# Determination of modulus of shear and elasticity of glued laminated timber and related examinations

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## Abstract

This paper deals with the determination of the modulus of elasticity of boards, finger joints in tension and hence builds up glued laminated timber (GLT). Emphasize has been taken on determination of G-modulus of GLT by execution of both standardized test methods acc. EN 408, by torsion tests and application of shear-fields in constant transverse force areas during destructive four-point bending tests acc. EN 408. Comprehensive evaluations of relationships between G- and E-module and related mechanical properties have been carried out. Furthermore product of (E · G) has been examined as relevant value for lateral torsional buckling based on test results and simulations. A proposal for further standardization for determination of G-modulus of GLT acc. EN 408 will be presented. Simulations evaluate the influence of selected parameters on expectable G-modulus. The data states as bases for further regulations concerning lateral torsional buckling of GLT in dependence of size in comparison to solid wood beams and should be considered for standardization.

## 1 Introduction

The elastic characteristics of isotropic materials can be described on the bases of two independent parameters. The relationships between the modulus of elasticity E and shear G are directly linked. Wood, as an anisotropic but describable orthotropic material, requires nine independent parameters to link the tensors of stress and strain. The module of elasticity of structural lumber parallel and perpendicular to the grain are relative simple to determine and well known. In contrast, shear module make some troubles in determination within static tests, and often underlie a certain bias due to minor deflections in combination with high loads and influences in regard to load configuration. General, the knowledge of the material inherent module is necessary for design and modelling of structures. To enable the determination of relevant paramters and comparison to publications standardized and robust testing procedures are necessary. So far it is ambitious to define relationships between G and easy to handle and dependent material properties to enable estimation of G-values through calculations. In current standards, the relationship between E and G is general utilized as constant ratio, for example $E_{m,mean}$ / $G_{mean}$ = 16 acc. EN 338 or $E_{t,0,l,mean}$ / $G_{mean}$ = 15.4 acc. EN 1194.This constant ratio assumes, that material properties like density and knottiness have no or equal influence on both, E and G (Görlacher and Kürth 1999). Furthermore it has to be mentioned, E derived by different methods are not general equal. The knowledge for accurate G values is of increasing importance with decreasing span-to-depth ratio (l / d) (Skaggs and Bender 1995, Gehri 2005) and in case of lateral-torsional buckling (Harrison 2006). As given in Kollmann 1951, following important influences on the shear modulus are given:

- density, share of late wood (positive relationship)
- moisture content (negative relationship)
- knottiness, grain deviations (up to seven-times of strain on the border between knot and surrounding 'clear wood')
- temperature (negative relationship)
- load direction (highly pronounced anisotropy)

Kollmann 1951 annotated that the ratio E / G can not be constant due to the anisotropic behaviour of wood. A literature study offer wide ranges of E / G (see Tab. 1).

Tab. 1: Literature review concerning E / G

| **Literature source**<br>**[--]** | **E / G**<br>**[--]** |
|---|---|
| Niemz 1993 | 12 ÷ 35 |
| Divos et al. 1998 | 8 ÷ 24 |
| Harrison 2006 | 11.6 ÷ 36.6 |

Görlacher and Kürth 1999 reported linear regression models for G vers. E and G vers. ρ, based on dynamical examined values determined on 1188 # board segments with l / w / d = 150 / 150 / 30 (35) mm and confirmed on the one hand the dependency of G from density, on the other hand the increasing ratio E / G with increasing E and hence increasing strength class and closed with a proposal for EN 338. As given, the increase of G is rather low, even G for main range of strength classes C18 to C40 acc. the proposal for EN 338 can be seen as more or less constant (increase from proposed G = 580 N/mm² to 660 N/mm² → + 14 %) in comparison to the increase of E = 9000 N/mm² to 14000 N/mm² (→ + 56 %).

Emphasize of this paper is to present and compare static test procedures for the determination of shear modulus of GLT with the background knowledge of E from boards in tension and hence build up GLT, tested flatwise and edgewise. To get as much information of E and G main parts of GLT have been part of examination. $E_{t,0,l}$ and $E_{dyn}$ of boards and $E_{dyn}$ of both parts of finger joint specimens have been determined. Hence homogenous build up GLT GL24h has been tested edgewise and flatwise in 4p.- and 3p.-bending acc. EN 408, and a sub sample of 10 # of GLT has been tested in torsion and by application of measurements of shear deflections in constant transverse force areas during standard 4p.-bending test acc. EN 408. Due to cutting pattern of halved roundwood it has not been possible to determine $G_{LR}$ and $G_{LT}$ accurately. Determined G-values gained from bending tests are in that case, according to torsion tests, smeared G-values, influenced by loading direction of the system structure GLT.

# 2 Materials and Methods

## 2.1 Materials

Boards of one breakdown, spruce (picea Abies karst.) with provenience Middle Europe, have been visual graded under industrial environment to grading classes S10, S13 and reject acc. DIN 4074. The lot of S10 has been used for further applications to produce glued laminated timber (GLT) of strength class GL24h acc. EN 1194. Specimens for tension tests of boards and finger joints have been selected randomly. Static tests have been carried out with boards, finger joints and hence build up GLT. The dimensions, tested quantity and carried out tests are given in Tab. 2.

Tab. 2: Overview of tested material, dimensions, carried out tests and examined properties

| material | quantity | dimension | | | tests | examined properties |
|---|---|---|---|---|---|---|
| [--] | [--] | l [mm] | w [mm] | d [mm] | [--] | [--] |
| **boards** | 100 # | 3000 | 150 | 40 | tension | u, ρ, $E_{dyn}$, $f_{t,0,l}$, $E_{t,0}$ |
| **finger joints** | 50 # | 1750 | 150 | 40 | tension | u, ρ, $E_{dyn,parts}$, $f_{t,j}$ |
| **GLT-GL24h** | 25 # | 3040 | 150 | 160 | 4-p. bending | u, ρ, $f_{m,g,ew}$, $E_{m,g,l\text{-}g,ew}$ |
| | 25 # | 6080 | 150 | 320 | 4-p. bending (25 #, 10 # shear field) | u, ρ, $f_{m,g,ew}$, $E_{m,g,l\text{-}g,ew\text{-}fw}$, $G_{m,g,ew\text{-}fw}$, $G_{SF,ew}$ |
| | | | | | 3-p. bending (25 #) | u, ρ, $E_{m,g,l\text{-}g,app,ew\text{-}fw}$, $G_{m,g,ew\text{-}fw}$ |
| | | | | | torsion (10 #) | u, ρ, $G_{t,1600\text{-}2950\text{-}5000}$ |

'l-g' … tested local and global; 'ew-fw' … tested edgewise and flatwise

## 2.2 Methods

All tests have been carried out with continuous measurement of time, deflections and forces. Bending- and torsion tests have been derived by application of hysteresis with peaks of deflections at 50 % of calculated average maximum stress level.

