Bearing model for glued laminated timber in bending – new aspects concerning modelling

In the frame of COST E55 – Modelling of the performance of timber structures

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Abstract Current product standard EN 1194 for glued laminated timber (GLT) is in revision. Based on grown knowledge and experience with the product GLT since the first erection of EN 1194 most characteristic values are still in discussion or are already corrected to constant factors. Task of this paper is to present current available data sets of boards of spruce (*picea Abies karst.*) tested in tension, and hence build up GLT. Emphasize has been taken on establishment of a bearing model for GLT in bending, based on a statistical mean regression function for description of the relationship between tension strength of boards and hence build up GLT which is conform to EN 1194. In addition knowledge of representative statistical distribution functions in combination with the determination of range of statistical parameters (mean, COV), sensitivity analysis related to the laminating effect have been carried out in respect to formulated constraints. Results are compared with researched publications concerning description of laminating effect of GLT. Influence of the mechanical potential of finger joints on bending strength of GLT has been theoretically examined and treated as second condition for GLT-model in bending and will be presented in a separate paper. At the end a proposal for further regulation of GLT-bending strength, based on the tension strength characteristics of the base material board is given.

Key words *glued laminated timber, laminating effect, bearing model in bending, sensitivity analysis, statistical analysis, mean function, representative statistical distribution model, coefficient of variation*

Introduction

Glued laminated timber (glulam or GLT), famous product of the wood industry and widely applied in engineered constructions, is one of the first one-dimensional structure which enables, in comparison to single solid wood beams, useable increased mechanical potential in strength and stiffness thanks to homogenization effects. To describe the essential relationship between the base material and the structure, the interdependency of the mechanical potential of structural components boards and finger joints – tested in tension parallel to grain as the key failure criteria in the beam – and the mechanical potential of GLT, multiplicity research projects have been carried out internationally. For description of the laminating effect, to enable calculation of bending strength of GLT based on tension strength of graded lamellas (boards and finger joints), past and current research projects can be divided into two main groups: First group is manifested in testing boards and hence build up GLT. This method is, related to the enormous variables which influence the mechanical potential, uneconomic, but essential for the second group which deals with modeling of interrelationships of components boards and finger joints in the structure GLT. Up to now complete mechanical and stochastic description of laminating effect in GLT is missing. Based on current knowledge of simulation techniques and test data sets it should be possible to define an engineered bearing model for GLT in bending with respect to main influencing parameters as mentioned – tension strength parallel to grain of boards and finger joints.

Main influencing parameters on bending strength of GLT

The main influencing parameters on the bending strength of GLT are well examined by Colling 1990. Following further main parameters are stressed: Knottiness (negative correlation with strength, homogenization through knot distribution along the cross section and board length), density (positive correlated to strength), modulus of elasticity (positive correlated and best estimator of strength), lamellas in tension zone of GLT (emphasize is taken on high stressed lamellas in the outer tension zone of GLT, probability of failure in compression zone can be neglected), finger joints (as limiting parameter of strength) and size of GLT (negative correlation between strength and volume due to statistical and energy related size effects (according to Bažant and Chen 1996, Bažant 2004, Bažant et al. 2004, Bažant and Pang 2005)).

Based on above mentioned parameters following listening contains the main influences concerning the laminating effect, as given in Colling 1990, Colling 1995, Falk and Colling 1995. By the way it has to be differentiated between mechanical- and statistical-(randomness)-based influences, interactions of both or influences based on testing and examination procedures:

- Difference between testing single boards in tension and tension load on boards / lamellas bonded in GLT
- Influence through reinforcement of low stiffness / strength areas within a board through neighbor boards / lamellas in the cross section of GLT
- Influence of further reinforcement effect through distribution and random positioning of low strength / stiffness lamellas within the cross section of GLT

In addition to Colling 1990, Colling 1995, Falk and Colling 1995 sub-effects, not on the laminating factor but on the test arrangement and further examination of calculated results, have to be considered (see Schickhofer et al. 2006):

- Influence of test execution and collection of test results and reproducibility
- Influence of examination of test results by application of statistical analysis
- Influence of subjective interpretation of test results in combination with experience of test executing personal

At this point it has to be mentioned: so far a mechanical and statistical exact description of the laminating effect is still missing and in respect to influencing parameters practically impossible. Mankind itself, as examiner, researcher and producer, often plays an underestimated role on the results of tests and production quality.

Following excursion should give an idea of the extension of a statistically related laminating effect as result of current standardized statistical analysis procedures.

Influence of examination of test results by application of statistical analysis procedures regulated in current standards

The characteristic value is defined as the lower boundary value of confidence interval representing the predictable fuzziness of 5 %-quantile as point estimation. The procedure for determination is dependent on the data set representing statistical distribution model (realizations of examined variable), related distribution parameters and the confidence α.

The 5 %-quantile, as statistical sensitive value, can be described as dependent on the statistical distribution model, parameters and on the factor k_p for description of the distance to the mean as function of the standard deviation (see [1]).

$$x_{0.05} = \bar{x} - k_p \cdot s \tag{1}$$

To take into account the confidence the factor k_s – expressing the range of possible occurrence of the real value in regard to the given confidence – is introduced to determine the characteristic value based on the 5 %-quantile.

So far characteristic tension strength of boards has to be calculated acc. EN 384. This standard regulates a procedure for calculation of the lower confidence boundary of the 5 %-quantile based on a distribution free method called ‘counting method’ (CM) and application of a modified factor k_s (direct multiplier for the 5 %-quantile) to take into account lack of statistical predictability of population characteristics concerning limited sample size n. Characteristic bending strength of GLT, which presents the second part of the ‘bearing model for GLT in bending’, has to be calculated acc. EN 14358 which includes a more statistic theory based procedure based on assumed logarithmic normal distribution (LND), for representing the bending strength, and the non-central-t-distribution (NCTD), as test distribution, to calculate the characteristic value based on the 5 %-quantile point estimate (see *Fig. 1*). The factor k_s of EN 384 is much more on a conservative basis and only a function of the sample size n. This leads to an underestimation of right skewed, minor deviated data sets and, in relation to the characteristic bending strength of

GLT – calculated acc. EN 14358 with factor k_s as a function of sample size, assumed statistical distribution, distribution parameters (especially COV) and confidence level – to a much higher reduction of the tension strength of boards and to a negative shift of relationship between these values.

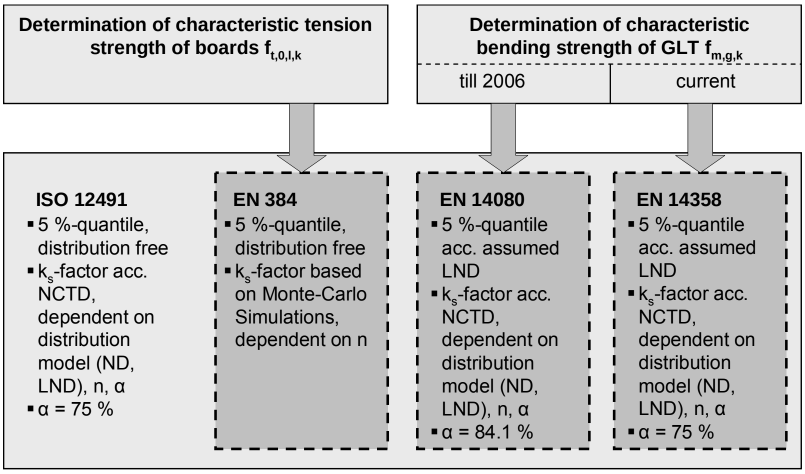

Fig. 1. – Standardized procedures for the determination of characteristic values for tension strength of boards and bending strength of GLT

For demonstration of this effect practically deviations between 10 % and 40 % and sample sizes of 40 # and 200 # specimens are applied. To be able to compare both calculation procedures the factor k_s is, as given in EN 384, calculated as relation between the characteristic value and the 5 %-quantile. The results are presented in *Tab. 1*. As given this can lead to an effect in the dimension of plus 26 % resulting in a 'statistical based laminating effect' of 1.26. This factor is generally reduced in practice thanks to minor sample size of GLT in comparison to tested quantity of boards tested in tension. For example by testing 100 # boards and 25 # GLT-beams with COV-$f_{m,g}$ = 15 %, a factor between both calculation schemes is given with 1.14.

Tab. 1. – Parameter study concerning the k_s-factors in determination of characteristic values acc. EN 384 and EN 14358 and relationship between both calculation procedures: the factor k_s is expressed as relationship between f_{05} vers. f_k as given in EN 384

n [--]	**k_s acc. EN 384** [--]	**k_s acc. EN 14358** [--]			**$k_{s,EN14358}$ / $k_{s,EN 384}$** [--]		
	COV	**COV**			**COV**		
	--	**10 %**	**20 %**	**40 %**	**10 %**	**20 %**	**40 %**
40 #	0,78	0.982	0.964	0.931	1.26	1.24	1.20
200 #	0,90	0.992	0.985	0.971	1.10	1.09	1.08

Calculation of both characteristic strength values acc. the given standards – which are compared afterwards for determination of the 'bearing model for GLT in bending' – introduce a statistical based 'laminating effect' as result of inconsistent statistical analysis.
It is proposed and applied for all calculations given further to determine the statistical sensitive 5 %-quantile based on determined best fitted and physically argumentable, representative statistical distribution model and hence carried out consistent and on statistics theory based procedures.

State of the art of researched bearing models for GLT in bending

Bearing models for GLT in bending of last 18 years have been researched to evaluate the range of proposed functions for description of the relationship between 5 %-quantile of GLT-bending strength and 5 %-quantile of board-tension strength (see *Tab. 2*).

