Determination of Shear Modulus by means of standardized Four-Point Bending tests

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Abstract

According to EN 408, the shear modulus can be determined by means of two standardized test methods, i.e. the single span method and the variable span method. In the last few years, two further methods, namely torsion tests and ‘shear field’ tests, have been developed and are now also performed in testing practice. The latter is based on a relatively simple and reproducible measurement of the shear distortion by means of standardized four-point bending tests according to EN 408. The measuring instruments are applied within the areas of constant transverse force. They are arranged symmetrically with respect to the neutral axis, which results in four ‘shear fields’ under investigation (left-right, front-back).

The practical results, gained from performing standardized test methods, torsion tests as well as the measurement of shear distortion within ‘shear fields’ on glued laminated timber beams (GLT) of strength classes GL24h (w_g / d_g = 150 / 320 mm), as already published by Brandner et al. (2007), are outlined, discussed and completed by current tests on GL36h and GL36c (w_g / d_g = 160 / 600 mm). Furthermore, the relation of the shear modulus and the GLT-strength class, in comparison with solid timber, is treated.

Torsion tests are simple, robust and do not require expensive equipment, but they only provide the shear modulus $G_{090,tor}$. This method is proposed for the determination of G-values on specimens of small cross sections and for obtaining G-values for solid timber. With the measurement of shear distortion by the application of ‘shear fields’ on specimens tested in four-point bending according to EN 408 not only the standard values $E_{m,l}$, $E_{m,g}$ and f_m can be determined, but it allows also an easy, affordable and robust determination of the material characteristic G-modulus. The ‘shear field’ test method is proposed and approved for GLT with $d_g \geq 300$ mm. A proposal for the consideration of both methods within the testing standard EN 408 is presented.

1 Introduction

Wood and timber, in particular, is a heterogenous, natural material with generally high dispering properties. A treatment of wood as orthotropic material in timber engineering and modelling requires nine independent parameters: to link the tensor of strength and elongation, three moduli of elasticity and three shear moduli are necessary. To determine these six material constants, reliable test configurations that also allow practical application are required. This way, robust and reproduceable characteristics can be gained on the one hand and, by means of international standardization, comparability and reduction of costs and resources can be enabled on the other.

When it comes to practical applications, the main focus lies on the modulus of elasticity parallel to the fiber, predominantly in bending, (E_m), e.g. for Nordic spruce (*picea Abies Karst.*) of about $E_{m,l,mean}$ = 12,500 N/mm². The expectable shear modulus in solid timber, by contrast, – due to varying cutting patterns and varying radial positions in the stem a smeared value of G_{12} and $G_{13} \rightarrow G_{090}$ – lies around $G_{090,mean}$ = 650 N/mm², calculated acc. to the regression function given in Görlacher and Kürth (1994) and in line with Niemz (1993) and Kollmann (1995). This reflects a relationship between $G_{090,mean}$ / $E_{m,0,mean}$ of around 1 / 19 and seems to lead to minor influence and relevance of a correct G-modulus for serviceability in comparison to the E-modulus considering the ratio between bending- and shear deflection. Acc. to EN 338, a constant relationship of $G_{090,mean}$ / $E_{0,mean}$ = 1 / 16 and acc. to EN 1194 a factor of $G_{090,mean}$ / $E_{0,mean}$ = 1 / 15.4 is given. Due to many important reasons (see Harrison (2006), Divos et al. (1998), Görlacher and Kürth (1994), Niemz (1993) and others), the ratio $G_{090,mean}$ / $E_{0,mean}$ can not be treated as constant and varies for example in Nordic spruce in the range of $G_{090,mean}$ / $E_{0,mean}$ = 1 / 11 ÷ 1 / 37, depending on timber quality and applied test methods (see e.g. Brandner et al. (2007)). The importance of a correct G-modulus has already been discussed in several papers. In case of wood modelling and timber engineering, the following question can be rised: how accurate is accurate enough. In case of beams of high span-to-depth ratio (l_{span} / d) under bending, shear deflection plays a minor and even neglectable role compared to bending deflection. Nevertheless, in several constructions G_{090} gains increasing importance, especially in decreasing span-to-depth ratios and in case of lateral torsional buckling (see e.g. Skaggs and Bender (1995), Gehri (2005)).

In this paper, the following two test methods for deriving G-modulus of timber and engineered timber products are discussed: torsion tests and the application of shear fields during standardized 4p.-bending tests. The first method has already been treated in detail in Brandner et al. (2007). Given recommendations for the standardization of torsion tests instead of the two methods regulated in the past in EN 408, the single span method and the variable span method already exist. A draft prEN 408 was worked out and distributed by Leijten (2008). The second method is treated in more detail in this paper as further encouraging experiments have been concluded that reflect and undermine the relatively simple and reliable test method.

2 Materials

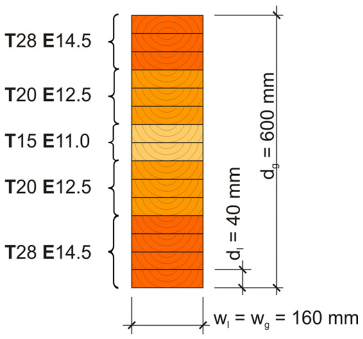

Fig 1: Cross section of GL36c: strength classes of boards

Three independent series of glued laminated timber of Nordic spruce (*picea Abies Karst.*) were tested in four-point bending (4pB) acc. EN 408. The first series – **GLT-I** – was glulam of strength class GL24h acc. EN 1194 of cross section w_g / d_g = 150 / 320 mm. Details are given in Brandner et al. (2007). 25 # glulam beams of the second series **GLT-II** of strength class GL36h acc. to EN 1194 were built up of boards graded to L40 acc. to EN 14081 by means of Golden Eye 706 / Microtec (combination of eigenfrequency and X-ray scanner) to fulfill **T**28**E**14.5 ($f_{t,0,l,k}$ = 28 N/mm², $E_{t,0,l,mean}$ = 14,500 N/mm²). 5 # GLT-beams of the third series **GLT-III** of GL36c acc. to EN 1194 were built up of three different lamella strength grades – **T**28**E**14.5, **T**20**E**12.5 and **T**15**E**11.0 – graded visually as well as by additional means of density and dynamical E-modulus $E_{dyn,US}$ (see Fig. 1). The cross sections of series **GLT-II** and **GLT-III** were w_g / d_g = 160 / 600 mm, built up of 15 # lamellae of thickness d_l = 40 mm.

