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Tensile strength of spruce glulam

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This article is dedicated to Gerd Wegener on the occasion of his retirement as professor at the Technische Universität München.

Abstract Comparative tests on spruce glulam members subject to tension and bending, respectively, were numerically simulated to determine the tensile-to-bending-strength ratio. Nine different grading methods were applied to cover a wide strength range. They are based on visual inspection and mechanical determination of density and MOE. The simulated tensile and bending strength values result in an almost constant tensile-to-bending-strength ratio of 0.88. The ratio is valid for fifth percentile values and for standardised tests with prescribed member sizes. It is independent of the grading method used. In addition the size effect in glulam tension members was numerically studied. The results show a strong dependence of the glulam tensile strength upon the length subject to tension in case of short members. The dependence slowly wears off in case of long members. The tensile strength for members 150 mm in length is 140 percent of the reference value. The limit strength for a quasi-infinite length is about 80 percent.

Zusammenfassung Vergleichende Versuche an Fichten-Brettschichtholz unter Zug- bzw. Biegebeanspruchung wurden numerisch simuliert, um das Verhältnis zwischen der Zug- und Biegefestigkeit genauer zu bestimmen. Zur Berücksichtigung eines weiten Festigkeitsspektrums wurden neun unterschiedliche Sortierverfahren angewendet, die auf visuellen Kriterien und den maschinellen Sortierparametern Rohdichte und Elastizitätsmodul beruhen. Die simulierten Festigkeitswerte führen auf ein nahezu konstantes, vom Sortierverfahren unabhängiges Verhältnis von 0,88 zwischen charakteristischer Zug- und charakteristischer Biegefestigkeit. Dieses

Verhältnis gilt für genormte Zug- und Biegeprüfungen mit entsprechenden Prüfkörpermaßen. Darüber hinaus wurde der Volumeneffekt in Zug beanspruchten Brettschichtholz-Bauteilen numerisch untersucht. Die Ergebnisse zeigen eine starke Abhängigkeit der Zugfestigkeit von der Bauteillänge im Falle von kurzen Bauteilen, wohingegen sich bei großen Bauteillängen diese Abhängigkeit allmählich verliert. Die Zugfestigkeit von 150 mm langen Zugbauteilen beträgt 140 Prozent und von gewissermaßen unendlich langen Bauteilen etwa 80 Prozent des charakteristischen Referenzwertes der Zugfestigkeit.

Introduction

The characteristic glulam tensile strength is fixed to approximately 70% of the characteristic bending strength in the European standard EN 1194 (1999). This is valid for homogeneous glulam. The percentage generally applies to the relationship between strength values obtained from standardised tensile and bending tests, respectively. Therefore, the relationship is associated with a particular member volume each, which is stressed in grain direction. According to EN 1194 (1999) a minimum depth of 600 mm of both specimens for tensile and bending tests is prescribed. The corresponding free member length (ℓ_t) has to be at least nine times the depth for tensile tests and the corresponding span (ℓ_m) 18 times the depth for bending tests (EN 408 2003). The ratio of 70% was confirmed by numerical investigation and small experimental study on the glulam tensile strength (Blaß et al. 1998). Hernandez et al. (2005) report an experimental tensile-to-bending-strength ratio of 0.70. Their ratio applies to particular comparative tensile and bending tests on glulam made from ponderosa pine.

Numerical studies on the glulam bending strength resulted in a new relation between the board and finger joint tensile, respectively, and the glulam bending strength (Blaß et al. 2009). According to this study, the board and the finger joint tensile strength have to be significantly increased to ensure the nominal strengths of the glulam grades GL24 to GL36. It is to expect that increasing board and finger joint strength necessarily have an effect on the glulam tensile strength too. Therefore, a revision of the current tensile-to-bending-strength ratio was considered necessary. For this purpose the present numerical study was performed. It involves comparative simulated tensile and bending tests, respectively, on glulam members. An existing finite element based computer model was adapted to simulate standardised tensile tests. (The computer model was originally developed to

simulate standardised bending tests on glulam in regard to glulam bending strength.) With the simulated test data obtained the glulam tensile strength was finally estimated. The adapted computer model also discloses the technical possibility to numerically study the size effect in glulam members. Consequently, the dependence of the glulam tensile strength upon the tensile stressed volume was also investigated.

The results from both the comparative study on the tensile-to-bending-strength ratio and the study on the size effect are presented in this paper. They aim at broadening and completing the concepts on bending strength of spruce glulam of a previous paper (Frese and Blaß 2009) published in this journal.

Methods

General

The principles in regard to the simulation of glulam bending strength by means of a finite element based computer model, a new and independent version of the Karlsruhe Rechenmodell (KAREMO), are already published in the previous paper. More background information is given in the corresponding research report (Blaß et al. 2009). Therefore, the following explanations in particular refer to the simulation of glulam tensile tests, the corresponding key conditions and the necessary technical adaptation of the computer model.