Tab. 2. – Researched bearing models for GLT in bending, based on the tension strength of boards

Author reference	**Reference dimensions, size factors**	**Bearing model for GLT in bending**
Riberholt et al. 1990	h_0 = 300 mm k_h = 0.20	$f_{m,g,k} = (2.7 - 0.04 \cdot f_{t,0,l,k}) \cdot f_{t,0,l,k}$
Riberholt et al. 1990	h_0 = 600 mm k_h = 0.20	Function fitted to h_0 = 600 mm by Gehri 1992: $f_{m,g,k} = (2.35 - 0.035 \cdot f_{t,0,l,k}) \cdot f_{t,0,l,k}$
Colling et al. 1991	h_0 = 300 mm $\left(\frac{h}{300} \cdot \frac{l}{5400}\right)^{0.10}$	$f_{m,g,k} = 10 + 1.4 \cdot f_{t,0,l,k}$
Gehri 1992	h_0 = 600 mm k_h = 0.20	$f_{m,g,k} = 12 + f_{t,0,l,k}$
Falk et al. 1992	h_0 = 600 mm b_0 = 150 mm	Referenced by Gehri 1995, function adjusted to reference dimensions: $f_{m,g,k} = 6 + 1.05 \cdot f_{t,0,l,k}$
Falk and Colling 1994	h_0 = 305 mm w_0 = 130 mm l_0 = 533 mm k_h = 0.10 k_w = 0.10 k_l = 0.10	Fitted to North American data sets: $f_{m,g,k} = 6.82 + 1.22 \cdot f_{t,0,l,k}$
Colling 1994	h_0 = 600 mm	$f_{m,g,k} = 9 + 1.20 \cdot f_{t,0,l,k}$

prEN 1194:1994		
Falk and Colling 1994	h_0 = 600 mm k_h = 0.20	Fitted to European data sets: $f_{m,g,k} = 7.35 + 1.12 \cdot f_{t,0,l,k}$
Gehri 1995	h_0 = 600 mm w_0 = 150 mm	$f_{m,g,mean} = 4.5 + f_{t,0,l,mean}$ Low COV-$f_{t,0,l}$: $f_{m,g,k} = 3.5 + 1.15 \cdot f_{t,0,l,k}$ High COV-$f_{t,0,l}$: $f_{m,g,k} = 3.5 + 1.25 \cdot f_{t,0,l,k}$ COV-$f_{t,0,l} < 0.30$: $f_{m,g,k} = 4 + 0.75 \cdot f_{t,0,l,mean}$
Falk and Colling 1995	h_0 = 305 mm w_0 = 130 mm l_0 = 533 mm k_h = 0.10 k_w = 0.10 k_l = 0.10	Fitted to European data sets: $f_{m,g,k} = 7.35 + 1.12 \cdot f_{t,0,l,k}$ Fitted to North America data sets: $f_{m,g,k} = 6.82 + 1.22 \cdot f_{t,0,l,k}$
Colling 1995	h_0 = 600 mm k_h = 0.20	$f_{m,g,k} = 7 + 1.15 \cdot f_{t,0,l,k}$
prEN 1194:1995		$f_{m,g,k} = 9 + 1.20 \cdot f_{t,0,l,k}$
Schickhofer 1996	h_0 = 600 mm k_h = 0.10	$f_{m,g,k} = 9.5 + f_{t,0,l,k}$
EN 1194:1999	h_0 = 600 mm w_0 = 150 mm k_h = 0.10 k_w = 0.05	$f_{m,g,k} = 7 + 1.15 \cdot f_{t,0,l,k}$
Gehri 2005	h_0 = 600 mm k_h = 0.10	Low COV-$f_{t,0,l}$: $f_{m,g,k} = 3.5 + 1.15 \cdot f_{t,0,l,k}$ High COV-$f_{t,0,l}$: $f_{m,g,k} = 3.5 + 1.25 \cdot f_{t,0,l,k}$ Power function fitted to model of EN 1194:1999 (unpublished): $f_{m,g,k} = 2.7 \cdot f_{t,0,l,k}^{\ 0.8}$
Proposal Germany 2006 (unpublished)	h_0 = 600 mm	$f_{m,g,k} = 6 + f_{t,0,l,k}$

	$k_h = 0.10$	
Blaß 2007	$h_0 = 600$ mm $w_0 = 150$ mm $k_h = 0.10$ $k_w = 0.05$	$f_{m,g,k} = 4.10 + 0.483 \cdot f_{m,j,k} - 0.0125 \cdot f_{m,j,k}^{2} +$ $+ 0.114 \cdot f_{t,0,l,k} - 0.0336 \cdot f_{t,0,l,k}^{2} +$ $+ 0.0446 \cdot f_{m,j,k} \cdot f_{t,0,l,k}$

Most of models presented are related to the erection of EN 1194. During this process also reference dimensions and size factors have been under constant revision due to test results, simulations and ongoing compromise finding process in the European standardizing committee. Nearly all models are related to test results and under influence of highly sensitive determination of 5 %-quantiles of GLT bending strength. As exception Colling 1990 established the 'Karlsruher Calculation Model' as 2D-simulation procedure of GLT, based on multiple regression functions describing characteristics of boards and board segments, implemented in a FEM-tool for calculation of GLT-bending strength by application of Monte-Carlo simulation technique. The model proposed by Blaß 2007 includes both, general separated models, a multiple regression function dependent on the tension strength of boards $f_{t,0,l,k}$ and bending strength of finger joints $f_{m,j,k}$. It has to be clarified so far how this model should be treated in case of GLT build up of unjointed lamellas.

Acc. to *Fig. 2* and *Fig. 3* wide and with strength increasing range of proposed models is presented and reflects the variability of influencing parameters on the determination of the simple relationship $f_{t,0,l,k}$ vers. $f_{m,g,k}$. Due to lack of knowledge and responsibility for safety also a decreasing trend of model gradient over time is apparent (Colling 1991 – EN 1194:1999 – proposal Germany (unpublished) 2006).

But which model represents 'reality'?

Generally a model always tries to represent reality but never reaches it. For engineering and production applications a model should in addition characterized by simplicity and wide applicability within defined constraints.

Concerning the bearing model for GLT in bending, tension strength of boards and finger joints – as main GLT failure inducing parameters – have been chosen as variables to calculate related bending strength of GLT. Based on the high influence on $f_{t,j}$ in regard to the production processes, maintenance and also for quality control purposes the relationship $f_{t,0,l,k}$; $f_{t,j,k}$ vers. $f_{m,g,k}$ has been separated (see [2], [3] acc. EN 1194:1999).

$$f_{m,g,k} = 7 + 1.15 \cdot f_{t,0,l,k} \qquad [2]$$

$$f_{t,j,k} \geq 5 + f_{t,0,l,k} \qquad [3]$$

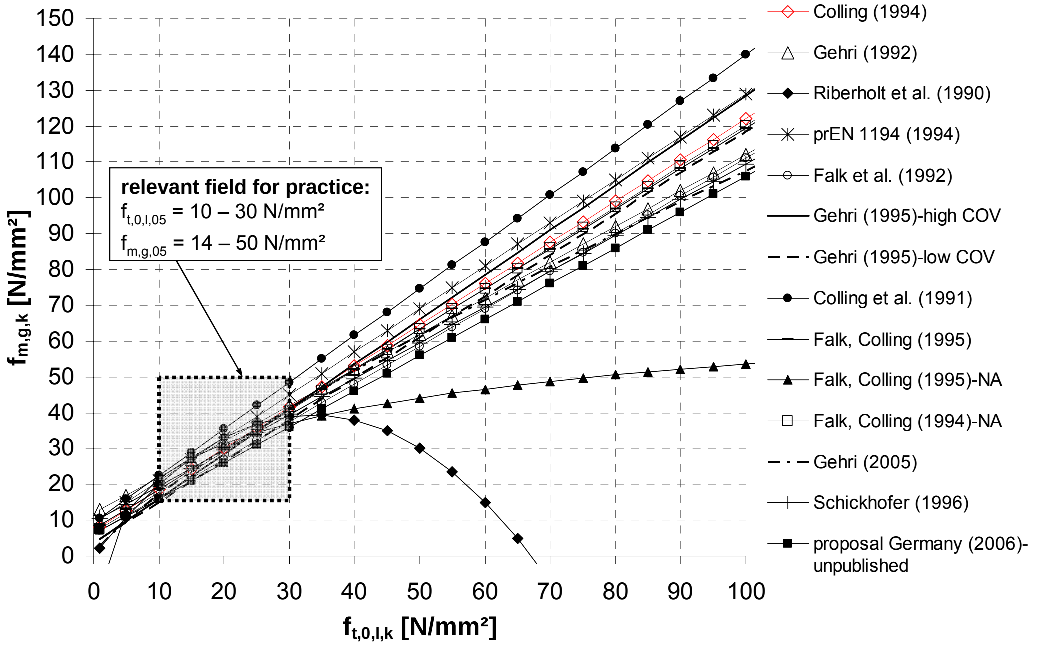

Fig. 2. – Researched proposed bearing models for GLT in bending of the last 18 years for description of the relationship between the characteristic tension strength of boards ($f_{t,0,l,k}$) and the characteristic bending strength of hence build up GLT ($f_{m,g,k}$); all models are adapted to current reference dimensions and size factors acc. EN 1194:1999: h_0 = 600 mm, w_0 = 150 mm

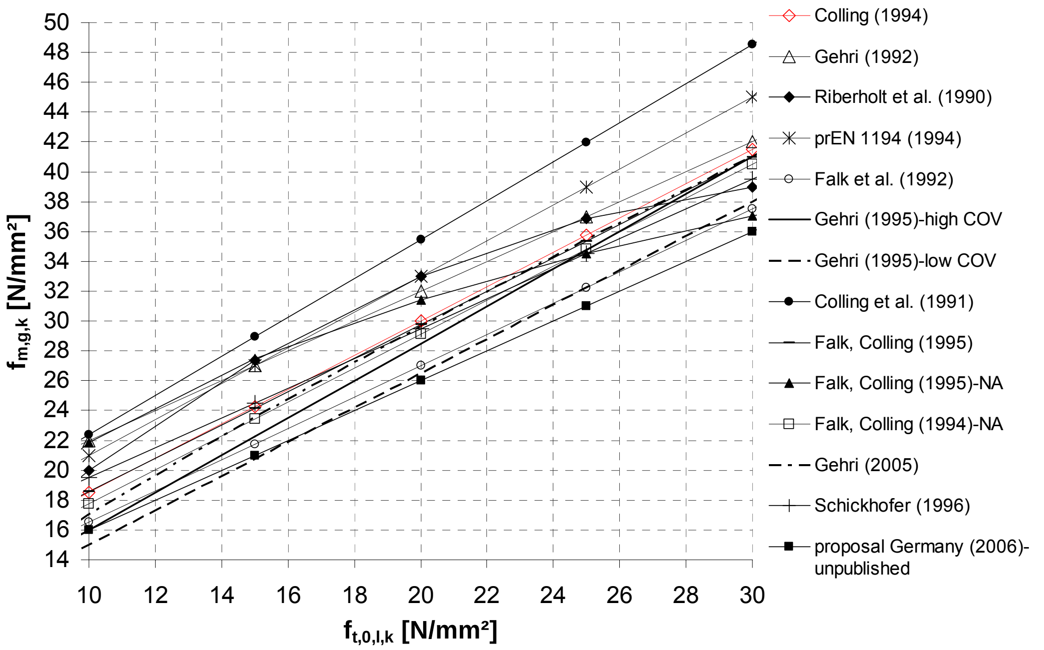

Fig. 3. – Relevant field for practical applications of researched proposed bearing models for GLT in bending of the last 18 years for description of the relationship between the characteristic tension strength of boards ($f_{t,0,l,k}$) and the characteristic bending strength of hence build up GLT ($f_{m,g,k}$); all models are adapted to current reference dimensions and size factors acc. EN 1194:1999: h_0 = 600 mm, w_0 = 150 mm