3 Methods

All tests were carried out by continuous measurements of time, deflections and forces. Failures were analysed and recorded. The four-point-bending tests were derived by application of hysteresis with peaks of deflections at 50 % of the calculated average maximum stress level. The test configurations for tension tests and 4p.-bending tests were performed acc. to EN 408.

3.1 Tensile tests of boards and finger joints

The tensile tests of boards parallel to the grain were carried out acc. EN 408, with a free testing length of $l_{test} > 9 \cdot w_l = 1{,}420$ mm in series **GLT-I**, $l_{test} > 9 \cdot w_l = 3{,}348$ mm in series **GLT-II**, and $l_{test} > 9 \cdot w_l = 4{,}350$ mm in series **GLT-III**, by measuring the global deflections over adjusted $l_{0,machine}$. Tension tests on finger joints were accomplished with a free testing length of $l_{test} = 200$ mm acc. EN 1194. The tension characteristics $f_{t,0,l}$, $f_{t,j}$ and the modulus of elasticity $E_{t,0,l}$ were calculated acc. to EN 408. The modulus of elasticity $E_{t,0,l}$ was adjusted to a reference moisture content of u = 12 % to $E_{t,0,l,12}$ as given in EN 384.

3.2 Four-point-bending tests on glulam

The standardized 4p.-bending tests on edgewise loaded GLT were conducted acc. to EN 408 with a span of $l_{span} = (18 \pm 3) \cdot d_g$ and with a distance of $l_{load} = 6 \cdot d_g$ between the loading points. During the 4p.-bending tests, measurements of local- (over a length of $l_1 = 5 \cdot d_g$) and global bending deflections and forces were recorded (see also Fig. 2). The mechanical characteristics $f_{m,g}$, $E_{m,g,l}$ and $E_{m,g,g}$ were calculated acc. to EN 408 and adjusted to a reference moisture content of u = 12 % to $E_{m,g,l,12}$ and $E_{m,g,g,12}$ as given in EN 384.

3.3 Applied test methods for the determination of shear modulus G_{090} of glulam

In total, four different test methods for deriving the G-modulus of GLT were applied. Firstly, the two methods regulated so far in EN 408 – the 'single span method' and the 'variable span method' – were investigated. Secondly, the shear distortion was measured by means of torsion tests on GL24h beams (series **GLT-I**), as this test method is already established and standardized in the United States (see ASTM D 198). The fourth method, scarce but also already established in practise, measures the shear distortion within shear fields by means of standardized four-point bending tests according to EN 408. The measuring instruments are applied within the areas of constant transverse force. They are arranged symmetrically with respect to the neutral axis, which results in four 'shear fields' under investigation (left-right, front-back). The first three methods have already been discussed in detail in Brandner et al. (2007). The last method – 'measurement of shear distortion within shear fields' – was examined in more detail within the series **GLT-II** and **GLT-III** and is described hereafter.

Measurement of shear distortion within shear fields by means of standardized four-point bending tests acc. to EN 408

Measurements of shear distortion in the area of constant transverse force during shear tests have already been developed in the past e.g. by FMPA (1983) and Gehri (2005). The idea was to adjust this test configuration, generally applied in shear tests, for the standard 4p.-bending test configuration given in EN 408 (see Fig. 2, Fig. 3 and Fig. 4).

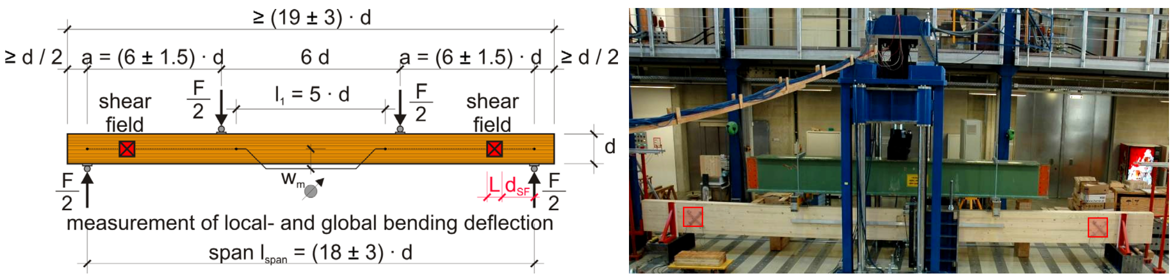

Fig. 2: Test configuration of 4p.-bending tests on GLT acc. to EN 408: measurement of local- and global bending deflection and application of shear fields for measurement of shear deflection (left), image of the 4p.-bending tests of series **GLT-II** and **GLT-III** (right)

Fig. 3: Application of shear fields of series **GLT-II** and **GLT-III**: fixing of holders for rubber bands (left), mounting of measurement device (left-middle), overview (middle-right), detail of distortion measurement device DD1 with metering needle placed on a nail-head (right)

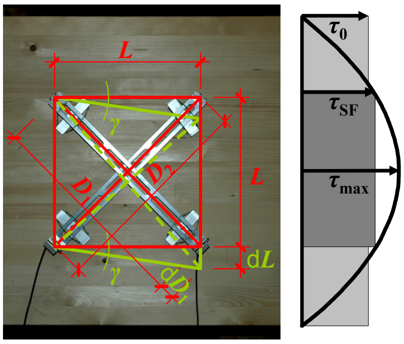

Fig. 4: Shear field and declaration of τ_0, τ_{max} and τ_{SF}

Due to minor induced shear distortion, the precise measurement device DD1 with 1 / 1000 mm accuracy was applied on all of the four shear fields of each GLT-beam, placed on both sides of the constant transverse force and opposite each side of the beam (left-right, front-back) and tested edgewise in 4p.-bending acc. to EN 408. The dimension of the squared shear fields was L / L = 283 / 283 mm with D = 400 mm and d_{SF} = 500 mm. They were arranged symmetrically to the neutral axis. In general a distance between the shear field and the bearing point of $d_{SF} \geq d$ is recommended to reduce the influence of compression stress perpendicular to the grain to a non-relevant level. Due to the squared parabola shape of the shear stress distribution over the cross section and the reduced monitoring field of shear distortion over the depth of the beam, the generally applied shear correction factor κ = 6 / 5 was adjusted and replaced by α acc. to [1], [2] and in reference to Gehri (2005). The calculation of α is a simple relationship of the distribution of shear stress over the whole depth of the beam versus the shear stress distribution within the shear field in relationship to the maximum shear stress in the middle of the beam τ_{max}. The calculation procedure for deriving $G_{090,SF}$ is given in [3] and [4].

