT-beams; bending*

pv_x#-xx	**1#-Ia**	**1#-Ib**	**1#-II**	**1#-III**	**2#-I**
[N/mm²]	$f_{m,g}$	$f_{m,g}$	$f_{m,g}$	$f_{m,g}$	$f_{m,g}$
n#	24	25	25	25	25
mean	38.1	30.1	34.4	40.3	41.9
CoV [%]	20.1	17.3	19.5	13.8	12.2
$\mathbf{x_{05,2pLND}}$	27.1	22.4	25.1	31.8	33.9
$\mathbf{k_{size,EN1194}}$	0.88	0.94	0.94	0.94	1.01
$\mathbf{x_{k,EN14358}}$	**22.6**	**20.2**	**22.6**	**28.8**	**33.2**

Table 10: *Test data and statistics directly taken from [31]*

[N/mm²]	**F_1#**	**F_2#**	**F_3#**	**F_4#**	**S_1#**	**D_1#**
$\mathbf{n_l\#/n_j\#}$ [--]	50/40				40/40	
$\mathbf{f_{t,0,l,mean}}$	38.8	34.4	41.9	36.3	35.2	33.4
$\mathbf{CoV(f_{t,0,l})}$	**21.5**	**32.4**	**22.9**	**25.0**	**19.8**	**19.0**
$\mathbf{f_{t,0,l,k}}$ 1)	**24.2**	**19.1**	**23.6**	**23.9**	**23.7**	**21.5**
$\mathbf{f_{t,j,mean}}$	35.8	42.0	34.3	31.5	34.1	34.4
$\mathbf{CoV(f_{t,j})}$	19.6	18.0	18.1	13.1	16.4	17.9
$\mathbf{f_{t,j,k}}$ 1)	**24.3**	**29.3**	**25.4**	**24.5**	**24.7**	**23.0**
$\mathbf{w_g/d_g}$ [mm]	140/540					140/600
$\mathbf{n_g}$ # [--]	8				20	
$\mathbf{f_{m,g,mean}}$	38.2	34.0	32.2	33.4	35.9	37.3
$\mathbf{CoV(f_{m,g})}$	9.0	14.0	19.6	11.5	9.7	11.0
$\mathbf{f_{m,g,k}}$ 1)	30.9	24.2	20.8	25.8	29.2	29.7
$\mathbf{f_{m,g,k}}$ 2)	**33.6**	**27.3**	**23.5**	**28.6**	**31.4**	**31.8**

1) characteristic value acc. EN 14358 including k_{size} acc. EN 1194

2) acc. 1) but additionally transformed from combined to homogenous build up GLT acc. the rigid composite beam theory

Table 11: *Test data and statistics; cit. in [32-36];*
w_g / d_g = 100 / 600 mm; partly re-evaluated

	G_1# (GL32c)			**G_2#** (GL36c)		
[N/mm²]	$\mathbf{f_{t,0,l}}$	$\mathbf{f_{t,j}}$	$\mathbf{f_{m,g}}$	$\mathbf{f_{t,0,l}}$	$\mathbf{f_{t,j}}$	$\mathbf{f_{m,g}}$
n# [--]	108	82	20	100	77	20
mean	35.4	39.0	32.5	49.7	45.7	41.9
CoV	**40.4**	14.9	13.7	**27.8**	10.3	7.6
$\mathbf{x_{05,2pLND}}$	17.3	30.2	25.7	30.6	38.4	36.9
$\mathbf{x_{k,EN14358}}$ 1)	**15.01**	**29.7**	24.4	**26.8**	**37.9**	35.6
$\mathbf{f_{m,g,k}}$ 2)	--	--	**25.5**	--	--	**36.3**

1) characteristic value acc. EN 14358 including k_{size} acc. EN 1194

2) acc. 1) but additionally transformed from combined to homogenous build up GLT acc. the rigid composite beam theory