As result of comparison of two different loading situations – tension parallel to grain vers. bending – statistical and mechanical effects take place:

- Differences due to stressed cross section
  - → Boards in tension: equal stressed cross section
  - → GLT-beams in bending: interaction of compression and tension in highly pronounced boundary layers, especially in tension after starting of plasticity in compression
- Differences due to stressed tested length
  - → Boards in tension: $l_0 = 2000$ mm
  - → GLT-beams in bending: $l_0 = (18 \pm 3) \cdot h_0$, but tested length (length of constant moment and range of expected failure of the beam) correspond to $l_{test} = 6 \cdot h_0 = 3600$ mm
- Differences due to reference dimensions
  - → Boards in tension: $w_0 = 150$ mm, $l_0 = 2000$ mm
  - → GLT-beams in bending: $w_0 = 150$ mm, $h_0 = 600$ mm, $l_0 = (18 \pm 3) \cdot h_0$
- Differences due to given influencing parameters (acc. Colling 1990, Colling 1995, Falk and Colling 1995)
- Differences due to different system structures
  - → Boards in tension: predominantly serial arranged reference volume elements (RVE's) tend to act acc. the weakest link theory (Weibull 1939)
  - → GLT-beams in bending: parallel arranged and rigid connected lamellas as system of serial arranged boards and finger joints, but serial loaded edgewise in bending

Further more and as a result of examination of characteristic values ($f_{t,0,l,k}$; $f_{t,j,k}$; $f_{m,g,k}$) all statistical parameters, which are necessary for calculation, have also to be considered during establishment of a bearing model for GLT but without parameters which express statistical uncertainty based on limited quantity of specimen in a sample (see [4]):

- Representative statistical distribution model
- Distribution parameter of location, dispersion and threshold

$$f_{05} \rightarrow f\left\{DM_f, f_{mean}, COV_f\right\} \tag{4}$$

In addition some constraints for the relationship $f_{t,0,l,k}$ vers. $f_{m,g,k}$ can be formulated (see [5], [6], [7]):

$$f_{t,0,l,k} = 0 \rightarrow f_{m,g,k} = 0 \tag{5}$$

$$f_{t,0,l,k} = \infty \rightarrow f_{m,g,k} = \infty \tag{6}$$

$$\lambda = \frac{f_{m,g,k}}{f_{t,0,l,k}} \rightarrow 1.00 \qquad [7]$$

The last constraint describes the relationship between $f_{m,g,k}$ and $f_{t,0,l,k}$ expressed as laminating factor λ which tends to decrease with increasing homogenization of the base material and assumed equal increase of finger joint quality. It follows an asymptotic approach of $f_{t,0,l,k}$ to $f_{m,g,k}$.
According the above statements and based on examined potential of boards in tension and hence build up GLT in bending a model has been formulated by combination of both sub-models (boards in tension – GLT in bending) and under consideration of the coefficient of variation of both strength values (COV-$f_{m,g}$ and COV-$f_{t,0,l}$) (see *Fig. 4*, [8]).

$$f_{m,g,05} \rightarrow f\left\{DM_{f_{t,0,l}}, DM_{f_{m,g}}, COV_{f_{t,0,l}}, COV_{f_{m,g}}\right\} \qquad [8]$$

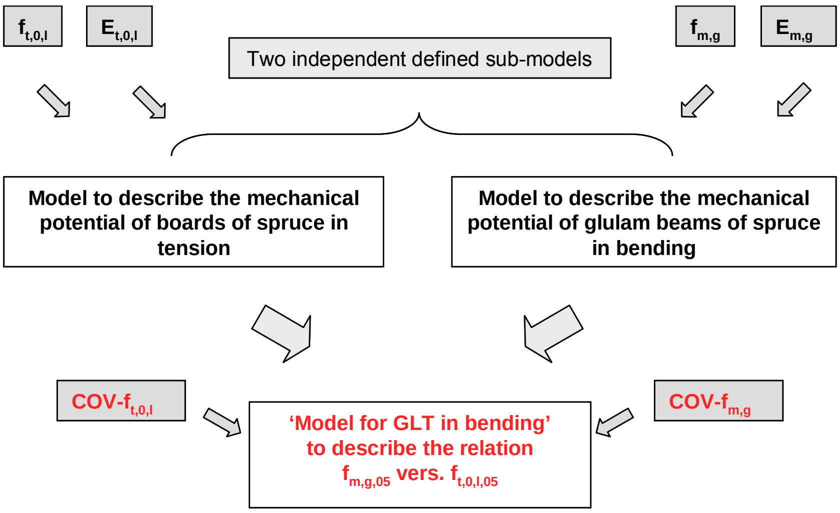

Fig. 4. – Scheme of model for GLT in bending to link two independent sub-models: $f_{t,0,l}$ vers. $E_{t,0,l}$ and $f_{m,g}$ vers. $E_{m,g}$

Materials and Methods

The data sets, as basis for further examination procedure and applied statistical analysis methods are presented afterwards.

Test data sets

Further examinations of internal data sets (test carried out since 1995 at the Graz University of Technology – Institute for Timber Engineering and Wood Technology, and at the Center of Competence holz.bau forschungs gmbh) are related to spruce as wood species, grown in Middle and Northern Europe, finger joints with profile 15 mm or 20 mm, and adhesives like melanin formaldehyde and polyurethane. *Tab. 3* and *Tab. 4* give an overview of tested series concerning the mechanical potential of boards in tension and GLT in bending, dimensions and quantities.

Tab. 3. – Overview of projects and related samples of boards tested in tension parallel to grain

Project	**Dimensions l / b / h**	**Tested nominal grading classification acc. DIN 4074**	**Sample size**
[--]	**[mm]**	**[--]**	**[--]**
p_1#-I Schickhofer et al. 1995	4000 / 160 / 32	MS10, MS13, MS17	120 #
p_1#-II Schickhofer et al. 1995	4000 / 170 / 36	MS7, MS10, MS13, MS17	217 #
p_2# Schickhofer et al. 1997	4000 / 155 / 37	MS10, MS13, MS17	144 #
p_3# Unterwieser 2005	4000 / 108 / 43	MS10, MS13, MS17	385 #
p_4# Hasewend 1998	4000 / 150 / 26	MS7, MS10, MS13	60 #
p_5# Ruli 2004	3000 / 175 / 40	3 stiffness grades	90 #
p_5# Ruli 2005	3000 / 170 / 43	MS10, MS13, MS17	392 #
		Total =	**1408 #**

It has to be remarked: all series and every data set concerning GLT-bending strength include only primary failures in wood. Predominant failures due to insufficient strength of finger joints are excluded of further examination. This enables direct comparison of GLT-bending strength $f_{m,g}$ with tension strength of boards $f_{t,0,l}$ of the same population without exact knowledge of the influence of finger joint characteristics on GLT. Further more all physical properties of GLT-beams are in regard to conditional necessary information of tension characteristics of the boards. Based on past and current knowledge visually, but also machine grading of boards – as base material – cannot guarantee the exact fulfillment of the characteristic properties given in EN 338. It is a fact: if the tension strength of the boards of hence build-up GLT is unknown, a relationship between $f_{t,0,l}$ and $f_{m,g}$ cannot be examined, neither on a mean nor on a 5 %-quantile level. General, lack of tension characteristics of the base material leads, in respect to the parameters of every mathematical or mechanical model, to insufficient estimates of examined relationships. Some past and current examinations concerning GLT-models (e.g. Blaß 2007) cannot guarantee the fulfillment of the requirements on the base material lamellas.

A conclusion drawn from the grading class of boards to tension characteristics, especially estimated strength values, would induce that actual grading works perfectly. According the coefficient of determination of the relationship of estimated and static measured strength – on optimistic level in the range of $0.4 < R^2 < 0.6$ – this can not be confirmed.

Additional mechanical properties like modulus of elasticity and density of both, boards and hence build up GLT, are important to characterize the base material and to judge the homogenization due to reduction of the relative dispersion, expressed as COV.

Tab. 4. – Overview over projects and related tested samples of boards and hence build up GLT

Project **[--]**	**Dimensions** **b / h** **[mm]**	**Nominal grading** **classification acc. DIN 4074** **[--]**	**Sample size** **GLT / boards** **[--]**
p_1#-01 Schickhofer et al. 1995	160 / 300	MS10 / MS10	21 # / 71 #
p_1#-02 Schickhofer et al. 1995	160 / 300	MS13 / MS13	27 # / 64 #
p_1#03 Schickhofer et al. 1995	160 / 300	MS17 / MS17	14 # / 69 #
p_1#-04 Schickhofer et al. 1995	160 / 300	MS13 / MS10	20 # / 64 #
p_1#-05 Schickhofer et al. 1995	160 / 300	MS17 / MS13	16 # / 69 #
p_1#-06 Schickhofer et al. 1995	160 / 600	MS10 / MS10	10 # / 71 #
p_1#-07 Schickhofer et al. 1995	160 / 600	MS17 / MS17	14 # / 69 #
p_2# Schickhofer et al. 1997	150 / 300	MS17 / MS17	15 # / 68 #
p_3#-01 Unterwieser 2005	90 / 300	MS17 / MS13 / MS10	16 # / 40 #
p_3#-02 Unterwieser 2005	45 / 300	MS17 / MS13 / MS10	24 # / 40 #
		Total (GLT-beams) =	**177 #**
		Average quantity of tested boards / GLT-series =	**62 #**

Test configurations and testing device

Generally all tests have been done acc. EN 408 with failure within 300 ± 120 s. The load has been applied continuous and way controlled.