### 2.2.1 Tension tests of boards and finger joints

The tension tests of boards parallel to the grain have been done acc. EN 408 with free testing length $l_{test} > 9 \cdot w = 1420$ mm (= 9.5 · w), by measurement of local- (acc. to EN 408 $l_{0,EN\ 408} = 5 \cdot w = 750$ mm) and global deflections ($l_{0,maschine} = 1645$ mm). Tension tests on finger joints have been accomplished at the Holzforschung Austria / Vienna, with free testing length of $l_{test} = 200$ mm acc. EN 1194. The tension strengths $f_{t,0,l}$, $f_{t,j}$ and modulus of elasticity $E_{t,0,l}$ have been calculated acc. EN 408.

### 2.2.2 Applied test methods for the determination of modulus of elasticity and shear of GLT GL24h

For the determination of E-, G-module and bending strength $f_{m,g}$ various static test configurations have been applied on glued laminated timber GLT GL24h which are given in detail afterwards. All deflections at bending tests have been measured by application of yokes to delete bias due to local indentations at loading points.

### *2.2.2.1 Single span method acc. EN 408*

Acc. to EN 408 method for the determination of G by ‚single span' has been applied on GLT, loaded edgewise and flatwise. This method enables calculation of G by confrontation of $E_{m,g,l}$ calculated out of deflections over $l_1 = 5 \cdot w$ in middle section free of transverse force and $E_{m,g,app}$ – including bending and shear deflection – of 3p.-bending tests with span $l = l_1 = 5 \cdot w$. The formulations for calculation of G are given in EN 408.

### *2.2.2.2 Variable span method acc. EN 408*

‚Variable span method' acc. EN 408 has been applied on all 25 # GLT-beams, edgewise and flatwise loaded, by variation of $(d / l)^2$ within $0.0028 \leq (d / l)^2 \leq 0.030$ (edgewise) and $0.0025 \leq (d / l)^2 \leq 0.030$ (flatwise). Calculation scheme is given in EN 408.

### *2.2.2.3 Torsion tests*

Torsion tests have been carried out acc. to ASTM D 198, but with some adaptations. Free testing length has been $l_{test} = 18 \cdot w = 5760$ mm, whereby six gages have been placed with distances of 1600, 2950 and 5000 mm, but reduced minimal distance to clamps of $1.2 \cdot w = 380$ mm. Rotations have been recorded by extensometers, placed on both sides of each gage point, and averaged (Fig. 1). Due to lack of deeper knowledge of $G_{LR}$ and $G_{LT}$ – small differences are published by Keunecke et al. 2007 ($G_{LR,mean} = 617$ N/mm² (COV-$G_{LR}$ = 12.1 %), $G_{LT,mean} = 587$ N/mm² (COV-$G_{LT}$ = 12.1 %) – calculation of $G_{tor}$, as smeared $G_{LR}$ and $G_{LT}$, has been accomplished under assumption of isotropic material acc. to Möhler and Hemmer 1977. Formulations are given in [1], [2]; some impressions are given in Fig. 2.

$$I_{tor} = \eta_1 \cdot d \cdot w^3 \qquad [1]$$

$$\hat{\vartheta} = \frac{M_{tor}}{G_{tor} \cdot I_{tor}} \rightarrow G_{tor} = \frac{M_{tor}}{\hat{\vartheta} \cdot I_{tor}} = \frac{dM_{tor}}{d\hat{\vartheta}} \cdot \frac{1}{\eta_1 \cdot d \cdot w^3} \qquad [2]$$

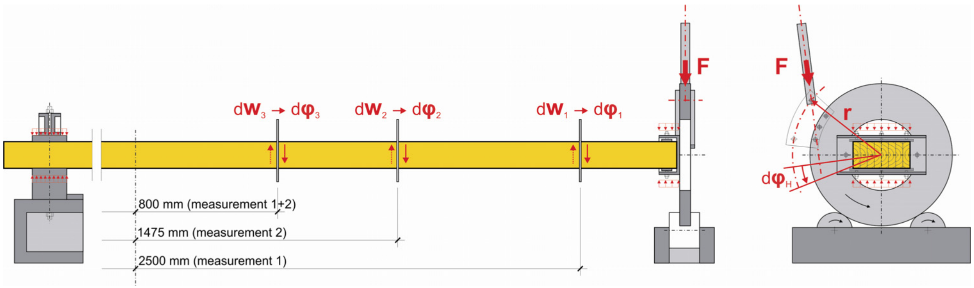


Fig. 1: Test configuration for the examination of $G_{tor}$ of GLT GL24h

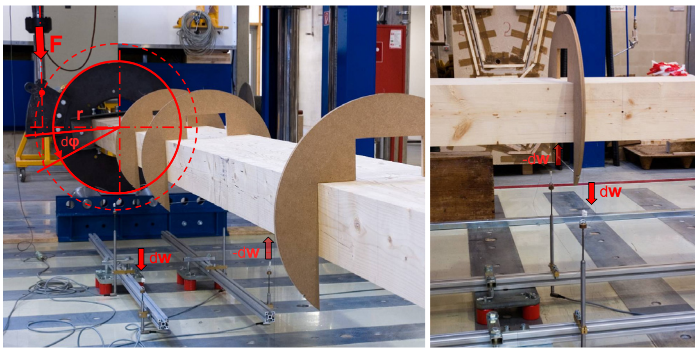


Fig. 2: Test configuration for the examination of $G_{tor}$ of GLT GL24h: transfer of force for torque (left), local measurement of torque by extensometers on both sides (right)