$$\alpha = \frac{\tau_{SF}}{\tau_0} + \frac{2}{3} \cdot \left(\frac{\tau_{max}}{\tau_0} - \frac{\tau_{SF}}{\tau_0} \right) = 1 + \frac{1}{3} \cdot \frac{\tau_{SF}}{\tau_0} \qquad [1]$$

$$\tau_0 = G_{090} \cdot \gamma = \frac{Q_z}{w \cdot d} \quad , \quad \tau_{SF} = \tau_{xz}\left(z = \frac{L}{2} \right) = \frac{Q_z \cdot S(z)}{I_y \cdot w} \quad , \quad \frac{\tau_{max}}{\tau_0} = \frac{3}{2} \qquad [2]$$

$$\gamma = \frac{dD_1 - dD_2}{L \cdot \sqrt{2}} \quad \text{.... with} \quad dD_1 > dD_2 \qquad [3]$$

$$G_{090,SF} = \alpha \cdot \frac{\tau_0}{\gamma} = \alpha \cdot \frac{\sqrt{2} \cdot L}{A} \cdot \frac{dQ_z}{dD_1 - dD_2} \qquad [4]$$

4 Results

4.1 $G_{090,SF}$ in connection with the GLT strength class of series GLT-II

4.1.1 Tensile test data of boards and finger joints

The results of the performed static tensile tests ($f_{t,0,l}$, $E_{t,0,l,12}$, $\rho_{l,12}$) of series **GLT-II** are given in Tab. 1. The statistical analysis reflects the expected COV-$f_{t,0,l}$ = (25 ± 5 %) = 26.9 % for the high strength class **T**28**E**14.5 and also the fulfilment of the requirements for the **T**28**E**14.5 strength class acc. to Brandner and Schickhofer (2008) with $f_{t,0,l,k}$ = 28.6 N/mm², $E_{t,0,l,mean,12}$ = 14,440 N/mm² and $\rho_{l,k,12}$ = 440 kg/m³. The statistics of the finger joints tensile strength values also corresponds with the expected COV-$f_{t,j}$ = (15 ± 5 %) = 18 %, but shows a bit too low ($\Delta f_{t,j}$ = 2.5 N/mm²) with a characteristic strength of $f_{t,j,k}$ = 31.1 N/mm² instead of required $f_{t,j,k,requ}$ = 1.2 · $f_{t,0,l,k,requ}$ = 1.2 · 28.0 = 33.6 N/mm² acc. to the proposed model given in Tab. 3.

Tab. 1: Statistics of tensile tests on boards and finger joints of the base material of series **GLT-II**

GLT-II Base material	**Tension tests – boards**			**Finger joints**
	$\rho_{l,12}$ [kg/m³]	$E_{t,0,l,12}$ [N/mm²]	$f_{t,0,l}$ [N/mm²]	$f_{t,j}$ [N/mm²]
Quantity	102 #	102 #	98 #	30 #
mean	**494**	**14,440**	**45.6**	**52.0**
COV	**6.9 %**	**8.7 %**	**26.9 %**	**18.1 %**
$x_{05,empD}$	439	12,600	26.6	33.3
$x_{05,DM}$	440 (2pLND)	12,620 (3pWD)	26.3 (3pWD)	32.6 (2pWD)
$k_{size,EN\ 1194}$	--	--	1.07	--
$\mathbf{x_{k,DM}}$	**--**	**--**	**27.2**	**31.1**
$\mathbf{x_{k,EN\ 14358}}$	**--**	**--**	**28.6**	**--**

4.1.2 Four-point-bending test data of GL 36h

The 25 # glulam beams were tested acc. Fig. 2-left, with a span of $l_{span} = 15 \cdot d_g = 15 \cdot 600 =$ 9,000 mm. The predominant failure criteria were analysed by continuously observing each 4p.-bending test and by painstaking examination of the fracture region under consideration of years of practical experience. Consequently, the failure criteria were grouped to 'predominant failures in timber due to bending' – 'wood failure' (WF) (16 #), 'predominant failure in timber due to shear' – 'shear failure' (SF) (3 #) and 'predominant failure in the finger joint' – 'finger joint failure' (FJF) (6 #). For further discussion relevant statistics are given in Tab. 2, including the values of $G_{090,SF}$.

Tab. 2: Statistics of series **GLT-II** – GL36h acc. EN 1194 – tested in 4p.-bending acc. EN 408: test results of all 25 # beams and statistiscs of beams with wood failures in bending (WF)

GLT-II_all	$\rho_{g,12}$ [kg/m³]	$E_{m,g,l,12}$ [N/mm²]	$E_{m,g,g,12}$ [N/mm²]	$G_{090,SF,12}$ [N/mm²]	$f_{m,g}$ [N/mm²]
quantity	25 #	25 #	25 #	25 #	25 #
mean	**498**	**15,880**	**14,650**	**660**	**41.9**
COV	**1.2 %**	**3.8 %**	**3.5 %**	**4.8 %**	**12.2 %**
$x_{05,empD}$	490	15,080	13,950	608	32.7
$x_{05,DM}$	489 (2pLND)	15,090 (3pWD)	13,960 (3pWD)	609 (2pLND)	33.5 (ND)
$\mathbf{x_{k,EN\ 14358}}$	**--**	**--**	**--**	**--**	**33.2**
GLT-II_WF	$\rho_{g,12}$ [kg/m³]	$E_{m,g,l,12}$ [N/mm²]	$E_{m,g,g,12}$ [N/mm²]	$G_{090,SF,12}$ [N/mm²]	$f_{m,g}$ [N/mm²]
quantity	16 #	16 #	16 #	16 #	16 #
mean	**499**	**15,750**	**14,540**	**662**	**42.3**
COV	**1.4 %**	**3.7 %**	**3.5 %**	**5.0 %**	**7.7 %**
$x_{05,DM}$	483 (2pWD)	15,050 (3pWD)	13,930 (3pWD)	609 (2pLND)	37.0 (ND)
$\mathbf{x_{k,EN\ 14358}}$	**--**	**--**	**--**	**--**	**36.7**

4.1.3 Verification of the 'Graz bearing model for GLT in bending'

The 'Graz bearing model for GLT in bending' consists, in accordance to EN 1194, of two sub-models: the first sub-model concerns the requirements for the tensile strength of boards, and the second sub-model regulates the minimum requirements for the tensile strength of finger joints. Furthermore, the sub-models are splitted into two practically relevant ranges of COV-$f_{t,0,l}$ as one of the main parameters which influences the homogenisation effect (laminating effect – k_{lam}) in the system structure GLT on the decisive 5 %-quantile-level. A comparison with other bearing models and further details are given in Brandner (2006) and Brandner and Schickhofer (2007, 2008). The model itself – a proposal for the glulam standard prEN 14080 – is given in Tab. 3.