All failures have been recorded. Specimens for determination of moisture content have been taken nearby the failure area.

Tension tests of boards parallel to the grain

The tension tests of boards parallel to the grain have been done acc. standardized testing procedure given in EN 408, with free testing length $l_0 \geq 9 \cdot w$. The measurement of deformation for calculation of local modulus of elasticity has been applied more or less in the middle of the specimens, over a length of $l_{E\text{-local}} = 5 \cdot w$. In addition global deformations have been recorded to gain more representative values for the tension modulus of elasticity $E_{t,0,l}$.

Bending tests of GLT

The bending tests on GLT have been carried out acc. 4-point bending test procedure given in EN 408. Beams were loaded in third points with $a = 6 \cdot h$ distance between loading points and span $l = 18 \pm 3$ h. Generally bending modulus of elasticity $E_{m,g}$ has been calculated based on measurement of local deformation in the middle section with $l_1 = 5 \cdot h$.

Adaptations on examined data sets

Values of modulus of elasticity ($E_{t,0,l}$ and $E_{m,g}$) and density (ρ_l and ρ_g) have been adapted acc. EN 384 to 12 % moisture content. The strength values ($f_{t,0,l}$ and $f_{m,g}$) have been adapted to the reference dimensions acc. EN 1194 (boards: $b_0 = 150$ mm, $l_0 = 2000$ mm; GLT-beams: $h_0 = 600$ mm, $b_0 = 150$ mm) and reverence size factors (see [9], [10]).

$$k_{size} = \left(\frac{b}{150}\right)^{0.1} \cdot \left(\frac{l}{2000}\right)^{0.1} \tag{9}$$

$$k_{size} = \left(\frac{b}{150}\right)^{0.05} \cdot \left(\frac{h}{600}\right)^{0.1} \tag{10}$$

Statistical analysis methods

All data sets of the mechanical properties of boards and GLT have been statistically examined to determine the representative statistical distribution model (DM). The normal distribution (ND), two- and three-parametric logarithmic normal distribution (2pLND, 3pLND) and two- and three-parametric Weibull distribution (2pWD, 3pWD) have been fitted to the data and compared with the empirical distribution function (empD), calculated acc. [11], [12] and [13] (this calculation scheme has to be chosen to pronounce generally insufficient representation of values in the tail of distribution functions). For this determination quantitative- (sums of residues, statistical tests like KS-test) and qualitative methods (qq-plots and residual-plots, whereby emphasize of fit has been taken on lower quantile range between 0 % - 10 % cumulative frequency) have been applied.

$$empD = \frac{rank - 0.3}{n + 0.4} [\%] \qquad [11]$$

$$empD_{\to 0} \to rank = 0.3 \qquad [12]$$

$$empD_{\to 1} \to rank = n + 0.7 \qquad [13]$$

Statistical parameters like mean, variance, standard deviation and COV have been calculated as point estimates acc. the empirical distribution.
Scatter plots and correlation methods have been carried out to examine relationships between mechanical properties. Further applied regression analysis – by monitoring the coefficient of determination – lead to mean-regression functions. These are, in comparison to relationships on the level of extreme values (5 %-quantiles), statistically efficient and stable formulations to describe relationships between two or more statistical variables.
To take each sample size into account statistic values and regression functions of each series have been weighted according the sample size in respect to the significance of each series. By knowledge of representative distribution models and expected range of COV, mean regression models have been shifted to the 5 %-quantile level.
By application of this relative simple and efficient analysis method examinations of trend-relationships on the range of boarder quantiles, based on stable and simple to determine mean regression functions with background of data concerning representative statistical distribution models and related parameters, are possible.

Results and Discussion

According to *Fig. 4* further sub-chapters are partitioned to represent the potential of boards and GLT separate and close with a bearing model for GLT in bending.

Mechanical potential of boards in tension parallel to the grain

EN 1194, annex A contains equations to enable conformity of GLT production on the basis of calculations. Direct relationship between strength and stiffness values is missing but based on given equations it is possible to determine both values, for boards and GLT (see [14] and [15]). *Tab. 5* gives an overview of characteristic values for GLT of all strength classes and related requirements for boards.

$$f_{t,0,g,k} = 5 + 0.8 \cdot f_{t,0,l,k} \qquad [14]$$

$$E_{0,g,mean} = 1.05 \cdot E_{0,l,mean} \qquad [15]$$

Tab. 5. – Requirements on GLT and on the base material board in tension parallel to grain to reach characteristics of GLT-strength classes regulated in EN 1194

GLT strength classes			**GL 24h**	**GL 28h**	**GL 32h**	**GL 36h**
boards	$\mathbf{f_{t,0,l,k}}$	**[N/mm²]**	14.4 (= C24)	18.1 (= C30)	21.9 (~ C35)	26.3 (≠ C40!)
	$\mathbf{E_{0,l,mean}}$	**[N/mm²]**	11050	12000	13050	14000
GLT	$\mathbf{f_{t,0,g,k}}$	**[N/mm²]**	16.5	19.5	22.5	26.0
	$\mathbf{E_{0,g,mean}}$	**[N/mm²]**	11600	12600	13700	14700

For comparison with EN 1194 strength and stiffness properties of boards tested in tension have been prepared. *Fig. 5* gives an overview of examined data sets and results of linear regression analysis and related coefficients of determination (R^2).

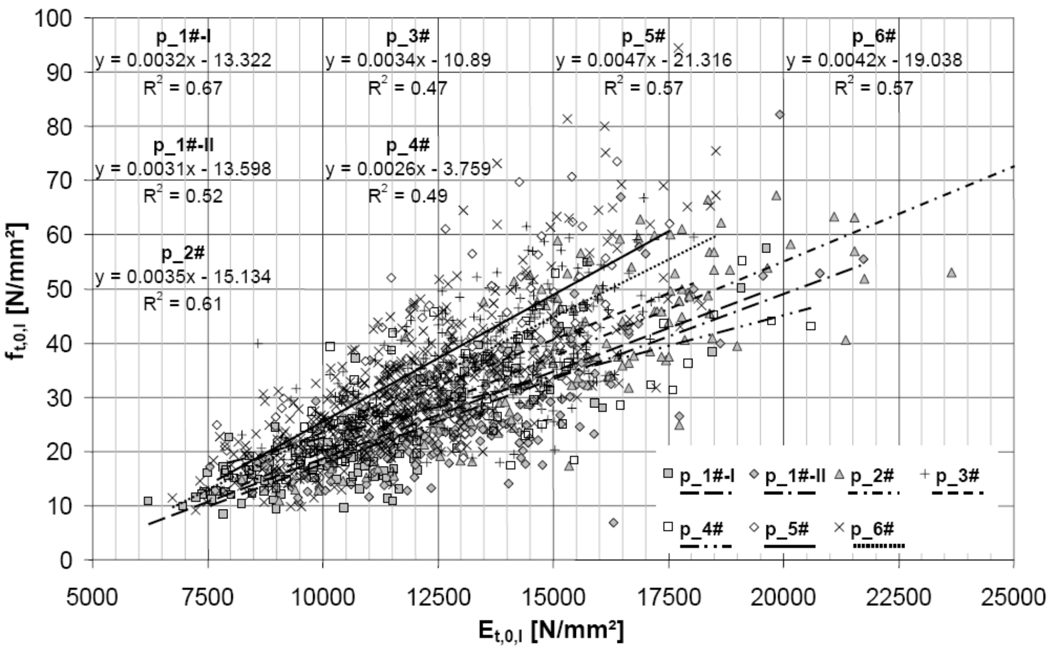

Fig. 5. – Relationship between tension strength $f_{t,0,l}$ and modulus of elasticity $E_{t,0,l}$ of boards of all examined samples: results of linear regression analysis and coefficient of determination

Based on statistical analysis and determination of representative statistical distribution models the normal distribution (ND) is proposed for the modulus of elasticity $E_{t,0,l}$ and the two-parametric logarithmic normal distribution (2pLND) for representing the tension strength values $f_{t,0,l}$ of the boards. Both distribution models can be additional explained by the mechanical properties itself: the modulus of elasticity is generally a mean value of the referred free tested length. Mean values and also mean trends tend to follow the central limit theorem which can be explained by the ND. Strength values – especially tension strength, characterized by brittle behavior – defines a minimum, the weakest section within the testing length (weakest link theory acc. Weibull 1939).

General, minimum values can statistically described by the extreme value theory. The physically logical distribution model would be the Weibull distribution (WD) defined with threshold $x_0 \geq 0$, indicating that strength values < 0 or nearly + 0 have the probability p(x) = 0. According to examined data sets the 2pLND – in comparison to the right skewed WD but also with $x_0 \geq 0$ – has been determined to best represent distribution of the tension strength values.
By consideration of both models the non-uniform and horn-shaped increase of scatter between strength and modulus of elasticity with increasing values can be explained as result of the marginal distributions.
Based on acc. sample sizes weighted statistical parameters and regression functions following results can be summarized (see *Tab. 6*):

Tab. 6. – Key figures and overall results of examined tension characteristics based on tension tests on boards parallel to the grain

Data extend	~ 1400 #
Quantity of series	7 #
Examined nominal grading classes	Nominal machine grading classes acc. DIN 4074 (MS7) MS10, MS13, MS17
Weighted average volume	l / w / h ~ 3600 / 150 / 39 mm
Weighted average free tested length	l_0 ~ 3000 mm
Weighted average COV-$f_{t,0,l}$	**27.2 %**

On the basis of the mean regression equation [16] and by consideration of expected range of COV-$f_{t,0,l}$ – for machine graded boards (20 % ≤ COV-$f_{t,0,l}$ ≤ 30 %) – the relationship between $f_{t,0,l,05}$ vers. $E_{t,0,l,mean}$ has been calculated (see [17] as example for COV-$f_{t,0,l}$ = 25 %) and compared with the current function implicit given in EN 1194 (see *Fig. 6*). This figure includes in addition calculated fields of minima and maxima of expected $E_{t,0,l,mean}$ and $f_{t,0,l,05}$ acc. to examined regression functions with lowest and highest gradient for strength and modulus of elasticity related to each GLT-strength class acc. the calculated requirements for boards given in EN 1194.