### 2.2.2.4 *Shear field tests during destructive 4-point bending tests*

Measurements of shear deflection in area of constant transverse force during bending tests have already been accomplished in the past by FMPA 1983 and Gehri 2005. The idea has been to adjust this test configuration, generally applied in shear tests, for the standard 4p.-bending test acc. EN 408 (see Fig. 3). Due to minor induced shear deflection precise measurement device has been applied on total four shear fields per each GLT-beam, placed on both sides of constant shear force and opposite each side of the beam, tested edgewise in 4p.-bending. Due to the squared parabola shape of shear strength over the cross section but reduced monitoring field of shear deflection over the depth of the beam, general applied shear correction factor κ = 6 / 5 has to be adjusted and replaced by α acc. to Gehri 2005 (see [3]).

$$\alpha = \frac{\tau_{SF}}{\tau_0} + \frac{2}{3} \cdot \left( \frac{\tau_{\max}}{\tau_0} - \frac{\tau_{SF}}{\tau_0} \right) \quad \text{with } \tau_0 = G \cdot \gamma = \frac{Q}{w \cdot d}, \; \tau_{SF} = \tau\left( z = \frac{L}{2} \right) = \frac{Q \cdot S(z)}{I_y \cdot w} \qquad [3]$$

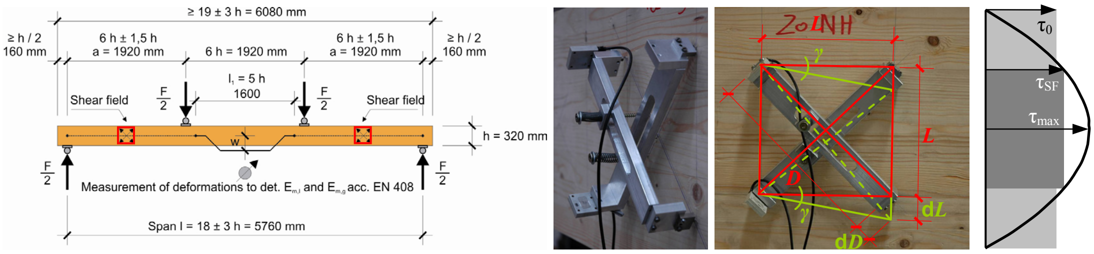


Fig. 3: Test configuration for the examination of $G_{SF}$ of GLT GL24h during 4p.-bending tests acc. EN 408 (left), measurement device and shear deflection as basis for calculation of $G_{SF}$ (middle), scheme for declaration of $\tau_0$, $\tau_{max}$ and $\tau_{SF}$ (right)

The calculation procedure for $G_{SF}$ is given in [4], [5].

$$\gamma = \frac{1}{2} \cdot \left( |dD_1| + |dD_2| \right) \cdot \frac{\sqrt{2}}{L} = dD_{mean} \cdot \frac{\sqrt{2}}{L} \qquad [4]$$

$$G_{SF} = \alpha \cdot \frac{\tau_0}{\gamma} = \alpha \cdot \frac{L}{A \cdot \sqrt{2}} \cdot \frac{dQ}{dD_{mean}} \qquad [5]$$

Exact determination of α by FEM acc. Bogensperger 2007 has shown good agreement of method proposed by Gehri 2005 [3], with $\alpha_{FEM}$ = 1.390 versus $\alpha_{Gehri}$ = 1.375 acc. given test configuration with L = 160 mm, placed in the middle of the $d_{GLT}$ and middle of constant shear force sections.

## 2.2.3 Modelling

The product (E · G) has been modelled by application of Monte-Carlo simulation method, introduction of stochastic and selected parameters for sensitivity analysis. For simulation, virtually GLT-beams have been generated. The lamellas and boards itself have been build-up of elements with $l_{seg}$ = 150 mm, width of $w_{board}$ = 150 mm and thickness of $d_{board}$ = 40 mm, referencing standard dimensions of boards cut in pieces lengthwise. Data concerning E and G for boards with definite length of $l_{board}$ = c · $l_{seg}$ (c for number of serial board segments lengthwise per each board: $c_{ref}$ = 27 # → $l_{board}$ = 4050 mm) have been generated, based on equal distributed random numbers and transformed by inverse transformation method. E and G have been assumed to be normal distributed (ND). Correlation between E and G is under discussion. Skaggs and Bender 1995 published values for r (E, G) between - 0.342 ≤ r (E, G)

≤ + 0.554, depending on lumber grade. For modelling, correlation r (E, G) has been accomplished by bivariate statistics. The E and G-values for the segments have been generated by the same method as for E and G for board totally, under assumption that $E_{board}$ and $G_{board}$ represent the mean value of the segments, with assumed COV-E = COV-G, whereby the segments itself have been divided into 'segments free of strength reducing properties' (F) and segments including strength reducing properties' (P), which have been also distributed randomly – within distribution constraints and without autocorrelation – over the length of the boards. Values for E and G of intermediate segments (between F's and P's) represent averaged neighbouring values. The dimension of virtually GLT-beams has been chosen equal to 4p.-bending test configuration of EN 408, with $l_{GLT} = 19 \cdot d_{GLT}$, $l_{span} = 18 \cdot d_{GLT}$, and loading at third points. Module of elasticity $E_y$, $E_z$ and shear $G_{xz}$, $G_{xy}$, $G_{tor}$ have been calculated acc. Blaß 2005 by first creation of packages with length = $l_{seg}$ = 150 mm of $(E \cdot G)$ over the beam depth by calculating the average value, and second, calculating the $(E \cdot G)$ of each beam under assumption of a serial system of packages. Due to main interest in E and G concerning lateral torsional buckling of edgewise loaded GLT-beams, $E_z$ and $G_{tor}$ (respective $E_{fw}$ and $G_{tor}$) have been applied for calculation of $(E \cdot G)$.

# 3 Results

## 3.1 Tensile test results of boards and finger joints

Results of tension test parallel to the grain of boards and finger joints are given in Tab. 3. Data of density ρ and modulus of elasticity ($E_{t,0,l}$ and $E_{dyn}$) have been adjusted to u = 12 % moisture content acc. EN 384.