Simulation of material

In the present investigation the glulam strength output (tensile/bending) of the computer model refers to homogeneous lay-up and is generally based on the simulation of a specific set of grading methods and materials, respectively. The methods were developed by Holzforschung München for the research project Blaß et al. (2009). They result in nine different simulated materials with different strengths covering a wide strength range. The first three columns in Table 1 give a brief overview on their denotation, principles and the corresponding characteristic board tensile strength values ($f_{t,t,k}$) obtained from previous experimental tests. For the current study, the level for the characteristic finger joint tensile strength ($f_{t,j,k}$) in the forth column of Table 1 was individually fixed for each grading method. It

was intended that this results in balanced relations between characteristic board and characteristic finger joint tensile strength for the simulated materials. In regard to simulated bending tests the balanced relations are associated with a portion of finger joint failure of approximately 50% each. The nine values for the characteristic finger joint tensile strength were estimated by means of the data in a previous paper. With both experimental board and estimated finger joint tensile strength the arithmetical values for the characteristic glulam bending strength ($f_{m,g,k,cal}$) in the last column of Table 1 were first of all calculated. For that the strength models in the previous paper were used. They apply to a homogeneous lay-up. With this the key strength properties of the simulated materials (boards, finger joints and glulam) are introduced.

Table 1 Grading methods, developed by Holzforschung München, and corresponding experimental board tensile strength; finger joint tensile strength and calculated reference values for the glulam bending strength

Tabelle 1 Sortierverfahren, entwickelt von der Holzforschung München, und entsprechende experimentelle Brett-Zugfestigkeit; Keilzinken-Biegefestigkeit und berechnete Werte für die Brettschichtholz-Biegefestigkeit

Name	Method	$f_{t,l,k}^b$ MPa	$f_{t,j,k}^c$ MPa	$f_{m,g,k,cal}^d$ MPa
VIS I	visual in S10 ^a	13.3	22.0	22.8
VIS II	visual in S10 ^a + S13 ^a	14.4	23.5	24.0
VIS III	visual in S13 ^a	21.3	27.5	28.5
DENS I	Density + knots	23.4	29.5	30.0
DENS II		24.6	32.5	32.1
EDYN I	Dynamic MOE + knots	26.7	29.5	31.1
EDYN II		29.0	30.0	32.3
EDYN III		33.0	32.0	35.0
EDYN IV		34.6	36.0	37.5

^a Visual grades according to DIN 4074-1 (2008)
^b Experimental values
^c By means of “Fig. 3” and
^d “Eq. 6” resp. “Eq. 9” in Frese and Blaß (2009)

Comparative simulation of glulam tensile and bending strength

The comparative tests (Fig. 1) to finally determine the tensile-to-bending-strength ratio were simulated according to EN 408 (2003). To simulate the tensile tests the

calculation model was adapted so that the modelled glulam structure is subject to constant tensile stress. The two tension grips, used in real tests, were modelled as a column of elements with infinite stiffness ($E=G=\infty$). That provides a linear strain distribution at the beginning of the free member length by the modelled grips (Fig. 2). The tensile force was transferred into the grips through two hinges. The position of the hinges by the centre line creates bending-free load transfer. According to the principles of KAREMO the element-wise simulated mechanical properties, depending on each grading method, were systematically distributed all over the finite element structure (*mesh*) resulting in a realistic model of a glulam tension specimen. The free member length of the tensile-stressed volume is expressed by the number of elements (n_t), 150 mm in length, in longitudinal direction. The corresponding depth depends on the number of laminations (n_d) in depth direction. The lamination depth is constant (30 mm). In case of the tensile test the ultimate load (F_{\max}) is achieved when a single brittle crack is modelled in any element in one of the outermost laminations. In case of a bending test it is only the outermost lamination in the tension zone. Element failure in the remaining tension zone does not constitute member failure. Therefore, this spatially restricted element failure is allowed during the calculation. The glulam tensile strength is finally calculated as the ratio F_{\max} to cross-section area. $N = 1000$ comparative tests were performed for tension and bending considering all the nine grading methods. Altogether there are 18.000 simulated tests to base the tensile-to-bending-strength ratio on.

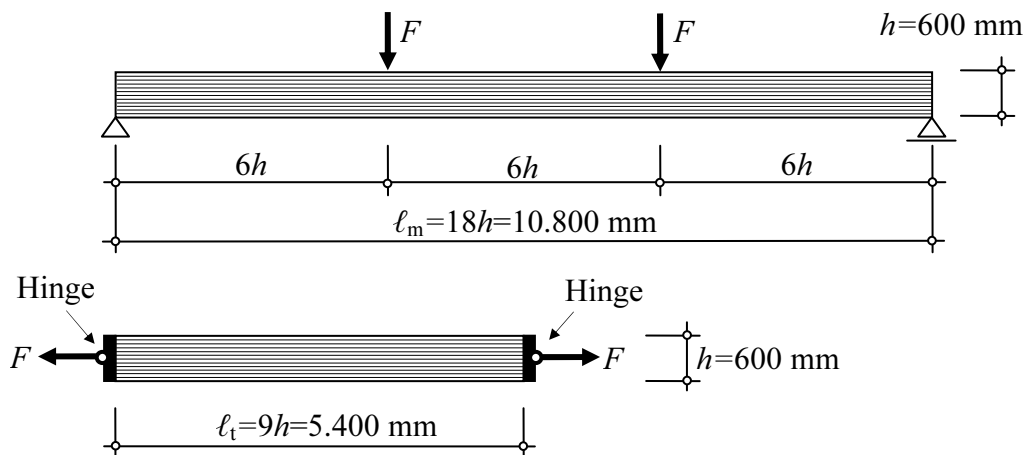


Fig. 1 Simulated test configurations for the comparative tests: (*top*) bending test with span (ℓ_m) and (*bottom*) tensile test with free member length (ℓ_t) and member depth (h)