$$f_{t,0,l,mean} = -12.55 + 0.0035 \cdot E_{t,0,l,mean} \qquad [16]$$

$$f_{t,0,l,05} = -9.22 + 0.0024 \cdot E_{t,0,l,mean} \qquad [17]$$

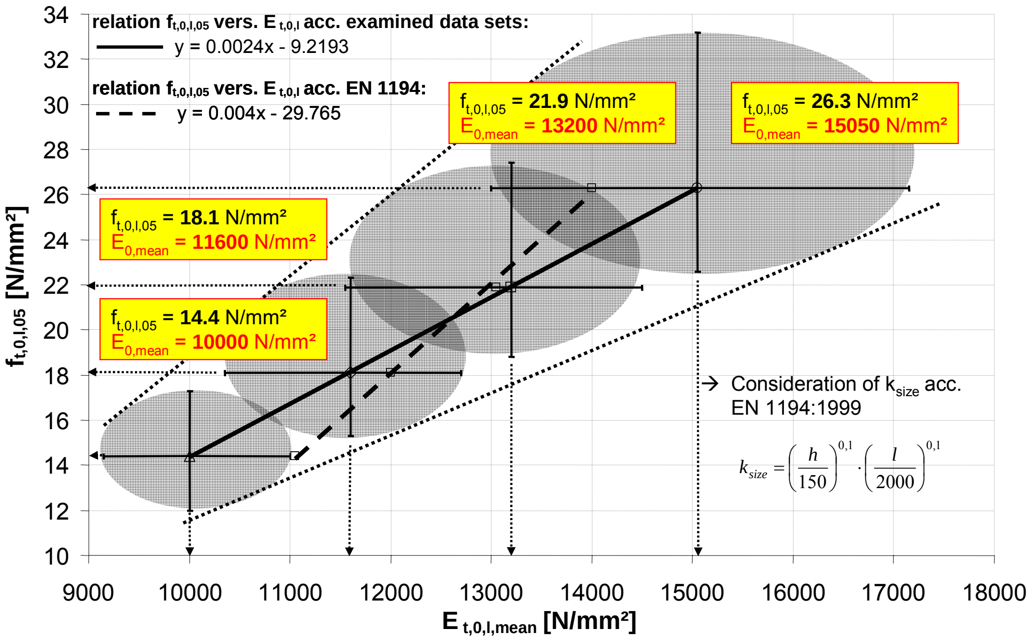

Fig. 6. – Relationship between $f_{t,0,l,05}$ and $E_{t,0,l,mean}$, based on examined data sets of Graz and assumed ND for $E_{t,0,l}$ and LND for $f_{t,0,l}$ with COV-$f_{t,0,l}$ = 25 %, in comparison to current regulations of EN 1194. Marked fields represent calculated minima and maxima of $f_{t,0,l,05}$ and $E_{t,0,l,mean}$ based on determined regression functions of lowest and highest gradient

It is apparent that the gradients of both functions – regression function of examined data sets and implicit equation given in EN 1194 – are different. Acc. the examined data sets current function of EN 1194 overestimates the $E_{t,0,l,mean}$ for GL24h but underestimates the $E_{t,0,l,mean}$ for higher GLT-strength classes GL32h and GL36h. By far and acc. the internal data sets current grading methods based on stiffness parameters (dynamic E-modulus or eigenfrequency) underestimate necessary strength values for lamellas for higher GLT-strength classes if the parameters for grading are set acc. the requirements for boards given in EN 1194.
Adaptation of the current relationship $f_{t,0,l,05}$ vers. $E_{t,0,l,mean}$, given in EN 1194, is proposed to take care of material inherent behavior (see [17]).

Mechanical potential of GLT in bending

Comparable to the examinations carried out with tension characteristics of boards also GLT-data sets, given in *Tab. 4,* have been evaluated in detail.
Fig. 7 reflect the scatter plot of relationship $f_{m,g}$ vers. $E_{m,g}$. Additional linear regression models and coefficient of determination (R^2), are given for each series. Apparent, in comparison with scatter plot of boards (see *Fig. 5*), is the uniform dispersion of compared data points. Also the regression equations are more or less parallel to each other. Based on statistical analysis with focus on specification of representative distribution model for both, bending strength $f_{m,g}$ and bending-E-modulus $E_{m,g}$, ND can be chosen.
This result can also be explained by the system structure and behavior of GLT itself: general, GLT can be described as a system of parallel arranged, rigid connected components lamellas, build up

of boards, board segments and finger joints. Bending tests have been carried out edgewise resulting in serial system behavior. This lead to an interaction of components and, as mentioned in former chapters, to a homogenization of the mechanical properties, expressed by an apparent decrease of the dispersion, herein expressed as COV. Especially the reduction of COV-$f_{m,g}$ is of interest because this leads to a benefit as increase of the 5 %-quantile which forms the basis for design and structure reliability judgment concerning the bearing capacity. The reduction of COV-$f_{m,g}$ and build-up of a system-acting structure lead to ND as representative distribution model. On the basis of ND, as margin distributions for $f_{m,g}$ and $E_{m,g}$, it follows the apparent uniform scatter plot.

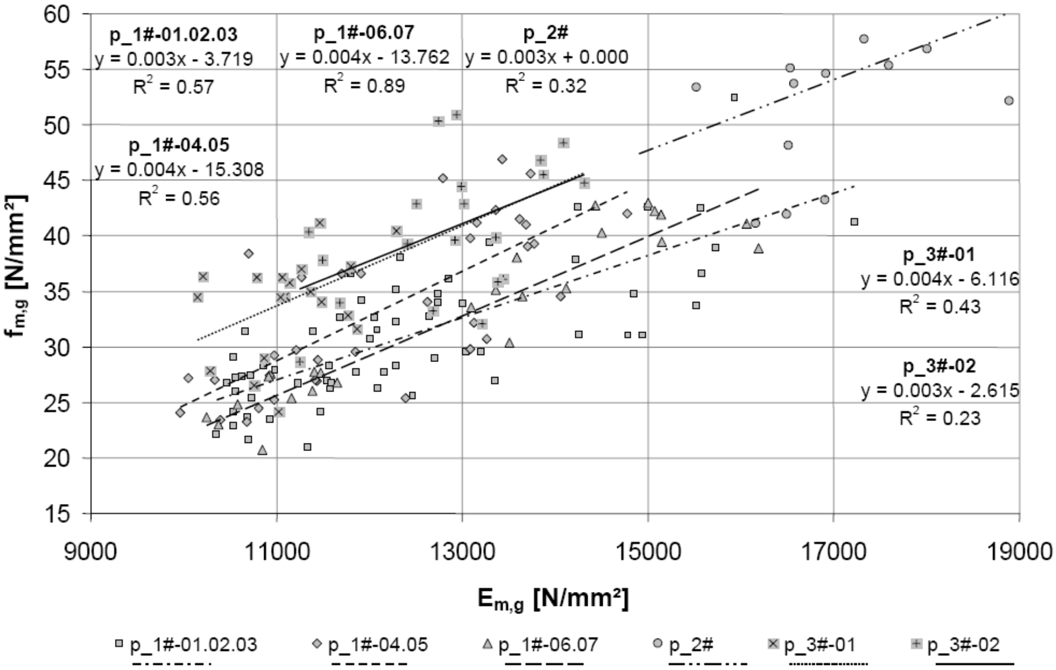

Fig. 7. – Relationship between bending strength $f_{m,g}$ and modulus of elasticity $E_{m,g}$ of GLT of all examined samples: results of linear regression analysis and coefficient of determination

Tab. 7 summarizes selected properties and additional key figures gained from examinations. On the basis of the statistical analysis following determined linear regression equation for description of the relationship $f_{m,g,mean}$ vers. $E_{m,g,mean}$ (see [18]) and expectable range of COV-$f_{m,g}$ between 10 % < COV-$f_{m,g}$ < 20 % is given.

$$f_{m,g,mean} = -2.95 + 0.003 \cdot E_{m,g,mean} \qquad [18]$$

Application of a shift of mean-regression function to the level of 5 %-quantile and expected COV-$f_{m,g}$ = 15 %, to describe $f_{m,g,05}$ vers. $E_{m,g,mean}$, has lead to equation given in *Fig. 8* and [19].

$$f_{m,g,05} = -2.22 + 0.0022 \cdot E_{m,g,mean} \qquad [19]$$

Tab. 7. – Key figures and overall results of examined bending characteristics based on four-point bending tests on GLT

Data extend	~ 180 #
Quantity of series (main / sub)	3 # / 6 #
Examined nominal grading classes of boards	Nominal machine grading classes acc. DIN 4074 MS10, MS13, MS17
Average quantity of boards / GLT sub-series	62 #
Failure criteria	GLT-beams with failure inducing criteria in finger joints are excluded!
Weighted average COV-$f_{m,g}$	**14.6 %**

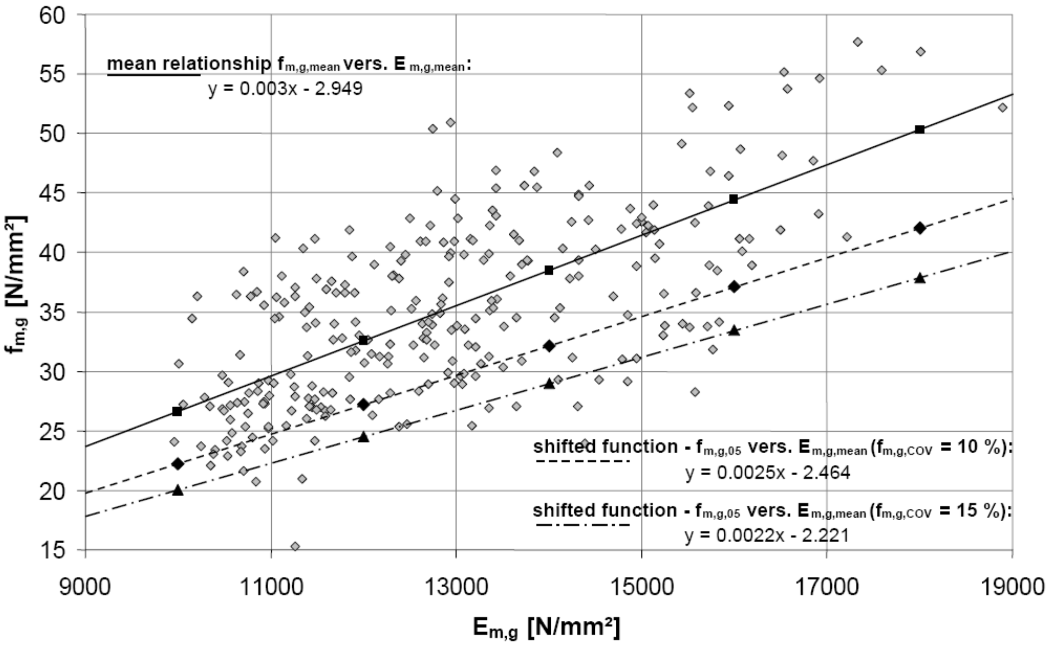

Fig. 8. – Relationship between bending strength $f_{m,g}$ and bending-E-modulus $E_{m,g}$ of all examined data sets: linear regression equations of $f_{m,g,mean}$ vers. $E_{m,g,mean}$ and $f_{m,g,05}$ vers. $E_{m,g,mean}$, by assumed ND and COV-$f_{m,g}$ = 10 % or 15 %