The verification of the 'Graz bearing model for GLT in bending' acc. to Tab. 3 by utilisation of the test results of series **GLT-II** can easily be carried out by means of two different verification processes: The first verification process only considers the requirements on the tensile strength of the boards, assuming a GLT without finger joints. Acc. to the results given in Tab. 1,

($f_{t,0,l,k}$ = 28.6 N/mm², COV-$f_{t,0,l}$ = 26.9 %) the bearing model for COV-$f_{t,0,l}$ = 25 ± 5 % was applied and led to $f_{m,g,k,calc-1} = 2.5 \cdot f_{t,0,l,k}^{0.8} \cdot k_{size,g,m} = 2.5 \cdot 28.6^{0.8} \cdot 1.00 = 36.6$ N/mm². The comparison with $f_{m,g,k}$ from performed tests, by only considering failures in timber (WF) (see Tab. 2-below) – as the verification only considers the mechanical requirements on the boards, but not those on the finger joints – , leads to $f_{m,g,k,calc-1} / f_{m,g,k,WF} = 36.6 / 36.7 =$ **99.7 % compliance**. The second verification process considers both parts of the bearing model – the requirements on the tensile strength of the boards and the minimum requirements on the tensile strength of finger joints. As visible from the statistics in Tab. 2 and Fig. 8-left (chapter 4.2), the finger joints were the limitative parameter of the 5 %-quantile and induced the lowest strength values of tested GL36h. Consequently, the tensile strength of the boards as necessary and economically meaningful for GLT acc. to the potential of the finger joints, can be calculated based on the requirement $f_{t,j,k} \geq 1.2 \cdot f_{t,0,l,k}$ with prefactor 1.2 for COV-$f_{t,0,l,k}$ = 25 ± 5 %. Taking the boarder case of $f_{t,j,k} = 1.2 \cdot f_{t,0,l,k}$ and the test results given in Tab. 1, the result is $f_{t,0,l,k,theor} = f_{t,j,k} / 1.2 = 31.1 / 1.2 = 25.9$ N/mm². The insertion of the tensile strength of the boards in the second relationship to calculate the bending strength potential of GLT on the decisive 5 %-quantile level leads to $f_{m,g,k,calc-2} = 2.5 \cdot f_{t,0,l,k,theor}^{0.8} = 2.5 \cdot 25.9^{0.8} = 33.8$ N/mm². The comparison of the calculated value with the test results given in Tab. 2, by consideration of the statistics of all tested beams, leads to $f_{m,g,k,calc-2} / f_{m,g,k,all} = 33.8 / 33.2 =$ **101.8 % compliance**. The test result, in comparison with other proposals and models for prEN 14080 and past models, is given in Fig. 5.

Tab. 3: 'Grazer bearing model for GLT in bending': proposal for the prEN 14080 (Brandner and Schickhofer (2008))

$\mathbf{f_{m,g,k}}$	$= 2.5 \cdot f_{t,0,l,k}^{0.8} \cdot k_{size,g,m}$	for COV-$f_{t,0,l}$ = 25 ± 5 %
	$= 2.8 \cdot f_{t,0,l,k}^{0.8} \cdot k_{size,g,m}$	for COV-$f_{t,0,l}$ = 35 ± 5 %
	$k_{size,g,m} = (d_g / 600)^{0.10}$	for $d_g \geq 150$ mm, else d_g = 150 mm
	$f_{t,j,k} \geq 1.2 \cdot f_{t,0,l,k}$	for COV-$f_{t,0,l}$ = 25 ± 5 %
	$f_{t,j,k} \geq 1.4 \cdot f_{t,0,l,k}$	for COV-$f_{t,0,l}$ = 35 ± 5 %

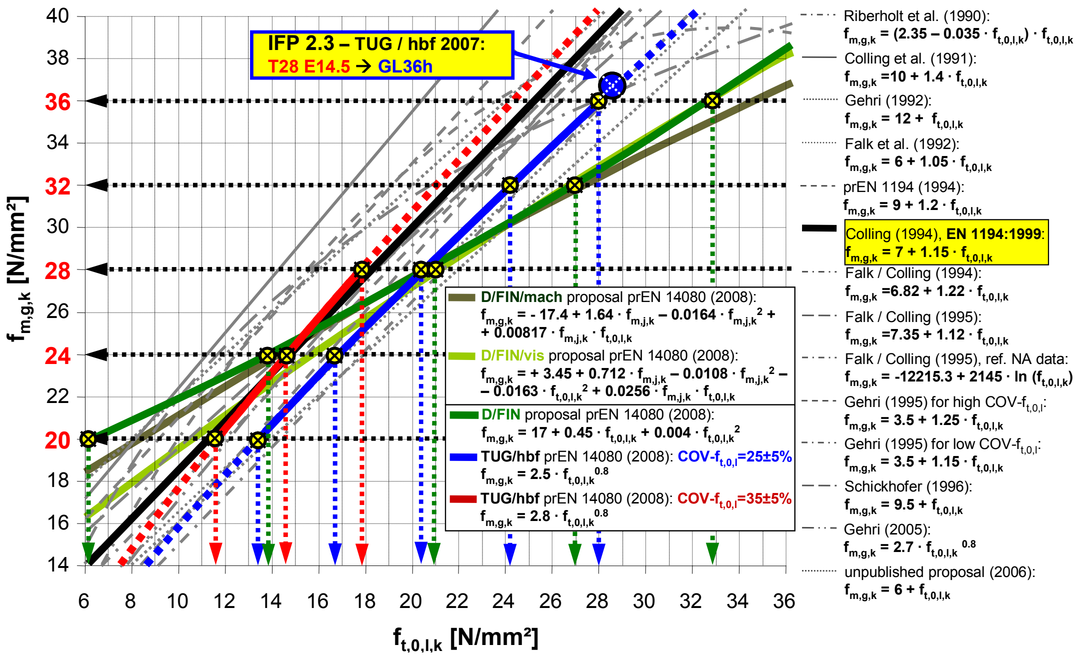

Fig. 5: 'Bearing models for GLT in bending' – sub-model concerning the requirements on boards – relationship $f_{m,g,k}$ vers. $f_{t,0,l,k}$: past models in comparison with current bearing models for prEN 14080 and the test result of series **GLT-II** of GL36h (see Brandner and Schickhofer (2008))