Abb. 1 Simulierte Prüfanordnungen für die vergleichenden Versuche: (*oben*) Biegeversuch mit Stützweite (ℓ_m) und (*unten*) Zugversuch mit freier Prüflänge (ℓ_t) und Bauteilhöhe (h)

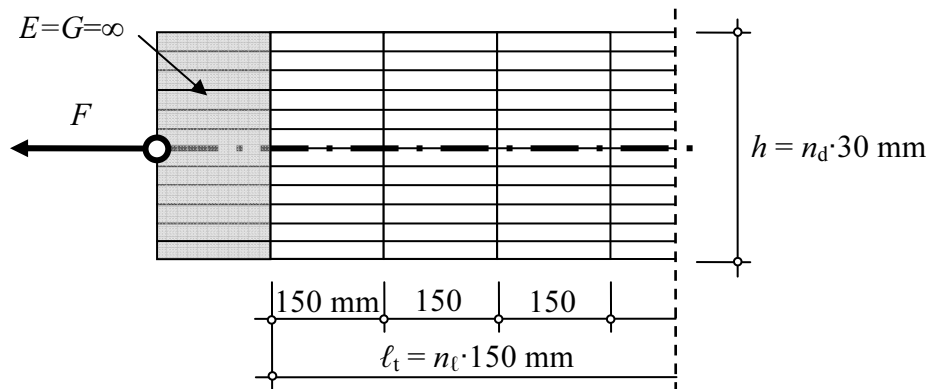


Fig. 2 Hinged and bending-free load transfer into the finite element structure (*mesh*), only left-hand side; the *grey zone* indicates infinite stiffness

Abb. 2 Gelenkige Lasteinleitung in die Finite-Elemente-Struktur (*Netz*) ohne Biegung, Darstellung der linken Seite; in *Grau* Elemente mit unendlich hoher Steifigkeit

Simulation of different member sizes

Investigated free member lengths and member depths for the tensile tests (Fig. 1, bottom) are given by the elements in Eq. 1. The variation in free member length (ℓ_t) originally depends on the number of elements in longitudinal direction ($n_t = 1, 3, 9, 18, 36$ to 360 in steps of 36). The variation in depth (h) results from the number of the laminations ($n_d = 4, 8, 12, 16$, and 20). According to the elements in Eq. 1, $14 \times 5 = 70$ ℓ_t - h -combinations were investigated with $N = 1000$ simulations each. Altogether 70.000 simulated tests create the database describing the size effect.

$$\begin{aligned} \ell_t &= \{150, 450, 1350, 2700; 5400 \text{ to } 54000 \text{ in steps of } 5400 [\text{mm}]\} \\ h &= \{120, 240, 360, 480, 600 [\text{mm}]\} \end{aligned} \quad (1)$$

The grading method EDYN II (Table 1), providing higher glulam strength, was exclusively used to study the size effect. The reasons for that are: It has already been shown that there is no major dependence of the size effect upon the nine grading methods in case of simulating bending tests (Blaß et al. 2009); the same was observed for these grading methods by a comparison between the characteristic bending strength effectively present in continuous beams with three supports

and single supported beams with half the length (Blaß and Frese 2010) – such a comparison is like a consideration of the size effect. Therefore, in case of simulating tensile tests it is to be expected that there is also no pronounced dependence of the size effect upon these grading methods. With this a single grading method is sufficient for the study. Later on, the division of the different size depending tensile strength values by a particular reference value will finally eliminate the connection with grading method EDYN II.

Results

Comparative strength values

The cumulative frequency distributions of the simulated glulam tensile and bending strength values are given in Fig. 3 to Fig. 5. The black dots represent the tensile strength (f_t) and the grey ones the bending strength (f_m) in the diagrams for each of the nine grading methods. Horizontal and vertical reference lines highlight the differences between the corresponding fifth percentile values, determined according to the parameter-free counting method. They are displayed in boxes on the vertical reference lines. The mean values, standard deviations and characteristic values are compiled in Table 2. The simulated characteristic glulam bending strength values ($f_{m,g,k,sim}$) in the seventh column of Table 2 are in line with the arithmetically determined ones ($f_{m,g,k,cal}$) in the last column of Table 1.