Bearing model for GLT in bending

Referencing *Fig. 4* and on the basis of two independent defined models for description of the mechanical potential of boards and GLT as relationships $f_{t,0,l}$ vers. $E_{t,0,l}$ and $f_{m,g}$ vers. $E_{m,g}$, a third model has been necessary to link both models together, to explain the important relationship $f_{t,0,l}$ vers. $f_{m,g}$. Based on the before discussed sensitive character of models on the level of the 5 %-quantile the approach of a mean relationship has been applied to define $f_{t,0,l,mean}$ vers. $f_{m,g,mean}$. Due to lack of direct comparability of all data sets of boards and hence build-up GLT only mean strength values of each sample or sub-sample can be utilized for further examinations. To enlarge the significance of carried out regression analysis additional data sets gained from literature have been introduced (see *Tab. 8*). All external values have been, so far information has been available, adapted to the reference dimensions and reference size factors acc. EN 1194.

Tab. 8. – External data sets extracted from Falk and Colling 1995

Source and lam. grade	Source and lam. grade	Source and lam. grade
Larsen 1982, T400+	Larsen 1982, Ucl+	Falk 1992, C30
Larsen 1982, T400	Larsen 1982, Ucl	Falk 1992, C37
Larsen 1982, T300+	Larsen 1982, Ucl-	Falk 1992, C37 / C30
Larsen 1982, T300-	Gehri 1992	--

All mean values ($f_{t,0,l,mean}$ and $f_{m,g,mean}$) from internal and external data sets are given in the scatter plot of *Fig. 9*. Various regression models have been fit to the values. The equations and related coefficient of determination (R^2) of linear-, logarithmic- and power-regression model are given. All three models represent the relationship between $f_{t,0,l,mean}$ and $f_{m,g,mean}$ in a proper way but by consideration of formulated constraints (see [5], [6], [7]) and as a result of section wise regression analysis the power-regression model, given in [20], has been nominated to describe the examined relationship.

$$f_{m,g,mean} = 2.251 \cdot f_{t,0,l,mean}^{\ 0.82} \qquad [20]$$

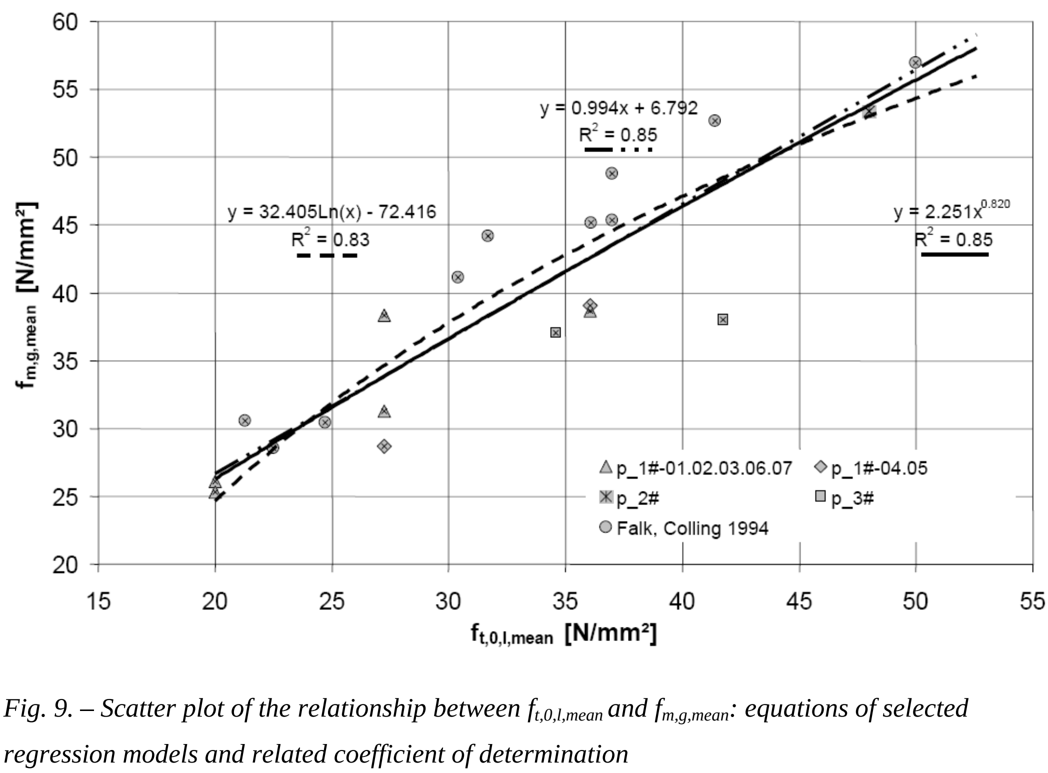

Fig. 9. – Scatter plot of the relationship between $f_{t,0,l,mean}$ and $f_{m,g,mean}$: equations of selected regression models and related coefficient of determination

The power model is already wide applied to characterise certain effects concerning wood. For example to describe size effects acc. the weakest link theory (Weibull 1939) or to describe the relationship between ($f_{t,0,k}$ / $f_{m,k}$) vers. $f_{m,k}$ (Burger and Glos 1997). Both mentioned applications are participating on the laminating effect.

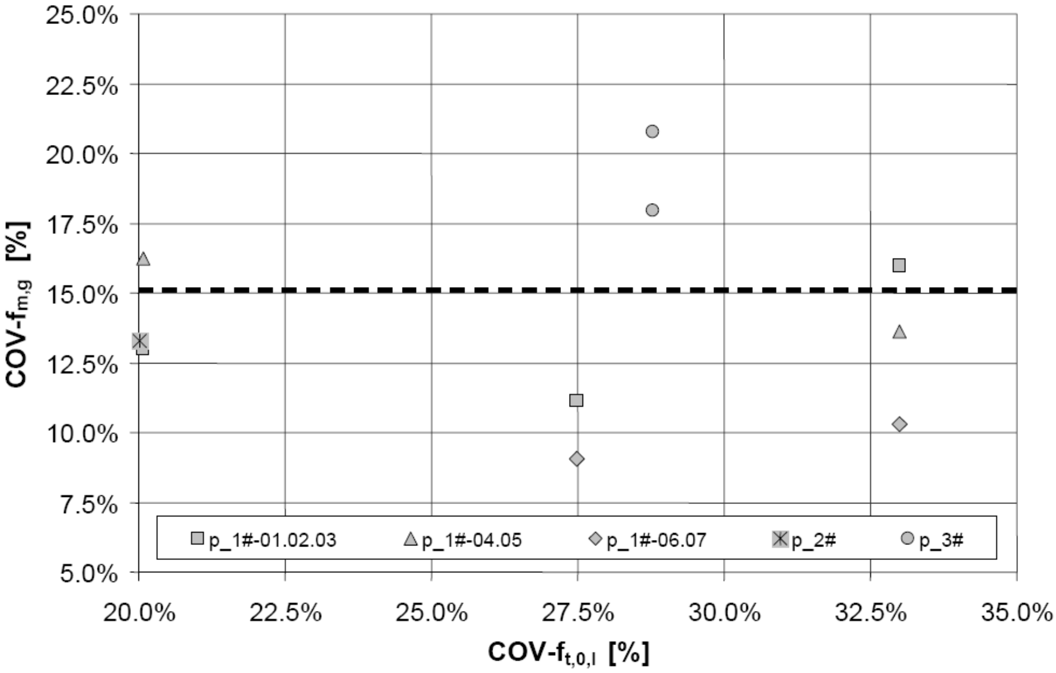

Fig. 10. – Scatter plot of the relationship COV-$f_{t,0,l}$ vers. COV-$f_{m,g}$ of internal data sets

The next step has been to examine the dependency of COV-$f_{t,0,l}$ on COV-$f_{m,g}$ (see *Fig. 10*). Only internal data sets have been included in this analysis because of lack of information concerning the dispersion of external strength values. On the basis of available data no dependency between COV-$f_{t,0,l}$ and COV-$f_{m,g}$ can be demonstrated but nevertheless a slightly distinct positive dependency cannot be neglected so far but assumed. Based on the results given in *Fig. 10* it is apparent that the homogenisation potential, due to the rigid system structure GLT harmonizes the high dispersing strength values of the boards to a certain level, more or less independent of the variability of strength values of the base material. It has already examined in detail and also established in statistic theory: high dispersions underlie distinctive regressive decrease with increasing quantity of interacting components in a system – e.g. expressed as system factor k_{sys} (Brandner 2006) or as size effect k_{size} (Brandner et al. 2007, Jeitler et al. 2007).

Based on publications of Glos 1981 and Augustin 2004 the expected COV-$f_{t,0,l}$ for visual or machine graded boards is in the range of (15 %) 20 % < COV-$f_{t,0,l}$ < 40 % (50 %) whereby general visual grading, due to lack of selectivity of limited grading parameters, can be classified in the range of 30 % < COV-$f_{t,0,l}$ < 40 %. The coefficient of variation of machine graded boards, if more than one single class for production is graded, can be defined in the range of 20 % < COV-$f_{t,0,l}$ < 30 %. For comparison the expected range of COV-$f_{m,g}$ for GLT can be identified between 10 % < COV-$f_{m,g}$ < 20 %, which only covers the half or less of possible relative dispersion of the base material board.