4.2 Further statistics of shear field test data by means of destructive 4-point bending tests acc. to EN 408

The test results and statistics of $G_{090,SF}$ of series **GLT-I** are summarized in Tab. 4. Data of **GLT-II** are included in Tab. 2 in chapter 4.1. Tab. 5 gives the 4p.-bending test results of series **GLT-III**.

Tab. 4: Statistics of series **GLT-I** – GL24h acc. EN 1194 – tested in 4p.-bending acc. EN 408

GLT-I	$\rho_{g,12}$ [kg/m³]	$E_{m,g,l,12}$ [N/mm²]	$E_{m,g,g,12}$ [N/mm²]	$G_{090,SF,12}$ **[N/mm²]**
quantity	10 #	10 #	10 #	10 #
mean	**436**	**11,170**	**10,190**	**694**
COV	**2.1 %**	**8.8 %**	**6.7 %**	**8.4 %**

Tab. 5: Statistics of series **GLT-III** – GL36c acc. EN 1194 – tested in 4p.-bending acc. EN 408

GLT-III	$\rho_{g,12}$ [kg/m³]	$E_{m,g,l,12}$ [N/mm²]	$E_{m,g,g,12}$ [N/mm²]	$G_{090,SF,12}$ [N/mm²]	$f_{m,g}$ [N/mm²]
quantity	5 #	5 #	5 #	4 #	5 #
mean	**492**	**15,140**	**14,030**	**653**	**42.0**
COV	**1.6 %**	**2.5 %**	**2.2 %**	**1.5 %**	**20.6 %**

5 Discussion

5.1 Test results of shear fields by means of 4p.-bend. tests acc. EN 408

5.1.1 Comparison of tests values of series GLT-I, GLT-II and GLT-III

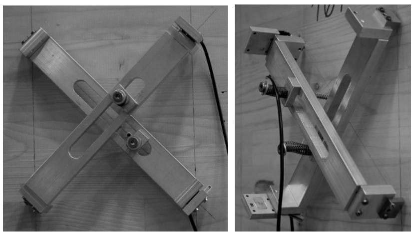

Fig. 6: Shear field test configuration of series **GLT-I** with L = 160 mm

The first tests for the determination of $G_{090,SF}$ within series **GLT-I** on GL24h with a size of L / L = 160 / 160 mm in 2007 (see Tab. 4) lead to $G_{090,SF,12,mean}$ = 694 N/mm² with an unexpected relatively high COV-$G_{090,SF,12}$ = 8.4 %. A possible explanation for the high COV-$G_{090,SF}$ lies in the fuzziness of the measurement of minor shear distortion in comparison to large bending deflection, in combination with instability of the load-distortion-relationship. A possible explanation of the relatively high $G_{090,SF,mean}$ compared to data from torsion tests $G_{090,tor,mean}$ lies in the former applied test configuration which induced a certain 'blocking-effect' due to the fixation of the measurement device by a spring pressing on a support and guided by a screw (see Fig. 6). The 'blocking effect' was visible in discontinuous force-distortion curves which showed partially unreliable and irregular, nonlinear relationships within some shear fields. The current test configuration, which has already been extensively and satisfactorily approved during measurements of deformations on concrete structures by the Laboratory of Structural Engineering of the Graz University of Technology / Austria / Europe, was solely positioned and fixed by rubber bands.

As already discussed in Brandner et al. (2007), the COV-$G_{090,SF}$ can be expected in the range of COV-$E_{m,g}$. The current test results on **GLT-II** and **GLT-III** are in line with this assumption. In general, $G_{090,SF}$ is an averaged value within and between the GLT-lamellae that results from the following three operations: 'balancing' the distortions within each shear field, averaging the $G_{090,SF}$ between both opposite shear fields on each side of the test specimen, and averaging $G_{090,SF}$-values between both ends of the specimen. The E-modules ($E_{m,g,l}$ and $E_{m,g,g}$) are also averaged values that result from the following operations: taking the mean of the bending deflection of opposite measurements, and, thanks to the homogenisation of the dispersion of E_0 through rigid connection, taking the mean within and between the GLT-lamellae.

The G-values $G_{090,SF,mean}$ of GL36h and GL36c, in the range of $G_{090,SF,mean}$ = 650 ÷ 660 N/mm², are more or less in between $G_{090,tor,mean}$ and $G_{090,SF,mean}$ of series **GLT-I** on GL24h. Both COV-$G_{090,SF}$ of **GLT-II** and **GLT-III** are in the range of expectation. Furthermore, the G-values appear unaffected by the strength class of the laminations as given by comparison of G-values of **GLT-II** and **GLT-III**: in series **GLT-II** the shear distortion was only measured over boards of strength class **T**28**E**14.5, in series **GLT-III**, the shear distortion was examined over a combination of board-strength classes **T**15**E**11.0 and **T**20**E**12.5. A constant $G_{090,g,mean}$ = 650 N/mm² for all GLT-strength classes GL20 up to GL36 of Norway spruce is proposed.

5.1.2 Stability, reliability and cost effectiveness of the shear field testing method

Standardized test methods and standardized material characteristics have to be reproduceable, reliable, repeatable and consistent. The torsion test method proposed in Brandner et al. (2007) and already standardized in ASTM D 198, has been proved a reliable, consistent and cost efficient test method for the derivation of G_{090}-values and can be applied to solid timber as well as to bar-like timber products e.g. GLT. The first shear field test configuration applied on **GLT-I** produced – in comparison to torsion tests – relatively high dispersing, and due to 'blocking effects' within the test configuration, unreliable data. The shear field test configuration applied on **GLT-II** and **GLT-III** led to reliable, robust and repeatable test values which was proved on four shear fields at least – in a 1st test run with DD1s placed on the nail-head, in a 2nd test run with DD1s placed direct on the timber surface – and led to maximal ± 10 N/mm² nominal difference within each shear field. For further illustration, randomly chosen load-distortion curves are given in Fig. 7.