According to the weakest link theory the GLT-bending strength is treated as a function of the minimum tensile strength potential of the lamella, board and finger joint, acc. to (17). This corresponds to a "0 / 1" decision process expressing either the tensile capacity of the boards or that of the finger joints limiting the bending capacity of the GLT beam. If the strength capacities of both components in the system GLT are balanced this corresponds to a 50 % to 50 % failure probability in the board and finger joint, respectively. Other ratios of failure probabilities are for simplification not taken into account.

$$f_{m,g,05,\exp} = \min \begin{cases} m \cdot f_{t,0,l,05,test}^{\;0.80} \\ m \cdot \left(\dfrac{f_{t,j,05,test}}{\xi} \right)^{0.80} \end{cases} \qquad (17)$$

Figure 8 shows a model verification-plot as relationship between the characteristic bending strength calculated based on models ($f_{m,g,k,calc}$) and that derived by tests acc. to EN 408 ($f_{m,g,k,test}$). Additionally, the distribution model and related parameters for the residue $\varepsilon = f_{m,g,k,calc} - f_{m,g,k,test}$ are given. The characteristic values were derived acc. EN 14358. All three examined models, the current model of EN 1194 with $f_{m,g,k} = 7 + 1.15 f_{t,0,l,k}$ and $f_{t,j,k} \geq f_{t,0,l,k} + 5$, the model given in equations (12-16) as well as the proposal given in Table 3 with defined values for m and ζ for two dispersion ranges of $CoV(f_{t,0,l})$, are slightly deviating from the test results with means of the residue $\varepsilon_{mean} \neq 0.00$. Whereas ε_{mean} of the herein derived models in Table 3 and in equation (12-16) represent the test data with a $\varepsilon_{mean} < 0.00$ a bit conservatively, the current models in EN 1194 is with $\varepsilon_{mean} = 0.31$ for the available data a bit too optimistic. Taken into account the standard deviation of around $s(\varepsilon) \approx 3.00$ the mean deviations of ε_{mean} from zero are absolutely negligible! Nevertheless, all three models represent the test results with R = 0.79 ÷ 0.81 very well and as expected, the additional considered parameter $CoV(f_{t,0,l})$ leads to a slightly reduction of the variance of the residue $s^2(\varepsilon)$. It has to be taken into account that the test series are not representative concerning the verification process of the models in the sense of an equal representation of samples over the whole range of application of the models. Beside that, the available data enable beside Figure 7 a second kind of verification by comparison of tests with predicted results. Furthermore, the samples in Figure 8 are divided into two groups acc. the $CoV(f_{t,0,l})$ as proposed in Table 3. As visible, in the range of GL24 and GL28 a high $CoV(f_{t,0,l})$ is given in 6 of 13 series which are all in particular in compliance with the new model results but also well presented by EN 1194. Nevertheless, the plot shows that a $CoV(f_{t,0,l}) \geq 30$ % seems to be not expectable in case of board material for GL32 or GL36. The biggest deviations between test and calculation are shown by Finnish test data F_1# and F_3# and the Danish data set D_1#. Explanations for the deviations are not available so far. A further observation shows that series of class with a high $CoV(f_{t,0,l})$ are well presented by all three models but series of lower $CoV(f_{t,0,l})$ show partly remarkable deviations between the herein derived models and that of EN 1194. The first mentioned follows from the fact that the function $f_{m,g,k}$ vs. $f_{t,0,l,k}$ of EN 1194 more or less corresponds with the model for $CoV(f_{t,0,l}) = (35 \pm 5)$ %. The second observation reflects the necessity of the current regulations of EN 1194 to slightly increase the requirements on the strengths of the base material in order to reach GLT of GL32 and especially GL36. This is directly linked with the expectable lower $CoV(f_{t,0,l})$ in this high GLT-strength classes. In addition, the possibility of producing GLT of strength class GL36 was approved.