Table 2 Statistics of the simulated tensile and bending strength; ratio of the values

Tabelle 2 Statistische Kennwerte der simulierten Zug- und Biegefestigkeit; Verhältnis der Werte

Grading method	Glulam tensile strength MPa			Glulam bending strength MPa			Ratio
	\bar{X}	s	$f_{t,0,g,k,sim}$	\bar{X}	s	$f_{m,g,k,sim}$	
VIS I	25.3	2.97	20.1	31.3	5.19	22.7	0.89
VIS II	26.7	3.02	21.3	33.3	5.21	24.2	0.88
VIS III	30.8	3.33	24.6	38.1	5.50	28.7	0.86
DENS I	33.4	3.45	26.9	41.0	6.30	30.6	0.88
DENS II	35.5	3.76	28.0	43.7	6.23	32.7	0.86
EDYN I	34.4	3.63	27.4	41.9	6.23	31.2	0.88

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EDYN II	35.8	3.79	28.2	43.5	6.64	32.1	0.88
EDYN III	38.6	3.87	32.0	47.1	6.56	36.3	0.88
EDYN IV	40.6	3.67	34.4	49.7	6.74	38.2	0.90

That is to expect: The strength models, used for the calculation of the arithmetical values, are themselves based on simulation results from bending tests. Therefore, the previous comparison serves as a simple plausibility check for the present bending strength output. The last column of Table 2 contains the nine tensile-to-bending-strength ratios. They apply to characteristic values. The standard deviation of these ratios is almost zero. Consequently, the ratios are independent of the grading methods and the corresponding strength levels. The average ratio is 0.88. On the level of mean strength values the average ratio is 0.81. The conversion from characteristic glulam bending strength to characteristic tensile strength is consequently given by Eq. 2.

$$f_{t,0,g,k} = 0.88 \cdot f_{m,g,k} \quad (2)$$

Blaß et al. (1998) propose a numerically determined ratio of 0.80 for characteristic values considering a free member length of 20 m for the simulated tensile tests, which is 3.7 times the reference length of 5.4 m. Taking into account this difference in length the coefficient in Eq. 2 is in good agreement with a correspondingly adapted ratio found by Blaß et al. (1998).

The relationship (Eq. 2) is restricted to stressed volumes according to the numerically reproduced standardised tests in this investigation (Fig. 1). The ratio of 0.88 shows that the current ratio of 0.70 is far too conservative in particular for the reference member length subject to tension.

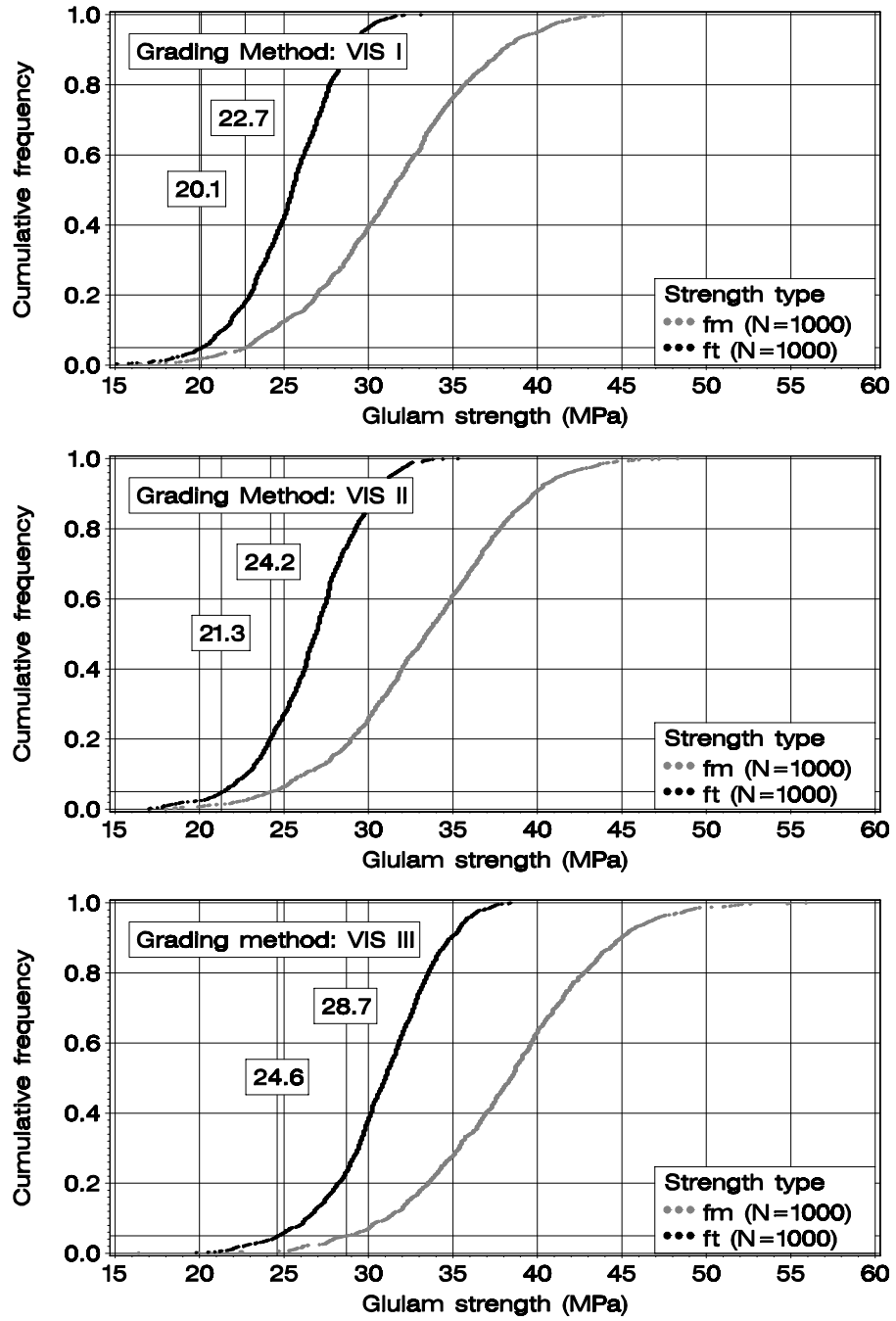


Fig. 3 Cumulative distributions for the tensile and bending strength, respectively; visual grading methods