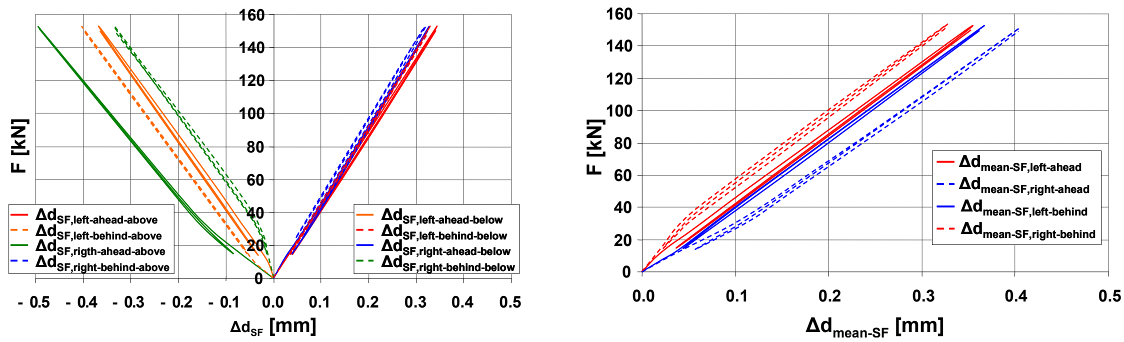

Fig. 7: Bending test diagrams: measurement of extensions of shear-field diagonals in relationship to applied force (applied force corresponds to 50 % of estimated $F_{max,mean,est}$) – elongation of each shear-field diagonal measurement (left), mean elongation of each shear-field diagonal (right)

Tab. 6: Summary of time-and-motion-study on four static test configurations for the determination of G_{090}

TIME-and-MOTION-Study [0]	Single span method acc. to EN 408	Variable span method acc. to EN 408	Torsion test method	Shear field test method by means of 4p.-bending tests acc. to EN 408
Determinable characteristics of interest	f_m, $E_{m,l}$, $E_{m,g}$, $G_{090,app}$, ρ	f_m, $E_{m,l}$, $E_{m,g}$, $G_{090,app}$, ρ	$G_{090,tor}$, ρ	f_m, $E_{m,l}$, $E_{m,g}$, $G_{090,SF}$, ρ
Summary of time-and-motion-study [1] (expectable values)	**54'**	**102' [2]**	**26' [3]**	**41'**

[0] Time for assembling and disassembling is excluded due to dependency on the specimen's dimensions

[1] Time steps were subdivided into: Preparation of the test specimen, application of the measurement device, test-duration (with hysteresis slope), modification of the test configuration (if necessary), first data examination (see Lackner et al. (2008))

[2] Acc. to EN 408 with a minimum of four variable spans

[3] To obtain the same characteristics as in the other three methods, the combination of torsion- and 4p.-bending test leads to an expectable time need of 23' + 22' = **45'**

The reliability is reflected by the low COV-$G_{090,SF}$ in the range of COV-$E_{m,g}$. For evaluation concerning the cost effectivness, data of time-and-motion-studies of tests on series **GLT-I** (GL24h) of all four applied test methods for the derivation of the G-modulus, updated by the new shear field test configuration, are given and compared in Tab. 6. The time for assembling and disassembling of the specimen has been excluded due to dependency on the specimen's dimensions.

In conclusion, the torsion test method is the best choice when testing timber components if G_{090}-values are derivated only. If bending characteristics like $f_{m,g}$, $E_{m,g}$, and $E_{m,l}$ are also of interest and the depth of the specimen is $d \geq 300$ mm (due to minimum, adviseable size of the shear field with $L \geq 150$ mm), the shear field test method is only recommended as a cost efficient and reliable test method if the accuracy of the measurement device is adjusted to the minor shear distortion. For smaller cross sections, a combination of torsion- and 4p.-bending test is suitable.

5.2 Examinations of potential relationships between G and other mechanical and physical characteristics

The interest in certain relationships between G and other characteristics of timber for modelling and other easy-to-handle values gained by calculations is evident. Fig 8 reflects the empirical distributions of $f_{m,g}$ and $G_{090,SF}$ of series **GLT-II** – the data points are marked acc. to the predominant failure criteria. The empirical distribution (empD) of $f_{m,g}$ can be divided into three nearly homogeneous regions acc. to the class of failure criteria, the empD of $G_{090,SF}$, as it was expected, shows no clear clustering or differentiability of certain regions of preferred failure criteria. All regions are widely overlapping with the field of 'WF' occurring within the whole range. Similar results are given in the box-plots of $f_{m,g}$, $E_{m,g,l,12}$ and $G_{090,SF}$ in Fig 9.

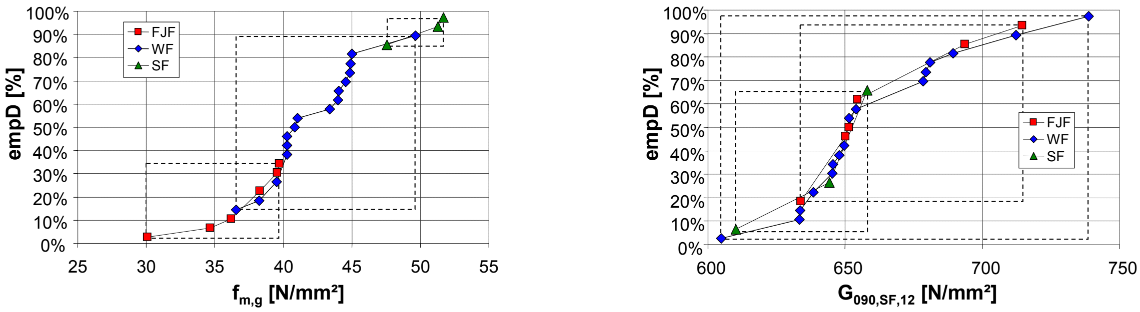

Fig. 8: Empirical distribution of the bending strength $f_{m,g}$ (left) and shear-modulus $G_{090,SF,12}$ (right) of series **GLT-II** – GL36h: classified failure criterias – wood failure in bending (WF), failure in the finger joint (FJF) and wood failure in shear (SF)