Tab. 3: Test results of tension tests on boards and finger joints, graded S10 acc. DIN 4074

| | **Tension tests – boards** | | | | **Finger joints** | | |
|---|---|---|---|---|---|---|---|
| | $\rho_l$ [kg/m³] | $E_{dyn}$ [N/mm²] | $E_{t,0,l}$ [N/mm²] | $f_{t,0,l}$ [N/mm²] | $\rho_{l,j}$ [kg/m³] | $E_{dyn}$ [N/mm²] | $f_{t,j}$ [N/mm²] |
| Quantity | 100 # | 100 # | 100 # | 100 # | 49 # | 49 # | 49 # |
| **mean** | **423** | **13650** | **10550** | **27.3** | **422** | **13540** | **26.5** |
| **COV** | **10.8 %** | **16.9 %** | **19.0 %** | **39.5 %** | **7.3 %** | **13.2 %** | **18.6 %** |
| 5 % qu. acc. CM | 351 | 10000 | 7550 | 14.0 | 380 | 10290 | 19.4 |
| 5 % qu. acc. DM | 352 (3pWD) | 10210 (2pLND) | 7580 (2pLND) | 14.0 (2pLND) | 375 (3pWD) | 10200 (2pWD) | 18.7 (3pWD) |
| 5 % qu. (DM, $k_{size}$) | -- | -- | -- | 13.7 | -- | -- | 18.7 |

Statistical analysis give high COV-$f_{t,0,l} \approx$ 40 % and COV-$f_{t,j} \approx$ 20 %. Nevertheless, demands for strength class C24 acc. EN 338 have been reached with $f_{t,0,l,05,DM}$ = 13.7 N/mm², $E_{t,0,l,mean}$ = 10550 N/mm² (COV-$E_{t,0,l} \approx$ 19 %) and $\rho_{l,05}$ = 380 kg/m³ (COV-$\rho_l \approx$ 11 %). Requirement on tension strength of finger joints acc. EN 1194, with $f_{t,j,05} \geq 5 + f_{t,0,l,05} \rightarrow f_{t,j,05} = 13.7 + 5 = 18.7$ N/mm², has been fulfilled.

## 3.2 Tests results of determined modulus of elasticity and shear of GLT

### 3.2.1 Single span method acc. EN 408

The test results for the local and global modulus of elasticity ($E_{m,g,l,ew-fw}$, $E_{m,g,g,ew-fw}$) of 4p.-bending tests and of 3p.-bending tests ($E_{m,g,app,ew-fw}$) are given, together with $G_{ew-fw}$, in Tab. 4 and 5. Comparison of $E_{t,0,l,mean}$ = 10600 N/mm² (COV-$E_{t,0,l}$ = 19 %) of boards with $E_{m,g,l,ew,mean}$ = 10800 N/mm² (COV-$E_{m,g,l,ew}$ = 10 %) gives nearly the same mean value. $E_{m,g,l,fw,mean}$ = 11900 N/mm² (COV-$E_{m,g,l,fw}$ = 6 %) reflects an increase of around 1000 N/mm² (+ 12 %) due to parallel loading of boards and predominant mature wood in the high stressed outer zones of GLT in flatwise bending. Due to homogenisation the COV-E decreases significantly. G-modulus with $G_{ew,mean}$ = 820 N/mm² (COV-$G_{ew}$ = 12 %) and $G_{fw,mean}$ = 790 N/mm² (COV-$G_{fw}$ = 12 %) appears rather high in comparison to literature (Görlacher and Kürth 1994: $G_{mean,C24}$ = 620 N/mm²). Also the COV-$G_{ew\text{-}fw}$ = 12 % show up non expectable high dispersion.

Tab. 4: Test results of G of GLT GL24h tested edgewise acc. EN 408 – 'single span method'

| | $E_{m,g,l,ew}$ [N/mm²] | $E_{m,g,g,ew}$ [N/mm²] | $E_{m,g,app,3pB,ew,1600}$ [N/mm²] | $G_{3pB,ew\text{-}4pB,ew,1600}$ [N/mm²] |
|---|---|---|---|---|
| quantity | 25 # | 25 # | 25 # | 25 # |
| **mean** | **10800** | **9870** | **6580** | **823** |
| **COV** | **9.5 %** | **8.2 %** | **6.2 %** | **12.2 %** |
| 5 %-qu. acc. CM | 9130 | 8130 | 6030 | 713 |
| 5 %-qu. (CM) / mean | 0.85 | 0.82 | 0.92 | 0.87 |

Tab. 5: Test results of G of GLT GL24h tested flatwise acc. EN 408 – 'single span method'

| | $E_{m,g,l,fw}$ [N/mm²] | $E_{m,g,g,fw}$ [N/mm²] | $E_{m,g,app,3pB,fw,750}$ [N/mm²] | $G_{3pB,fw\text{-}4pB,fw,750}$ [N/mm²] |
|---|---|---|---|---|
| quantity | 25 # | 25 # | 24 # | 24 # |
| **mean** | **11940** | **11610** | **6890** | **790** |
| **COV** | **6.3 %** | **5.1 %** | **6.3 %** | **11.5 %** |
| 5 %-qu. acc. CM | 10780 | 10740 | 6240 | 656 |
| 5 %-qu. (CM) / mean | 0.90 | 0.93 | 0.91 | 0.83 |

### 3.2.2 Variable span method acc. EN 408

Tab. 6 and 7 contain particular test results gained from accomplished 'variable span method' to determine G of GLT. Corresponding $E_{m,g,app,ew\text{-}fw}$ values for all spans edgewise and flatwise are given and reflect clearly the increasing influence of shear (due to increasing shear deflection) with decreasing span. Calculated data for $E_{m,g,3pB,ew\text{-}fw}$ is given.