Abb. 3 Summenhäufigkeit der Zug- bzw. Biegefestigkeit; visuelle Sortierverfahren

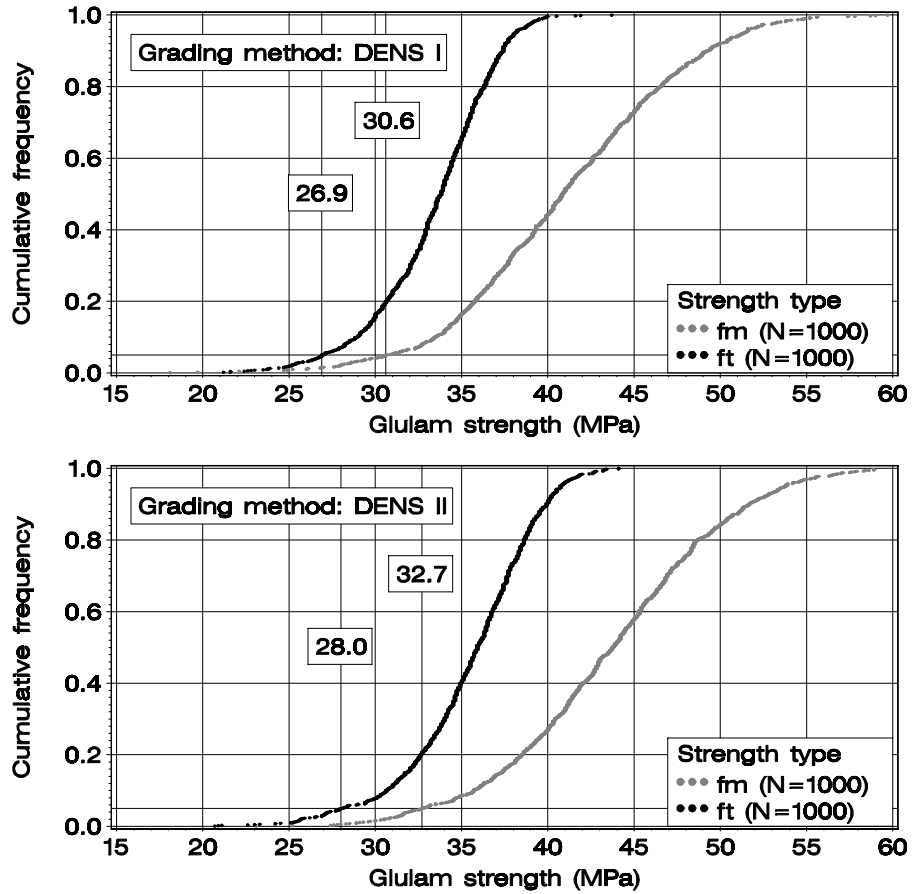


Fig. 4 Cumulative distributions for the tensile and bending strength, respectively; grading methods based on density and knots

Abb. 4 Summenhäufigkeit der Zug- bzw. Biegefestigkeit; Sortierverfahren auf Grundlage der Rohdichte und der Ästigkeit

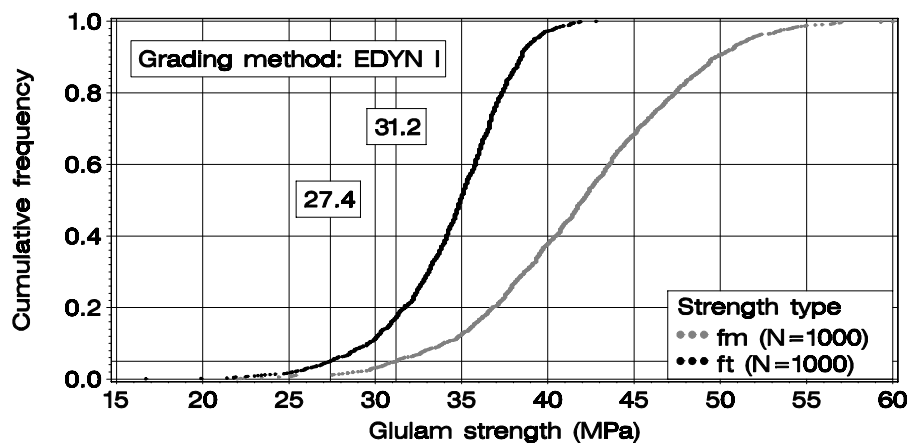


Fig. 5 Cumulative distributions for the tensile and bending strength, respectively; grading methods based on dynamic MOE and knots

Abb. 5 Summenhäufigkeit der Zug- bzw. Biegefestigkeit; Sortierverfahren auf Grundlage des Elastizitätsmoduls und der Ästigkeit