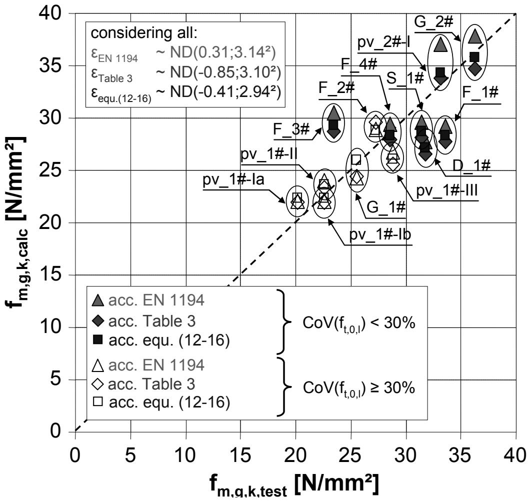

***Figure 8:** Verification plot $f_{m,g,k,calc}$ vs. $f_{m,g,k,test}$: classification of data points acc. $CoV(f_{t,0,l})$*

The calculation of some statistics concerning the ratio $FIT = f_{m,g,k,calc} / f_{m,g,k,test}$ gives a more or less equal $CoV(FIT) \approx 11$ %, a nearly 100 % congruence with $FIT_{mean,equ} = 99.5$ % in case of application of equations (12-16), an underestimation of 2 % with $FIT_{mean,prop} = 98.0$ % by the proposal of Table 3, but an overestimation of 2 % with $FIT_{mean,EN\ 1194} = 101.9$ % by the equations of EN 1194.

5 CONCLUSIONS

- A new "bearing model for GLT in bending" was derived by means of extensive internal and external test data, under consideration of essentially gathered constraints and integration of powerful stochastics.
- The importance of considering expectable stochastic parameters, e.g. the RSDMs with their expectable distribution parameters like mean and coefficient of variation was discussed and presented by the herein derived new BMB-GLT.
- The comparison of the new model with EN 1194 shows partly remarkable improvements and necessary adjustments in the upper GLT strength classes but not essentially the implementation of the new model. As shown in Figure 7 the current model of EN 1194 appears as model of consensus lying in between of all investigated BMB-GLT. The same can be said for the new BMB-GLT which beyond especially provides an explanation for the range of investigated internationally BMB-GLT and which points out the power of the additional dispersion parameter $CoV(f_{t,0,l})$. Furthermore, the new model considering directly the stochastics simplifies adjustments in case of implementation of new wood species, especially hardwoods, by providing deeper understanding and background-knowledge for the laminating effect.
- The remarkable standard deviation of the residue $s(\varepsilon) \approx 3.00$ in the range of nearly one GLT strength class mark an essential information for future discussions regarding new GLT strength class systems. Nevertheless, it is apparent that the test data of [31] shows explicitly higher deviations from the model predictions than the other internal and external data sets. Excluding the data of [31] from calculating the statistics for ε improves the results remarkable and leads to $\varepsilon_{EN\ 1194} \sim ND(0.69;2.03^2)$, $\varepsilon_{Table\ 3} \sim ND(-0.51;1.67^2)$ and for the "exact" model to $\boldsymbol{\varepsilon_{equ.\ (12-16)} \sim ND(0.02;1.52^2)}$.
- Beside all that and as present in the current revision process of prEN 14080 more open discussions and an active scientific discourse would be helpful for the standardisation process and for the development of the wood and timber industry and timber engineering as competitive partner in the building sector in general. In that sense, the protection of acquired possessions seems to be counterproductive for the community.

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Standards

DIN 4074-1/4:2004 – Strength grading of wood

EN 338:2003 – Structural timber – Strength classes

EN 384:2004 – Structural timber – Determination of characteristic values of mechanical properties and density

EN 408:2005 – Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties

EN 1194:1999 – Timber structures – Glued laminated timber – Strength classes and determination of characteristic values

prEN 14080:2008 – Timber structures – Glued laminated timber and glued laminated solid timber – Requirements

EN 14358:2007 – Timber structures – Calculation of characteristic 5-percentile values and acceptance criteria for a sample