Tab. 6: Test results of G of GLT GL24h tested edgewise acc. EN 408 – 'variable span method'

| | $E_{m,g,app,6000}$ [N/mm²] | $E_{m,g,app,2948}$ [N/mm²] | $E_{m,g,app,2204}$ [N/mm²] | $E_{m,g,app,1836}$ [N/mm²] | $E_{m,g,3pB,ew}$ [N/mm²] | $G_{3pB,ew}$ [N/mm²] |
|---|---|---|---|---|---|---|
| quantity | 25 # | 25 # | 25 # | 25 # | 25 # | 25 # |
| **mean** | **10450** | **9100** | **7990** | **7190** | **10950** | **767** |
| **COV** | **7.1 %** | **6.7 %** | **6.9 %** | **6.3 %** | **7.5 %** | **11.7 %** |
| 5 %-qu. acc. CM | 9200 | 8180 | 7130 | 6560 | 9630 | 629 |
| 5 %-qu.(CM) / mean | 0.88 | 0.90 | 0.89 | 0.91 | 0.88 | 0.82 |

Tab. 7: Test results of G of GLT GL24h tested flatwise acc. EN 408 – 'variable span method'

| | $E_{m,g,app,3000}$ [N/mm²] | $E_{m,g,app,1382}$ [N/mm²] | $E_{m,g,app,1034}$ [N/mm²] | $E_{m,g,app,860}$ [N/mm²] | $E_{m,g,3pB,fw}$ [N/mm²] | $G_{3pB,fw}$ [N/mm²] |
|---|---|---|---|---|---|---|
| quantity | 25 # | 25 # | 25 # | 25 # | 25 # | 24 # |
| **mean** | **11410** | **9680** | **8470** | **7580** | **11840** | **752** |
| **COV** | **5.4 %** | **5.5 %** | **5.4 %** | **5.8 %** | **6.4 %** | **10.7 %** |
| 5 %-qu. acc. CM | 10440 | 8850 | 7660 | 6880 | 10540 | 650 |
| 5 %-qu.(CM) / mean | 0.91 | 0.91 | 0.90 | 0.91 | 0.89 | 0.86 |

Compared to the test results of 'constant span method' COV-$E_{m,app}$ confirm COV-$E_{m,g}$ with around 6 %. Also the data for $G_{ew,mean}$ = 770 N/mm² (COV-$G_{ew}$ = 12 %) and $G_{fw,mean}$ = 750 N/mm² (COV-$G_{fw}$ = 11 %) are a bit lower but confirm more or less the foregoing presented results. Calculated values of $E_{m,g,3pB}$, with $E_{m,g,3pB,ew,mean}$ = 10950 N/mm² (COV-$E_{m,g,3pB,ew}$ = 8

%) and $E_{m,g,3pB,fw,mean}$ = 11840 N/mm² (COV-$E_{m,g,3pB,fw}$ = 6 %), are on the same level as $E_{m,g,l,ew-fw,mean}$, gained from 4p-bending tests.

### 3.2.3 Torsion tests

Tab. 8 reflects data of carried out torsion tests by testing each beam twice, first running with gage points at distances 1600 mm and 2950 mm, second running with gage points at 5000 mm and second time at 1600 mm. Calculated $G_{tor,mean}$ show a slight increasing trend with decreasing distance to the clamps, combined with a slight decrease of COV-$G_{tor}$. Last observation can be explained by the averaging effect of local G-values with increasing measurement length. Test results of $G_{tor,mean}$ = 620 N/mm² (COV-$G_{tor}$ = 4 %) contradict the G-values gained with bending tests on the mean- and COV-basis, but confirm test data of Görlacher and Kürth 1994. As given in Tab. 8, test results for the measurement distance of 1600 mm of running's express high stability, accuracy and robustness of this simple to apply test method.

Tab. 8: Torsion test results for $G_{tor}$ of GLT GL24h

| | $G_{tor,1600,1}$ [N/mm²] | $G_{tor,1600,2}$ [N/mm²] | $G_{tor,1600,mean}$ [N/mm²] | $G_{tor,2950}$ [N/mm²] | $G_{tor,5000}$ [N/mm²] |
|---|---|---|---|---|---|
| quantity | 10 # | 10 # | 10 # | 10 # | 10 # |
| **mean** | **606** | **606** | **606** | **616** | **627** |
| **COV** | **4.6 %** | **4.1 %** | **4.3 %** | **4.2 %** | **3.4 %** |
| 5 %-qu. acc. CM | 564 | 566 | 565 | 583 | 597 |
| 5 %-qu. (CM) / mean | 0.93 | 0.93 | 0.93 | 0.95 | 0.95 |

### 2.2.4 Shear field tests during destructive 4-point bending tests

Enforced recording of shear deflections in four observation fields with L / L = 160 / 160 mm placed in constant transverse force sections enable calculation of G as additional characteristic, determined during standard 4p.-bending tests acc. EN 408. The results of calculated G-module of the same 10 # GLT-beams as for torsion tests of averaged measured deflections within opposite paced shear fields (SF) of each side of the beam ($G_{SF,left,mean}$, $G_{SF,right,mean}$) and statistics of mean G-values of both sides are given in Tab. 9.

Tab. 9: Test results of shear field tests for G of GLT GL24h, during 4p-bending tests acc. EN 408

| | $G_{SF,left,mean}$ [N/mm²] | $G_{SF,right,mean}$ [N/mm²] | $G_{SF,mean}$ [N/mm²] |
|---|---|---|---|
| quantity | 10 # | 10 # | 10 # |
| **mean** | **654** | **705** | **694** |
| **COV** | **12.2 %** | **12.8 %** | **8.4 %** |
| 5 %-qu. acc. ND | 525 | 554 | 603 |
| 5 %-qu. (ND) / mean | 0.80 | 0.79 | 0.87 |

It has to be remarked, calculated average expectable shear deflection of the diagonal within observation field with $D = L \cdot \sqrt{2} = 226.3$ mm has been calculated with dD = 0.1 mm. This underlines the high requirements concerning accuracy of measurement device.

## 3.3 Modelling

Based on computer code written by Bogensperger in Java®, sensitivity analyses for (E · G) have been accomplished. The reference values for modelling are given with: $E_{board,mean}$ = 12500 N/mm², $G_{board,mean}$ = 650 N/mm², COV-E,$G_{boards}$ = 20 %, COV-E,$G_{board\_segments}$ = 20 %, $l_{board}$ = 27 # board-segments · $l_{board\_segment = 150\ mm}$ = 4050 mm, $l_{GLT}$ = 19 · $d_{GLT}$ = 19 · $d_{GLT = 40\ mm}$

$\cdot$ 15 # = 600 mm = 11400 mm, $DM_{E,G}$ ~ ND and r (E, G) = 0.00. Neither variation of COV-$E,G_{boards}$, COV-$E,G_{board\_segments}$ nor quantity of segments per each board had a significant impact on results of $(E \cdot G)_{mean}$ or $(E \cdot G)_{05}$. Significant influence is only present on COV-(E · G). The minor influence on $(E \cdot G)_{05}$ despite variation of COV-(E · G) can be explained by the low reference value of COV-$(E \cdot G)_{ref}$ = 4.5 %.