Following the given power regression equation of [20] has been shifted on the level of the 5 %-quantile to describe the dependency of $f_{m,g,05}$ from $f_{t,0,l,05}$ by variation of the model parameters COV-$f_{t,0,l}$ and COV-$f_{m,g}$ and representative statistical distribution model ND and LND. An example for COV-$f_{t,0,l}$ = 25 % and COV-$f_{m,g}$ = 15 % is given in *Fig. 11* and compared with available characteristic values of internal and external tests. The bold line in *Fig. 11* represents the in foregoing chapters defined representative distribution models with LND for characterising $f_{t,0,l}$ and ND for bending strength values $f_{m,g}$. This combination is on a conservative basis in relation to assumed ND or LND for both strength characteristics.

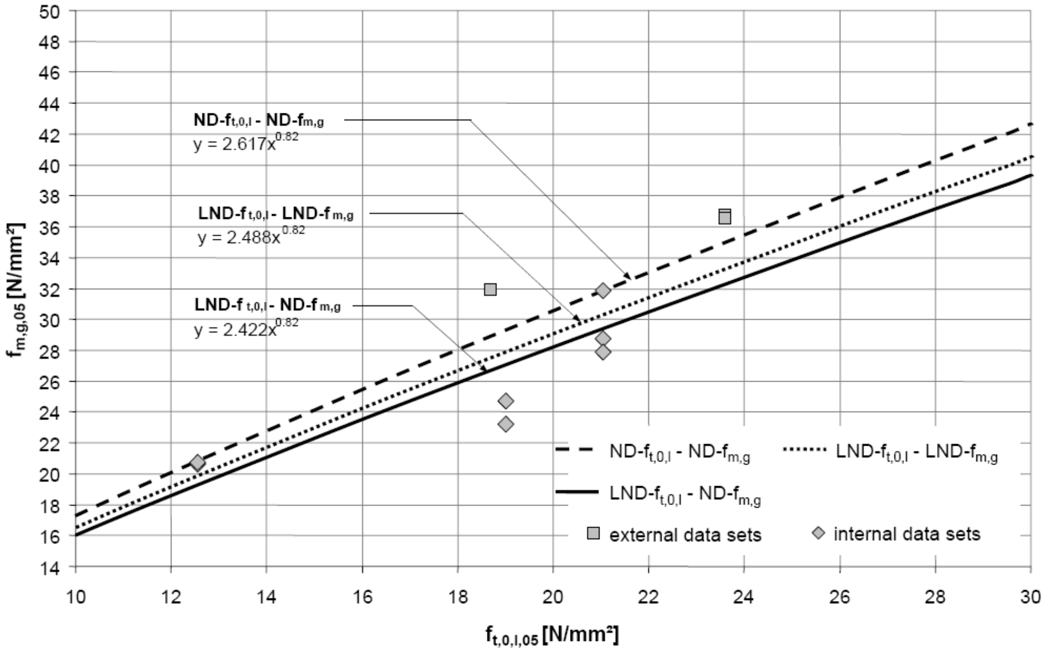

Fig. 11. – Scatter plot of the relationship $f_{t,0,l,05}$ vers. $f_{m,g,05}$ of internal and external data sets compared to shifted power function based on COV-$f_{t,0,l}$ = 25 %, COV-$f_{m,g}$ = 15 % and variation of representative statistical distribution models for $f_{t,0,l}$ and $f_{m,g}$ as parameter study

As result of carried out parameter study and by consideration of determined representative distribution models following bearing model for GLT in bending (GBM) can be formulated (see [21], [22] and [23]) defined for the range of COV between 20 % < COV-$f_{t,0,l}$ < 40 % and 10 % < COV-$f_{m,g}$ < 20 %:

$$f_{m,g,05} = m \cdot f_{t,0,l,05}^{\;0.82} \qquad [21]$$

$$m \rightarrow f\left\{DM_{f_{t,0,l}}, DM_{f_{m,g}}, COV_{f_{t,0,l}}, COV_{f_{m,g}}\right\} \qquad [22]$$

$$m = 1.67 \cdot \exp\left(1.48 \cdot COV_{f_{t,0,l}}\right) \cdot \left(1.33 - 2.18 \cdot COV_{f_{m,g}}\right) \qquad [23]$$

Gehri 2005 proposed the description of relationship between $f_{t,0,l,k}$ and $f_{m,g,k}$ by application of a power function to take into account the zero-threshold and non-linear decreasing laminating effect with increasing strength class of GLT by fitting a power model to current function of EN 1194 (see *Tab. 2*). Furthermore Gehri proposed already 1995 the importance of the consideration of COV of boards as result of attracting two samples with identical 5 %-quantile but deviating COV-$f_{t,0,l}$ whereby the sample with higher COV enables expected higher homogenisation potential due to higher $f_{t,0,l,mean}$ and related increased volume of boards in the higher strength region. In other words: improved grading methods and grading of population in more than one strength class (without reject) leads to a reduction of the dispersion COV-$f_{t,0,l}$. A comparison of two graded samples of boards with identical mean values $f_{t,0,l,mean}$ lead to higher 5 %-quantile $f_{t,0,l,05}$ in case of lower COV-$f_{t,0,l}$. Based on the model given in equation [21] the decrease of expectable laminating effect due to reduced COV-$f_{t,0,l}$ has to be weighted up with the increase of the 5 %-quantile $f_{t,0,l,05}$ as result of the reduction of COV-$f_{t,0,l}$ thanks to more significant grading parameters and / or high scaled internal quality control.

The influence of different grading methods and expectable COV-$f_{t,0,l}$ is visualized in *Fig. 12*. Two areas with defined ranges of COV-$f_{t,0,l}$ are highlighted. One area in the range of COV-$f_{t,0,l}$ = 35 ± 5 % refers to visual graded or e.g. only in one class machine graded boards (without reject). The higher COV-$f_{t,0,l}$ lead to higher expectable laminating effect expressed in a higher factor m if compared to the second field with COV-$f_{t,0,l}$ = 25 ± 5 % referred to accurate machine graded boards into more than one class.

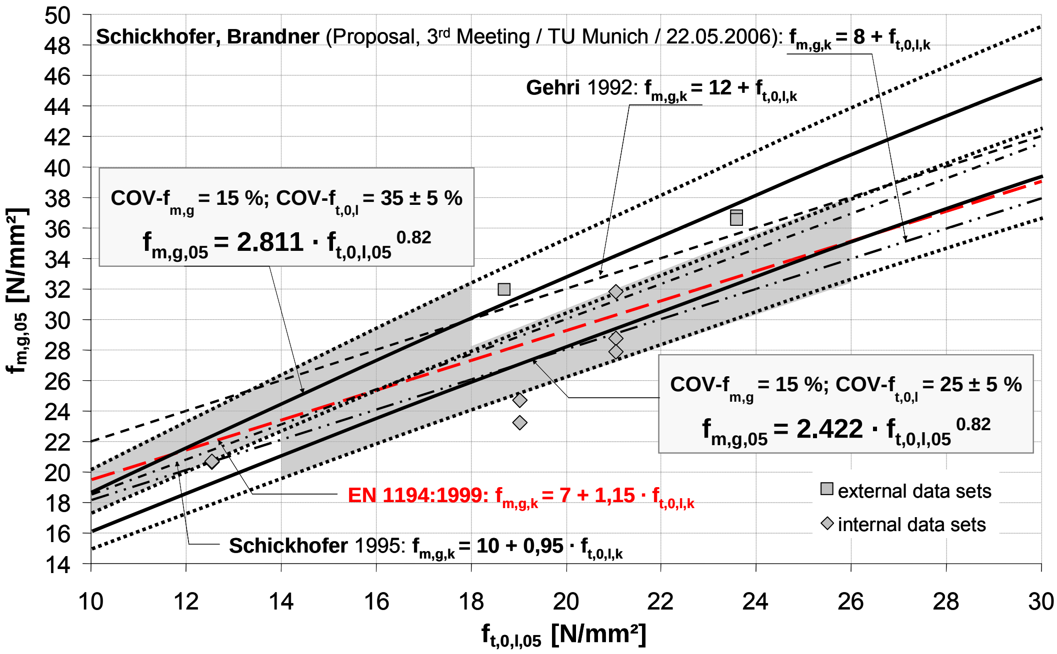

Fig. 12. – Relationship $f_{t,0,l,05}$ vers. $f_{m,g,05}$: parameter study concerning the influence of COV-$f_{t,0,l}$ on related laminating effect by assumed COV-$f_{m,g}$ = 15 % in comparison to selected published and proposed bearing models for GLT in bending

The results express the demand of consideration of the significant influence of the material inherent dispersion on the related laminating effect and hence on the expectable mechanical potential of GLT in bending. To that effect regulation of the relationship $f_{t,0,l,05}$ vers. $f_{m,g,05}$, by keeping in mind COV-$f_{t,0,l}$ and COV-$f_{m,g}$, is necessary and proposed as for example by definition of two areas of dispersion for application. This appears essential on the one hand to take care of efficient use of the raw material timber, on the other hand to guarantee the safety and reliability of the engineered product GLT.