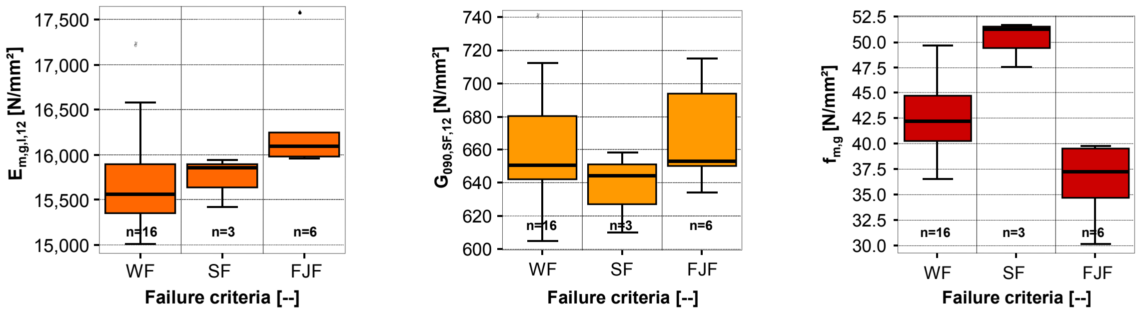

Fig. 9: Box-plots of series **GLT-II** – GL36h: according failure criteria grouped mechanical properties: local bending E-modulus $E_{m,g,l,12}$ (left), shear modulus $G_{090,SF,12}$ (middle) and bending strength $f_{m,g}$ (right)

Scatter-plots with linear regression lines of $G_{090,SF}$ vers. $E_{m,g,l,12}$ and $E_{m,g,g,12}$ in Fig. 10-left-above may appear to reflect a certain positive tendency. By consideration of the negative tendencies for $G_{090,SF}$ vers. $f_{m,g}$ and $\rho_{g,12}$ in Fig. 10-right-above and -left-below – with a generally positive correlation r ($E_{m,g}$; ($f_{m,g}$, $\rho_{g,12}$)) >> 0 – this can not be confirmed. A residual positive, weak correlation of $G_{090,SF,12}$ vers. $u_{g,middle}$, with r ($G_{090,SF,12}$, $u_{g,middle}$) ≈ 0.45, is given in Fig. 10-right-below and may reflect that the G-modulus is more moisture sensitive than the E-modulus because the G-values were already adjusted to u_{ref} = 12 % acc. the adjustment for E-values as given in EN 384.

In general, a quantifiyable dependency of G on the examined mechanical and physical properties can not be confirmed. This is also in compliance with the G staying constant in all GLT-strength classes by simultaneous variation of E, f and ρ. Furthermore, shear fields of 20 # specimens of series **GLT-II** and all 5 # beams of series **GLT-III** were examined, concerning the influence of knots within the measuring field in the data of shear deflection. All four shear fields of each specimen with / and without knots were separately analysed. The results reflect no significant influence of knots on the recorded shear distortion measurements.

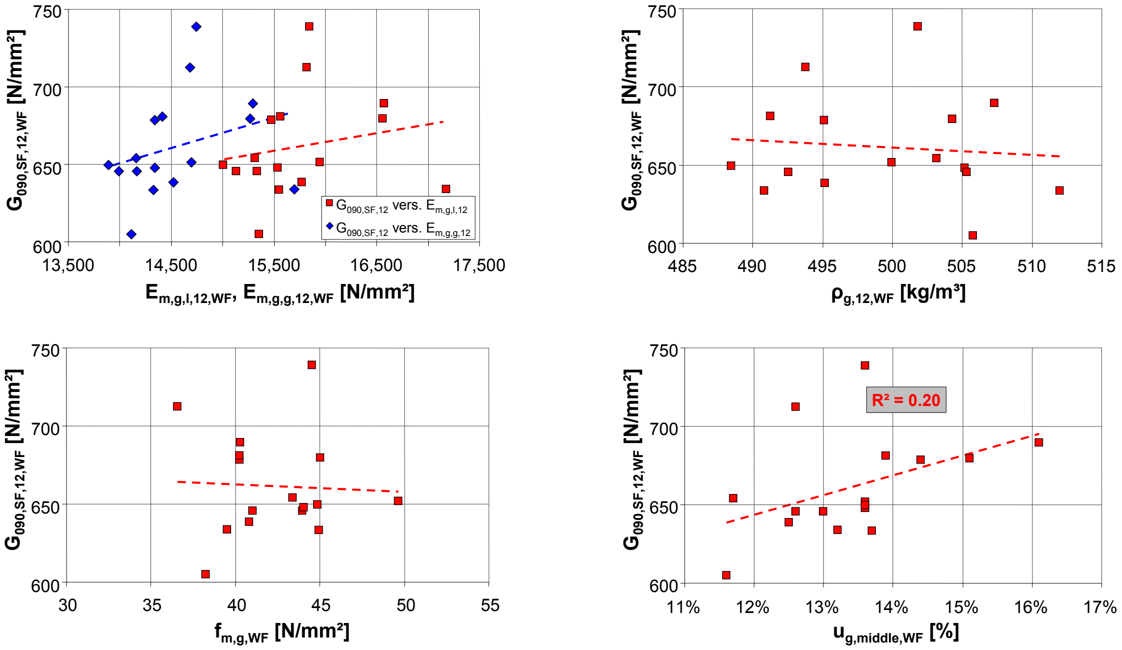

Fig. 10: $G_{090,SF,12,WF}$ vers. $E_{m,g,l,12,WF}$, $E_{m,g,g,12,WF}$ (left-above), vers. $\rho_{g,12,WF}$ (right-above), vers. $f_{m,g,WF}$ (left-below) and vers. moisture in the middle of beam-depth $u_{g,middle,WF}$ (right-below) – series **GLT-II** / WF

5.3 G-modulus of GLT in comparison to G-modulus of solid timber

Acc. to EN 338, a ratio of G / E = 1 / 16 for solid timber is standardized. In EN 1194 a ratio of G / E = 1 / 15.4 is given. Thus, there is one important question to be asked: Is there a difference between the G of GLT and G of solid timber? First of all, the distribution of E and G can be well described by the statistical normal distribution function. Through homogenisation within the system structure of GLT, the mean level of both values – solid timber and GLT – can be treated as being constant, but the COV and the 5 %-quantiles change significantly as given in Brandner et al. (2007) and Blaß (2005). There is no reason why the expectable values of G_{090} in solid timber and GLT should be different, but for stability considerations the reduction of COV-G_{090} provoking an increase of $G_{090,05}$ lead to a quantifiable, well-tempered performance of GLT. The dependency of G_{090} on the strength class in GLT cannot be confirmed by the tests, a constant value of $G_{090,g,mean}$ = 650 N/mm² is proposed based on test results on GL24h, GL36h and GL36c. From this point of view, it does not appear logical why G_{090} in solid timber should behave in a different manner. A certain dependency is published e.g. in Görlacher and Kürth (1994), based on vibration tests. Due to test results and for simplification of design of timber structures of Norway spruce, a constant value of $G_{090,mean}$ = 650 N/mm² also for solid timber is proposed.