Emphasize of this study has been to evaluate the product $(E \cdot G)_{05}$ by taken into account $E_z$ and $G_{tor}$ of the same GLT-beam, which is of importance for judgement of lateral torsional buckling. The product $(E \cdot G)_{05}$ defines a kind of material value and contradicts the current calculation schema with $(E_{05} \cdot G_{05})$ (see [6]). Generally, $(E \cdot G)_{05} \neq (E_{05} \cdot G_{05})$, only in case of r (E · G) = 1.00 this relationship lead to an equation. By assumption of a positive correlation between E and G, $(E_{05} \cdot G_{05})$ compared to $(E \cdot G)_{05}$ is on the conservative and hence safe side for stability calculations. In case of negative correlation of E and G, as mentioned by Skaggs and Bender 1995, the maximum failure is given with 5 %.

$$\sigma_{m,crit} = \frac{M_{y,crit}}{W_y} = \frac{\pi \cdot \sqrt{E_{0,05} \cdot I_z \cdot G_{05} \cdot I_{tor}}}{l_{ef} \cdot W_y} \qquad [6]$$

Significant increase of $(E \cdot G)_{05}$ is given with increasing quantity of interacting lamellas in the GLT-beam. Further examinations, by considering variation of COV-$E,G_{boards}$, reflect a high impact of system size on $(E \cdot G)_{05}$, up to a level of around 15 # laminations, representing the reference GLT-beam with $d_{GLT,ref} = 15 \cdot d_{board,ref} = 15 \cdot 40$ mm = 600 mm. The relative and absolute decrease of COV-(E · G) can be described by application of a power function, whereby the power itself appears high influenced by the parameters COV-$E,G_{board}$. Variation of COV-$E,G_{board}$ further influences the expectable relative value of $(E \cdot G)_{05}$. Due to interaction of parallel and serial elements the relative relationship between COV-$E,G_{board}$ and $d_{GLT}$ appears like the behaviour of the 'system factor', with constant $(E \cdot G)_{mean}$, decreasing COV-(E · G) and nonlinear increase of $(E \cdot G)_{05}$, and can be expressed by the herein introduced factor $k_{EG} = (E \cdot G)_{05,n} / (E \cdot G)_{05,1}$.

# 4 Discussion

## 4.1 Dependency of G from selected mechanical and physical properties

General, correlation between E and ρ can be expected on a level of r = 0.7 ÷ 0.8. Because of constricted spectrum of examined test series a relationship between E and ρ cannot be supported neither negated. The same holds true for G vers. ρ, which leads to limited explanatory power for G vers. E. Nevertheless, there has to be a lack of relationship between E and G expressed by an observable decreasing coefficient of determination $r^2$ with increasing share of shear deflection of $E_{m,app}$ is given. Together with results of modelling with minor influence of r (E, G) on (E · G) for stability considerations, the importance of correct r (E, G) is not of great importance, but due to apparent difficulties in determination of G by static tests it would be helpful.

## 4.2 Differences between E-modulus, gained by flatwise and edgewise bending

As given in Tab. 4-5 and Tab. 6-7, $E_{m,g,fw}$ reflects a bit lower COV as $E_{m,g,ew}$, due to increasing homogenisation potential with increasing quantity of interacting laminations in loading situation. Furthermore, $E_{m,g,fw,mean}$ is generally about 1000 N/mm² higher than

$E_{m,g,ew,mean}$ which can be explained by predominant occurrence of mature wood in high stressed regions in case of flatwise bending.

## 4.3 Evaluation of applied static test methods for the determination of G-modulus

Fig. 4 reflects derived G-values in dependence of applied test method. Test methods regulated in EN 408 lead to high $G_{mean}$ and unexpected high COV-G if compared to COV-$G_{tor}$. The higher dispersion may be explained by the difficulty of deriving share of shear-deflection out of total deflection whereby test method of 'constant span' appears more appropriate due to determined deflections within the same material area and equal measurement length. In case of 'variable span method' additional bias is given by calculation of the gradient of linear regression model between $1 / E_{m,app}$ and $(d / l)^2$ due to overestimation of boarder pairs of variates. Additional, by variation of span a certain dispersion of gained E- and G-values can be expected due to material inhomogeneities. The dispersion of G-values gained from torsion tests with COV-$G_{tor}$ = 4 % nearly thirds the COV-$G_m$ = 12 % and confirms the assumption of COV-E ≈ COV-G. The test results for $G_{SF}$ gained from shear fields are about in the middle of $G_m$ and $G_{tor}$, on the mean level and by attracting COV-$G_{SF}$. Higher COV-$G_{SF}$, compared to COV-$G_{tor}$, can be explained by bias in measurement of minor shear deflections under influence of local material inhomogeneities.

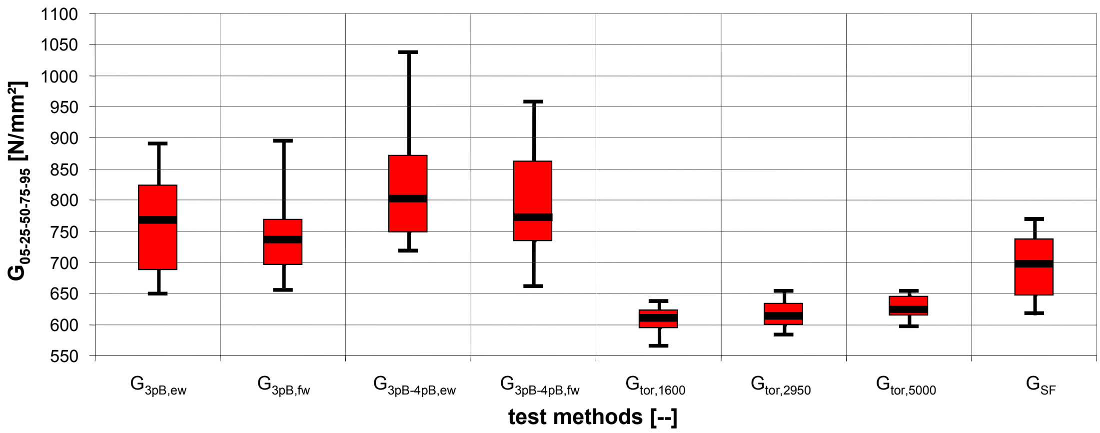


Fig. 7: Box-plots of calculated G-values, gained from applied static test methods