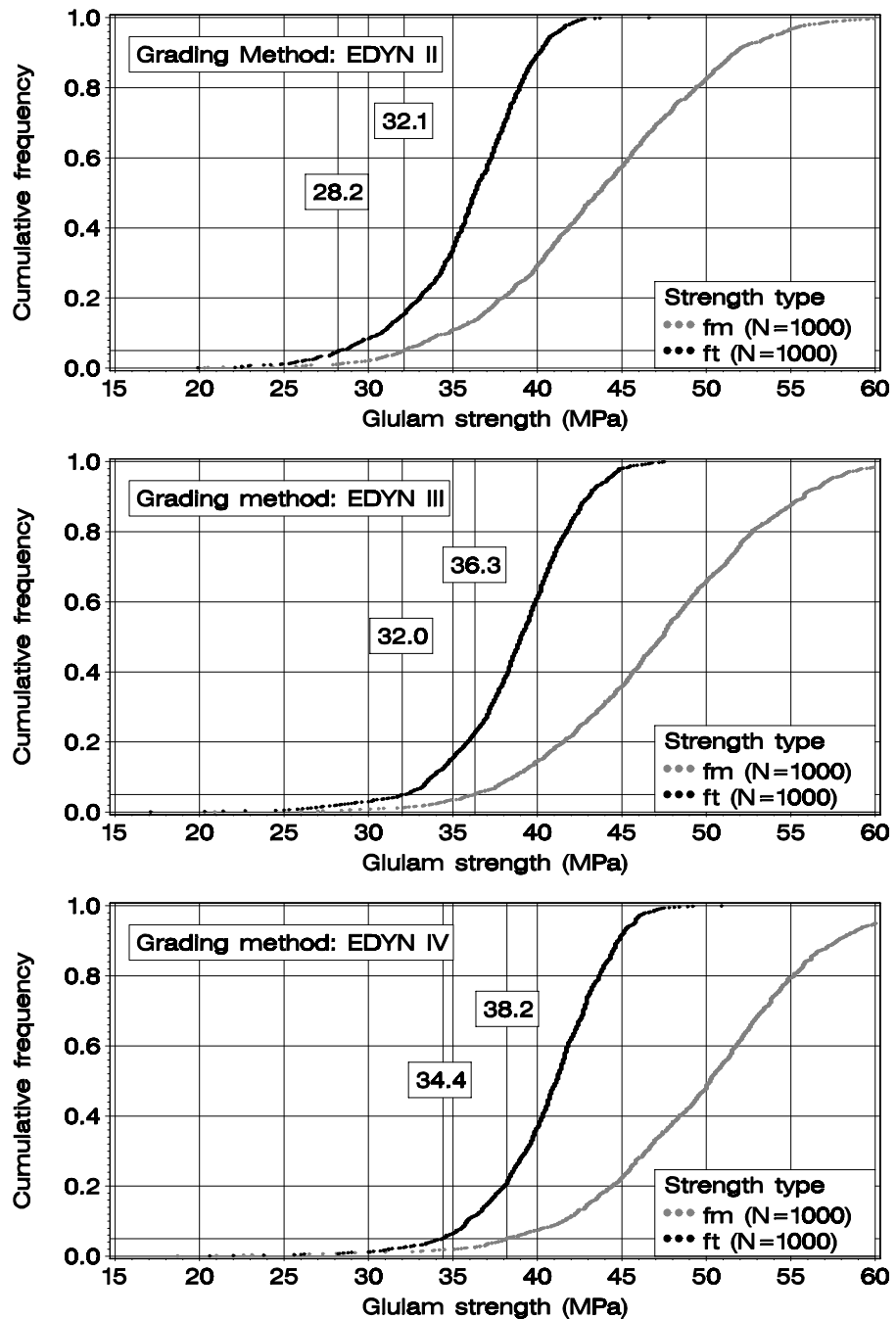


Fig. 5 (Continuation) Cumulative distributions for the tensile resp. bending strength; grading methods, based on dynamic MOE and on knots

Abb. 5 (Forts.) Summenhäufigkeit der Zug- bzw. Biegefestigkeit; Sortierverfahren auf Grundlage des Elastizitätsmoduls und der Ästigkeit

Size effect

The relationships between the characteristic glulam tensile strength ($f_{t,0,g,k}$) and both the free member length (ℓ_t) and the member depth (h) are shown in Fig. 6.

The course of the characteristic tensile strength is strongly dependent upon the free member length in case of short members. The influence of the member depth on the strength is weak for the depths investigated. This is explained by the fact that the brittle failure criterion exclusively refers to the two outermost laminations. Consequently, the occurrence probability of weak points in the outermost laminations is independent of the member depth. This causes an almost similar failure probability for same free member lengths. This corresponds to observations by Blaß et al. (1998) and Peterson (1978). With this it is sufficient to describe the size effect as a function of the free member length by means of Weibull's theory: The characteristic reference strength ($f_{t,0,g,k,ref}$) is highlighted in Fig. 6. As expected, this value approximately matches the characteristic tensile strength in the fourth column of Table 2 (28.5 MPa \approx 28.2 MPa, EDYN II). The elementary Eq. 3, the definitions 4 and the reference values 5 result in Eq. 6. The exponent B in Eq. 6 was determined to 1/10.8 through a nonlinear regression analysis. The regression was performed from the ratios $f_{t,0,g,k}/f_{t,0,g,k,ref}$ on the free member length ℓ_t . The coefficient of determination r^2 is 0.98. Fig. 7 shows the curve of the non-dimensional $k_{\ell,k}$ -factor ($k_{\ell,k}$) according to Eq. 7. The curve is obviously in line with the simulated ratios.