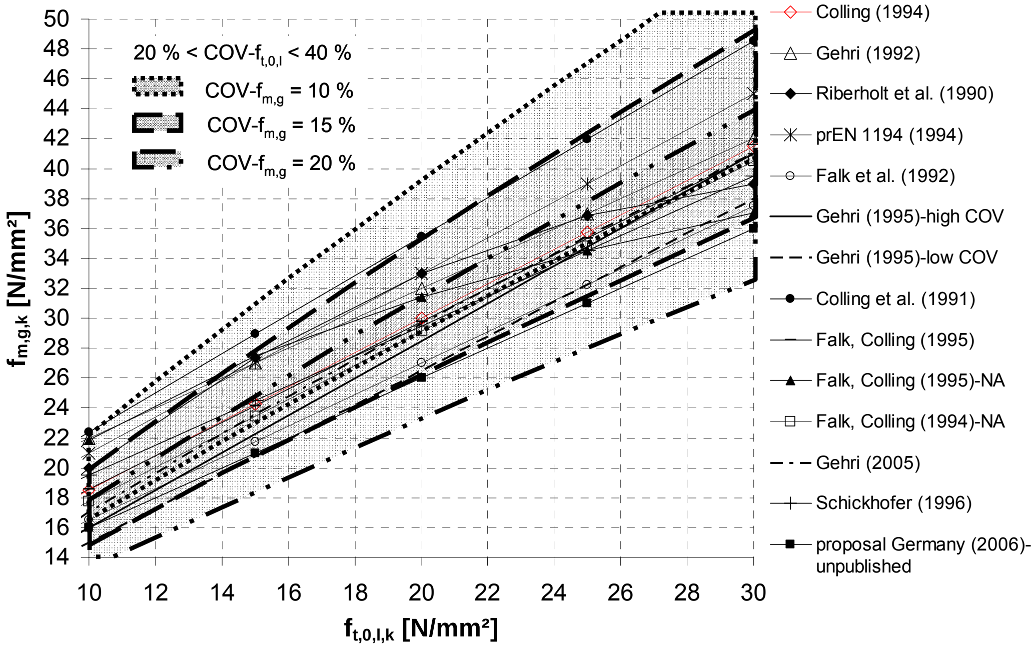

Fig. 13. – Relationship $f_{t,0,l,05}$ vers. $f_{m,g,05}$: comparison of GBM with researched models for GLT in bending by variation of COV-$f_{t,0,l}$ and COV-$f_{m,g}$

Tab. 9. – Range of needed characteristic tension strength ft,0,l,05 to fulfil the requirements for characteristic bending strength fm,g,05 of GLT acc. the given strength classes: COV-ft,0,l = 30 ± 10 %, COV-fm,g = 15 %

GLT-strength classes **[--]**	**$f_{m,g,k}$** **[N/mm²]**	**$f_{t,0,l,k}$** **min - EN 1194:1999 - max** **[N/mm²]**
GL24h	24	11.5 – 14.8 – 18.0
GL28h	28	14.5 – 18.3 – 22.0
GL32h	32	17.5 – 21.7 – 26.0
GL36h	36	20.5 – 25.2 – 30.0

For discussion the proposed GBM-model acc. [21] has been compared to all researched bearing models for GLT in bending by variation of COV-$f_{m,g}$ and COV-$f_{t,0,l}$. The result is presented in *Fig. 13*, related calculated tension strength values of the boards ($f_{t,0,l,05}$) to build-up GLT of given strength classes are given in*Tab. 9*. As can be seen by assumption of expected and most relevant dispersion range (20 % < COV-$f_{t,0,l}$ < 40 %; COV-$f_{m,g}$ = 15 %) nearly all researched bearing models of literature are covered by the parameter study. All these models are able to represent a certain combination of the relationship $f_{t,0,l,05}$ vers. $f_{m,g,05}$ by consideration of related relative dispersions.

For further applications it appears necessary to take care of examined high influencing parameter COV to take account for the statistical necessity of these values to enable calculations of the 5 %-quantiles and the judgement of homogenisation potential by cognition of the marginal constraints for the system structure GLT.

Conclusions

On the basis of so far carried out studies and gained results of foregoing chapters following statements and proposals are given:

- The laminating effect, expressed as ratio of $f_{m,g,k}$ / $f_{t,0,l,k}$, is a result of mechanical and statistical based sub-effects and related interactions which have so far not clarified in detail.
- Researched models for GLT in bending over the last 18 years reflect a wide variability in characterizing $f_{t,0,l,k}$ vers. $f_{m,g,k}$. Furthermore a trend of decreasing gradient of models of the last years is apparent (Colling 1991 – EN 1194:1999 – unpublished proposal of Germany 2006).
- The influence of the coefficient of variation of the base material board and hence build up GLT (COV-$f_{t,0,l}$, COV-$f_{m,g}$) on the laminating effect has already published by Gehri 1995 but not considered so far in EN 1194.
- Determination of relationship $f_{t,0,l}$ vers. $f_{m,g}$ on the 5 %-quantile-level, based on limited sample size, is statistically high sensitive. Examination of a mean-relationship and further shift of the regression equation to the level of 5 %-quantile, by known representative statistical distribution models and related parameters (especially COV) of participating variables is proposed.
- Examination of around 1400 # boards, tested in tension parallel to the grain, lead to a lower gradient of the describing regression model $f_{t,0,l,05}$ vers. $E_{t,0,l,mean}$ than implicit given in EN 1194. Based on this result stiffness properties of boards concerning higher GLT-strength classes are underestimated. If grading machines are adjusted acc. stiffness requirements on boards given in EN 1194 this may lead to insufficient characteristic strength values $f_{t,0,l,k}$ for higher GLT-strength classes.
- Acc. the examined data sets and referenced publications (Augustin 2004, Glos 1981) following expectable spans of COV-$f_{t,0,l}$ can be defined:

- → 20 % < COV-$f_{t,0,l}$ < 30 %: in case of machine graded boards into more than one class (without reject)
- → 30 % < COV-$f_{t,0,l}$ < 40 %: in case of visual graded boards, insufficient machine grading or machine grading only in one class (without reject)

- Following representative statistical distribution models to characterize tension characteristics of boards have been determined:
  - → $E_{t,0,l}$ → ND
  - → $f_{t,0,l}$ → LND
- Examination of the mechanical potential of GLT tested in bending reflects, in addition to tension characteristics of boards, a lower gradient of the regression function $f_{m,g,05}$ vers. $E_{m,g,mean}$ if compared to the requirements given in EN 1194.
- The higher mean of $E_{m,g}$ if compared to $E_{t,0,l}$ of 5 %, due to the system compound GLT regulated in EN 1194, could not be confirmed. It is proposed that $E_{m,g,mean} = E_{t,0,l,mean}$
- Acc. the examined data sets the ND has been determined to represent the distribution of $f_{m,g}$ and $E_{m,g}$. Furthermore the expectable range of COV-$f_{m,g}$ can be defined between 10 % < COV-$f_{m,g}$ < 20 %.
- On the basis of foregoing defined regression models – $f_{t,0,l,05}$ vers. $E_{t,0,l,mean}$ and $f_{m,g,05}$ vers. $E_{m,g,mean}$ – a third model to describe $f_{t,0,l}$ vers. $f_{m,g}$ has been established by a mean regression function and under consideration of external data sets. Thereby the power regression model has been determined to describe the relation best.
- An accurate description of $f_{t,0,l,05}$ vers. $f_{m,g,05}$ has been established by shifting the mean power regression model $f_{t,0,l,mean}$ vers. $f_{m,g,mean}$ in regard to the representative distribution models of $f_{t,0,l}$ and $f_{m,g}$ and related ranges of dispersion of COV-$f_{t,0,l}$ and COV-$f_{m,g}$.
- Examination of COV-$f_{t,0,l}$ vers. COV-$f_{m,g}$ has reflected the enormous homogenization potential due to the system build-up of GLT, expressed by more or less harmonization of COV-$f_{m,g}$ to a certain level around COV-$f_{m,g}$ = 15 %, independent of COV-$f_{t,0,l}$.
- Based on parameter studies by variation of COV-$f_{t,0,l}$ and COV-$f_{m,g}$ all researched GLT-beam models can be covered by a range of COV-$f_{t,0,l}$ = 30 ± 10 % and COV-$f_{m,g}$ = 15 %. It can be assumed that all so far proposed models are correct by taken into account a certain combination of the dispersion values and further influencing parameters. Furthermore it has to be declared: the influence of COV on expectable laminating effect is significant and in regard to the relative dispersion COV increasing with increasing GLT-strength class.

Proposal for required tension characteristics of boards acc. GLT-strength classes regulated in current EN 1194

On the basis of above statements and the proposed GBM for GLT in bending given in formula [21] requirements for the tension characteristics of boards as base material are formulated in *Tab. 10*, by assumption of expectable COV-$f_{t,0,l}$ = 35 ± 5 % and *Tab. 11* for COV-$f_{t,0,l}$ = 25 ± 5 %. The dispersion of GLT-bending strength has been, for practical simplification, assumed as constant value with COV-$f_{m,g}$ = 15 %.

Because of special requirements on boards in tension parallel to the grain – in contrast to the strength classes for solid timber, regulated in EN 338 – it is proposed to term the strength classes by **T**xx.x **E**xx.x, with abbreviation **T** for tension, followed by the required characteristic tension strength $f_{t,0,l,k}$ in [N/mm²] and **E** for tension-E-modulus $E_{t,0,l,mean}$, followed by the required mean E-modulus in [10^{-3} N/mm²]. To be able to differentiate strength classes for boards with expected different COV-$f_{t,0,l}$ an additional sign (+) terms the higher COV-$f_{t,0,l}$ for the proposed values given in *Tab. 10*.

Tab. 10. – Proposal for required tension characteristics of boards acc. GLT-strength classes regulated in current EN 1194: assumed COV-$f_{t,0,l}$ = 35 ± 5 %, COV-$f_{m,g}$ = 15 %

GLT-strength class [--]	$f_{m,g,k}$ [N/mm²]	$E_{m,g,mean}$ [N/mm²]	Board-strength class [--]	$f_{t,0,l,k}$ [N/mm²]	$E_{t,0,l,mean}$ [N/mm²]
GL24h	24.0	11000	**T**14.5 **E**11.0 +	14.5	11000
GL28h	28.0	12500	**T**18.0 **E**12.5 +	18.0	12500

Tab. 11. – Proposal for required tension characteristics of boards acc. GLT-strength classes regulated in current EN 1194: assumed COV-$f_{t,0,l}$ = 25 ± 5 %, COV-$f_{m,g}$ = 15 %

GLT-strength class [--]	$f_{m,g,k}$ [N/mm²]	$E_{m,g,mean}$ [N/mm²]	Board-strength class [--]	$f_{t,0,l,k}$ [N/mm²]	$E_{t,0,l,mean}$ [N/mm²]
GL24h	24.0	11000	**T**16.5 **E**11.0	16.5	11000
GL28h	28.0	12500	**T**20.0 **E**12.5	20.0	12500
GL32h	32.0	14000	**T**24.0 **E**14.0	24.0	14000
GL36h	36.0	15500	**T**28.0 **E**15.5	28.0	15500

This paper clearly reflects the necessity for consideration of COV as further and high influencing parameter in bearing models of system structures and even in the regulation of solid timber elements. The presented studies and the proposals are seen as important contribution for the revision of EN 1194 to enable, on the one hand, a product conform regulation, and on the other hand additional information to enable judgment of the safety and reliability of timber structures build up by glued laminated timber.

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