The differences of various G-values on the mean-level can be interpreted as a result of interacting different material characteristics $G_{LR}$ and $G_{LT}$, together with different loading situations combined with differences between high stressed regions, system actions, and the influence of shear warping in the symmetry of GLT-beam in 3p-bending and general in every discontinuity of transverse force. In case of 'variable span method' every deformation underlies blocking due to shear warping and this may lead to higher G-values than expectable as material property. By application of 'constant span method' $E_{m,app}$ based on 3p-bending is influenced by shear warping combined with reduced deflections, in contrast to $E_{m,g,l}$ based on local and free of shear warping measured bending deflection. The differences between 'blocked' and 'not blocked' deformations may lead to higher G-values than in case of 'variable span method'. In contrast, measurements of shear deflection within shear fields during 4p-bending test is placed in high stressed shear region and thereby lead to higher deflections as by averaging the shear deflection over the whole beam. This may explain the lower $G_{SF,mean}$ compared to $G_{3pB,ew}$ and $G_{3pB-4pB,ew}$. Shear warping in case of edgewise loading situation can be expected higher than in flatwise bending. This may also explain the higher $G_{ew,mean}$ compared to $G_{fw,mean}$.

Due to ongoing discussion of ratio E / G, values concerning this test series are given with $E_{m,g,g,ew,mean}$ / $G_{3pB\text{-}4pB,ew,mean}$ = 12.0 in contrast to $E_{m,g,g,ew,mean}$ / $G_{tor,5000,mean}$ = 15.7, which reflects the influence of applied test method for the determination of G. For comparison Görlacher and Kürth 1999 published for strength class C24 a ratio of E / G = 18.

Considering the importance of robustness of applied test methods for determination of material characteristics and by taken into account economic aspects current test methods given in EN 408 can not be proposed for further application. Due to bias in measuring minor shear deflections within shear fields in 4p-bending tests this test method seems first appropriate for shear tests or in case of standard 4p-bending tests acc. EN 408 on beams with d ≥ 600 mm (L ≥ 300 mm) or second for beams with high homogenisation factor like plywood, with d ≥ 300 mm (L ≥ 150 mm). The big advantage of this method is given by additional measurement of a material property during standardized tests. The disadvantage lies in low proportion of tested material in shear compared to test methods like torsion or 'variable span'. The torsion tests itself can be proposed as simple to apply static test configuration with low requirements on test equipment, low forces and well measurable torque. Advantage of torsion is given by testing a high proportion of the beam volume and robustness of gained values. Further advantage of torsion is given in case of stability examinations and the necessity of knowledge of $G_{tor}$. The disadvantage of torsion test is given by only determination of one material property in contrast to 4p-bending tests with measurements in shear fields, whereby characteristics like $f_{m,g}$, $E_{m,g,l}$, $E_{m,g,g}$ and $G_{SF}$ can be calculated out of data of one single test.

## 4.4 Handling of $(E \cdot G)_{05}$ for the design of GLT under lateral torsional buckling

General and under assumption of statistical normal distributed data 5 %-quantiles of material parameters are derived in dependency of a statistical parameter of location (e. g. mean) and dispersion (e. g. COV) [7].

$$x_{05} = \bar{x} - 1.645 \cdot s = \bar{x} \cdot \left(1 - 1.645 \cdot COV\right) = \bar{x} \cdot k_{05} \quad \text{with} \quad k_{05} = \left(1 - 1.645 \cdot COV\right) \qquad [7]$$

The factor $k_{05}$, as multiplier for $x_{mean}$ to derive $x_{05}$, is hence only dependent on COV. Acc. to EN 338 $k_{05}$ for calculation of $E_{0,05}$ is given with $k_{05}$ = 0.67, comprising COV-E = 20 %. EN 1194 regulates calculation of $E_{0,g,05}$ in dependence of $E_{0,l,mean}$ with $k_{05}$ = 0.85 or $k_{05}$ = 0.81 if $E_{0,g,05}$ is derived in relation to $E_{0,g,mean}$, representing COV-$E_{0,g}$ = 12 %. Based on presented test series and simulation results it can be demonstrated, that COV-E,G – by assumption of COV-G ≈ COV-E – depends predominately on the system size and thus on the quantity of interacting lamellas, boards and board segments in the system GLT.

Fig. 5 gives the relationship between (E · G) vers. $d_{GLT}$ for the reference input parameters of the simulations. In addition data of test series, with $(E \cdot G)_{mean} = 7.33 \cdot 10^6$, $(E \cdot G)_{05} = 6.55 \cdot 10^6$ and COV-(E · G) = 7.1 % are included. The dispersion of static tests confirm the simulation results, deviation on the mean- and 5 %-quantile level follow from lower $E_{m,g,g,mean,fw}$ of practical tests. The reference $d_{GLT,ref}$ = 600 mm and assumed $d_{board,ref}$ = 40 mm leads to n = 15 # laminations within one beam and to COV-$(E \cdot G)_{ref}$ = 4.5 %. As result a $k_{05}$ for deriving $E_{0,g,05}$ and $G_{g,05}$, based on mean values $E_{0,g,mean}$ and $G_{g,mean}$, for n = 15, representing reference GLT-beam, of $k_{05}$ = 0.9 can be proposed. For n < 15, $k_{05}$ has to be decreased in dependence of n to $k_{05}$ = 0.67 in case of n = 1, as given in EN 338 for structural timber.