$$\frac{\sigma_2}{\sigma_1} = \left(\frac{\ell_1}{\ell_2} \right)^{1/B} \quad (3)$$

$$\begin{aligned} f_{t,0,g,k} &= \sigma_2 \\ \ell_t &= \ell_2 \end{aligned} \quad (4)$$

$$\begin{aligned} f_{t,0,g,k,ref} &= \sigma_1 = 28.5 \text{ MPa} \\ \ell_{ref} &= \ell_1 = 9 \cdot h = 9 \cdot 600 \text{ mm} = 5400 \text{ mm} \end{aligned} \quad (5)$$

$$\frac{f_{t,0,g,k}}{f_{t,0,g,k,ref}} = \left(\frac{\ell_{ref}}{\ell_t} \right)^{1/B} \rightarrow \frac{f_{t,0,g,k}}{28.5} = \left(\frac{5400}{\ell_t} \right)^{1/B} \quad (6)$$

$$k_{\ell,k} = \left(\frac{5400}{\ell_t} \right)^{1/10.8} \quad (7)$$

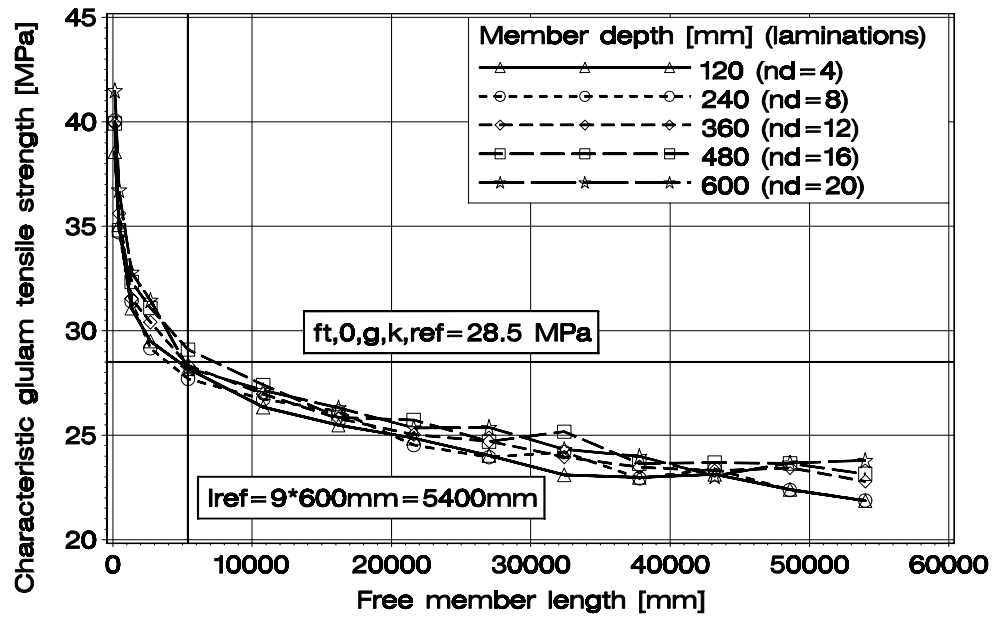


Fig. 6 Simulated characteristic glulam tensile strength and free member length and Depth, respectively; results are based on grading method EDYN II; reference values $f_{t,0,g,k,ref}$ and l_{ref} highlighted by *thick lines*

Abb. 6 Simulierte charakteristische Brettschichtholz-Zugfestigkeit und Bauteillänge bzw. -höhe; Ergebnisse auf Grundlage des Sortierverfahrens EDYN II; Referenzwerte $f_{t,0,g,k,ref}$ und l_{ref} durch *dicke Hilfslinien* gekennzeichnet