6 Conclusion

Further proposals include test results and related considerations. They are only valid for the related standard with regard to solid timber or glued laminated timber of Norway spruce (*picea Abies Karst.*). Because of the equality of numerous mechanical and physical properties of Norway spruce and fir (*abies Alba Mill.*) – when used for engineering purposes – the proposals may also be valid for this wood species.

- For the determination of static G_{090} of solid timber and bar-like timber products with d < 300 mm, an application of the torsion test method is proposed which should be standardized in EN 408.
- For the determination of static G_{090} of solid timber and timber products with d ≥ 300 mm, an application of shear fields by means of shear tests or by means of standardized 4p.-bending tests acc. EN 408 is proposed and enables an aditional examination of $E_{m,l}$, $E_{m,g}$ and f_m.

Tab. 7: Proposed values and models for $E_{m,0,mean}$, $E_{m,0,05}$, $G_{090,mean}$ and $G_{090,05}$ for solid timber (EN 338) and glued laminated timber (EN 1194 and EN 14080)

Shear modulus	$G_{090,mean}$	= 650 N/mm²	1)
	$G_{090,05,n}$	$= G_{090,mean}\cdot\min\left\{\begin{array}{c}\frac{1}{60}\cdot(n-1)+0.67\\ 0.90\end{array}\right.$	2)
		$= G_{090,mean}\cdot\min\left\{\begin{array}{c}\left[1-1.645\cdot\frac{0.20}{\sqrt{n}}\right]\\ 0.90\end{array}\right.$	3)
	$G_{090,05}$	$= 0.67\cdot G_{090,mean}$ = 435 N/mm²	4)
Modulus of elasticity	$E_{m,0,05,n}$	$= E_{m,0,mean}\cdot\min\left\{\begin{array}{c}\frac{1}{60}\cdot(n-1)+0.67\\ 0.90\end{array}\right.$	2)
		$= E_{m,0,mean}\cdot\min\left\{\begin{array}{c}\left[1-1.645\cdot\frac{0.20}{\sqrt{n}}\right]\\ 0.90\end{array}\right.$	3)
	$E_{m,0,05}$	$= 0.67\cdot E_{m,0,mean}$	4)

1)	proposal acc. to presented test results for consideration in EN 1194, EN 14080 and EN 338
2)	proposal for linearized calculation of $X_{05,n}$ in dependency of the quantity of interacting components n with a max. of $X_{05,n} / X_{mean}$ = 0.9 at n = 15 representing a GLT of 15 laminations with d_l = 40 mm → d_g = 15 · 40 = 600 mm = $d_{g,ref}$, acc. to Brandner et al. (2007) for consideration in EN 1194 and EN 14080
3)	proposal for calculation of $X_{05,n}$ in dependency of the quantity of interacting components n and approximation of G- and E-module by the statistical normal distribution with COV-X = 20 %, for consideration in EN 1194 and EN 14080
4)	proposal for calculation of X_{05} for solid timber with COV-X = 20 %, for consideration in EN 338

- The determination of G_{090} by means of shear fields leads to two independent G_{090}-values of each specimen and each applied test. In comparison only one value for E-modulus can be gained in one test.
- The achieved 4p.-bending tests on GL24h, GL36h and GL36c reflect no or minor dependency of G_{090} from the board's strength class. A constant value of $G_{090,mean}$ = 650 N/mm² for all strength classes of GLT (GL20 to GL36) in EN 1194 and EN 14080 is proposed. Furthermore, a constant value of $G_{090,mean}$ = 650 N/mm² for solid timber for consideration in EN 338 is proposed.
- The statistical normal distribution was found to represent the values of E_0 and $G_{090,SF}$ satisfactorily. Because of the averaging of the E_0 and G_{090}-values of boards within the system structure GLT a reduction of the COV-$G_{090,SF,n}$, in dependency the quantity of interacting boards n, acc. [5] can be assumed. The calculation scheme of the characteristic G- and E-values in dependency of n is given in [6].

$$COV_n = \frac{COV_{n=1}}{\sqrt{n}} \qquad [5]$$

$$X_{05} = X_{mean}\cdot(1-1.645\cdot COV_n) = X_{mean}\cdot\left(1-1.645\cdot\frac{COV_{n=1}}{\sqrt{n}}\right) \qquad [6]$$

- As given in Brandner et al. (2007) a COV-$G_{090,n=1}$ = COV-$E_{m,0,n=1}$ = 20 % can be assumed. Furthermore the proposed level of homogenisation is restricted to n = 15 # interacting lamellae and leads to a maximum of $X_{05,n}$ = 90 % of X_{mean}. The calculation procedure for the 5 %-quantile $G_{090,05}$ and $E_{m,05}$ for solid timber (n = 1) and for the system product GLT (n ≥ 2) are given in Tab 7 and proposed for consideration within EN 1194, EN 14080 and EN 338.

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8.2 Standards

ASTM D 198:2003-05 Standard Test Methods of Static Tests of Lumber in Structural Sizes

EN 338:2003-07-01 Structural timber – Strength classes

EN 384:2004-05-01 Structural timber – Determination of characteristic values of mechanical properties and density

EN 408:2005-04-01 Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties

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EN 1194:1999-09-01 Timber structures – Glued laminated timber – Strength classes and determination of characteristic values

pr**EN 14080**:xxxx-xx-xx Timber structures – Glued laminated timber and Glued laminated solid timber - Requirements

EN 14081:2006-02-01 Timber structures – Strength graded structural timber with rectangular cross section