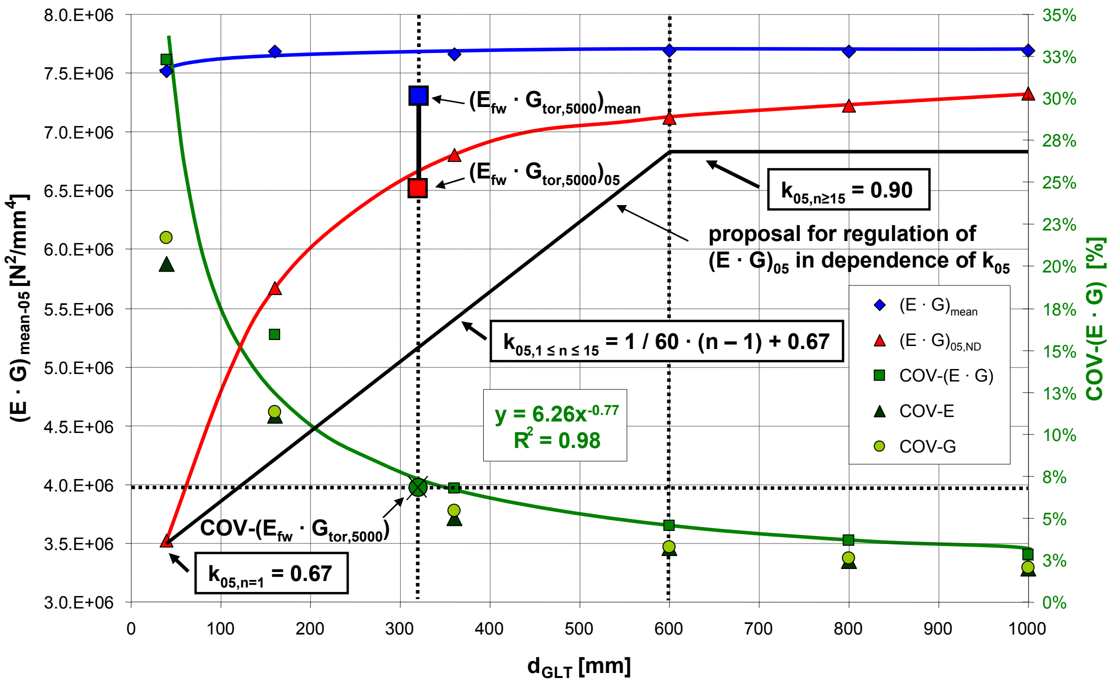


Fig. 5: Relationship between $(E \cdot G)_{mean\text{-}05}$ and COV-$(E \cdot G)$ vers. $d_{GLT}$: Comparison of test results and data gained from simulation, including a proposal for further regulation of $(E \cdot G)_{05}$ for GLT

# 5 Conclusion

Emphasize of presented research project has been to examine various static test configurations for the determination of G of glued laminated timber GLT GL24h. Both test configurations given in EN 408 – 'single span method' and 'variable span method' – have been applied and compared to torsion tests and $G_{SF}$ derived from measurements of shear deflections in 'shear fields'. As discussed, both methods of EN 408 cannot be proposed for further application due to lack of robustness and by consideration of economic aspects. Measurement of shear deflections during standardized 4p-bending tests acc. EN 408 enables enlarged knowledge of tested beam and may reflect robustness in case of consideration of constraints concerning size and material inhomogeneities. The torsion method, in contrast, enables simple, robust and cost efficient determination of G-values, relevant for stability considerations. Both methods torsion test and measurement of shear deflections in shear fields are proposed for implementation in EN 408, torsion in regard to ASTM D 198 and shear field method in regard to standard 4p.-bending test of EN 408 by consideration of discussed constraints!

Additional accomplished simulations of E, G and (E · G) for the design process concerning lateral torsional buckling reflect perfect agreement with data of practical tests and enables an advanced further regulation and derivation of $E_{0,g,05}$ and $G_{g,05}$ in EN 1194 (see Tab. 10). In regard to $G_{tor,mean}$ = 620 N/mm² and $G_{SF}$ = 690 N/mm², gained from static tests, and by consideration of minor variation of $G_{mean}$ compared to $E_{0,mean}$ (see Görlacher and Kürth 1999) a constant value of $G_{g,mean}$ = 650 N/mm² can be proposed for all strength classes of homogeneous and heterogeneous GLT out of softwood. This confirms a proposal of Blaß 2005. Based on data gained from simulations a higher $k_{05}$ = 0.9 for GLT with $d_{GLT} \geq 600$ mm and / or $n \geq 15$ # can be proposed in contrast to current $k_{05}$ = 0.81 acc. EN 1194. This leads to an increase of + 11 % of $l_{ef}$ in the design of lateral torsional buckling ($\sqrt{E_{0,g,mean} \cdot 0.81 \cdot I_z \cdot G_{g,mean} \cdot 0.81 \cdot I_{tor}} = \mathbf{0.81} \cdot \sqrt{E_{0,g,mean} \cdot I_z \cdot G_{g,mean} \cdot I_{tor}}$ vers. $\sqrt{E_{0,g,mean} \cdot 0.90 \cdot I_z \cdot G_{g,mean} \cdot 0.90 \cdot I_{tor}} = \mathbf{0.90} \cdot \sqrt{E_{0,g,mean} \cdot I_z \cdot G_{g,mean} \cdot I_{tor}}$ → **increase of $l_{ef}$ = + 11.1 %**) and in contrast to structural timber to an increase of + 34 %, based on $k_{05}$ = 0.67. For example in case of $d_{GLT}$ = 300 mm and n = 8 # $k_{05}$ has to calculated with $k_{05} = 1 / 60 \cdot (n - 1) + 0.67 = 1 / 60 \cdot (8 - 1) + 0.67 = 0.78$.

Tab. 10: Proposed models for $E_{0,g,mean}$, $E_{0,g,05}$, $G_{g,mean}$ and $G_{g,05}$ for the regulation of glued laminated timber in EN 1194

| | | |
|---|---|---|
| Modulus of elasticity | $E_{t,0,g,mean}$ | $= E_{t,0,l,mean}$ |
| | $E_{t,0,g,05}$ | $= E_{0,g,mean} \cdot \min\begin{cases} \frac{1}{60} \cdot (n-1) + 0.67 \\ 0.9 \end{cases}$ |
| Shear modulus | $G_{g,mean}$ | $= 650$ N/mm² |
| | $G_{g,05}$ | $= G_{g,mean} \cdot \min\begin{cases} \frac{1}{60} \cdot (n-1) + 0.67 \\ 0.9 \end{cases}$ |

n … quantity of laminations

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DIN 4074-1:2004-01-19 Strength grading of wood – Part 1: Ciniferous sawn timber

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 385:2002-05-01 Finger jointed structural timber – Performance requirements and minimum production requirements

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

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