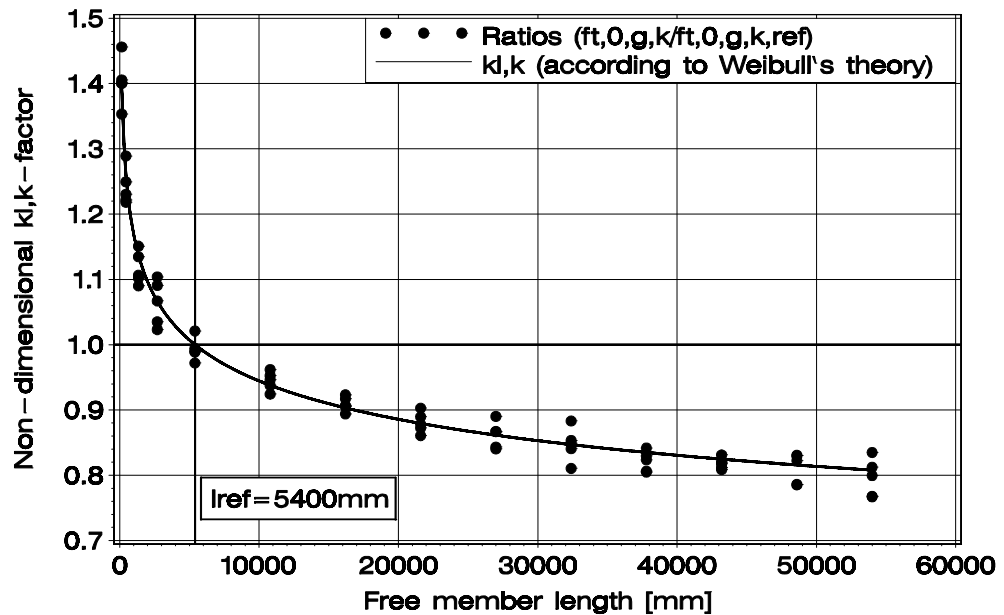


Fig. 7 $k_{l,k}$ -factor (curve) and strength ratios (dots), calculated with the reference value 28.5 MPa, in dependence of free member length; reference length ($l_{ref} = 5400$ mm) and corresponding $k_{l,k}$ -factor (= 1.0) highlighted by *thick lines*

Abb. 7 $k_{\ell,k}$ -Faktor (*Kurve*) und Festigkeitsverhältnisse (*Punkte*), berechnet mit dem Referenzwert 28,5 MPa, in Abhängigkeit von der Bauteillänge; Referenzlänge ($\ell_{\text{ref}}= 5400$) und entsprechender $k_{\ell,k}$ -Factor (= 1.0) durch *dicke Hilfslinien* gekennzeichnet

Analogous to the descriptions and considerations regarding the characteristic tensile strength Fig. 8 shows the courses of the mean glulam tensile strength ($f_{t,0,g,\text{mean}}$) over free member length and depth, respectively. There is almost no dependence of the mean strength upon the member depth. In Fig. 9 the corresponding curve of the non-dimensional $k_{\ell,\text{mean}}$ -factor ($k_{\ell,\text{mean}}$) according to Eq. 8 is depicted. In the equation the exponent B was found to be $1/8.83$. For that the reference strength on mean level ($f_{t,0,g,\text{mean,ref}}$) was fixed to 35.8 MPa (Table 2, second column, EDYN II) to first calculate the ratios $f_{t,0,g,\text{mean}}/f_{t,0,g,\text{mean,ref}}$. The k_{ℓ} -factors of both the characteristic and the mean strength almost show a similar trend.

$$k_{\ell,\text{mean}} = \left(\frac{5400}{\ell_t} \right)^{1/8.83} \quad (8)$$

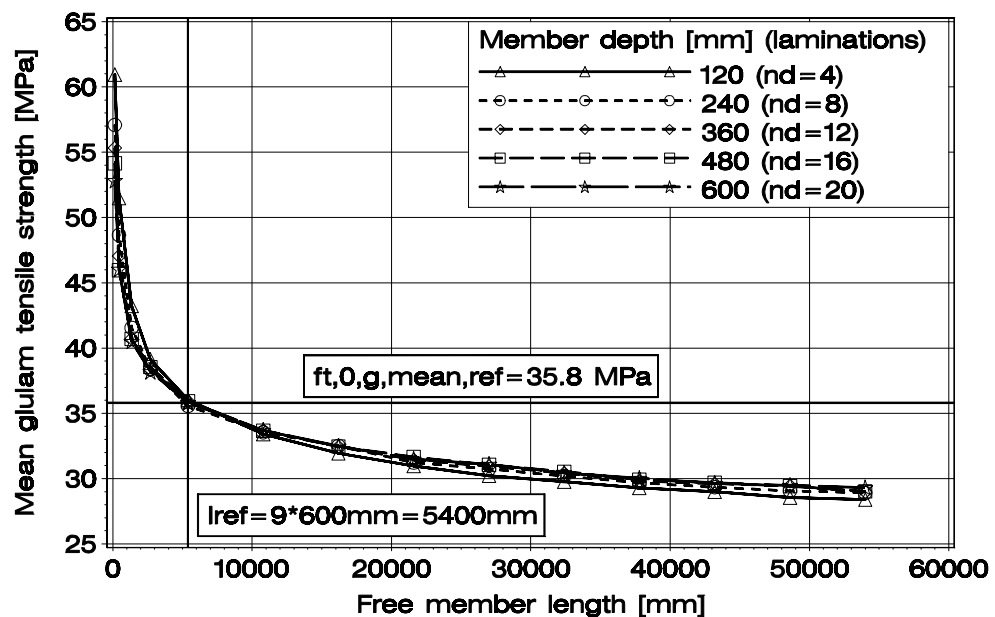


Fig. 8 Simulated mean glulam tensile strength and free member length and depth, respectively; results are based on grading method EDYN II; reference values $f_{t,0,g,\text{mean,ref}}$ and ℓ_{ref} highlighted by *thick lines*

Abb. 8 Simulierte mittlere Brettschichtholz-Zugfestigkeit und Bauteillänge bzw. -höhe; Ergebnisse auf Grundlage des Sortierverfahrens EDYN II; Referenzwerte $f_{t,0,g,\text{mean,ref}}$ und ℓ_{ref} durch *dicke Hilfslinien* gekennzeichnet

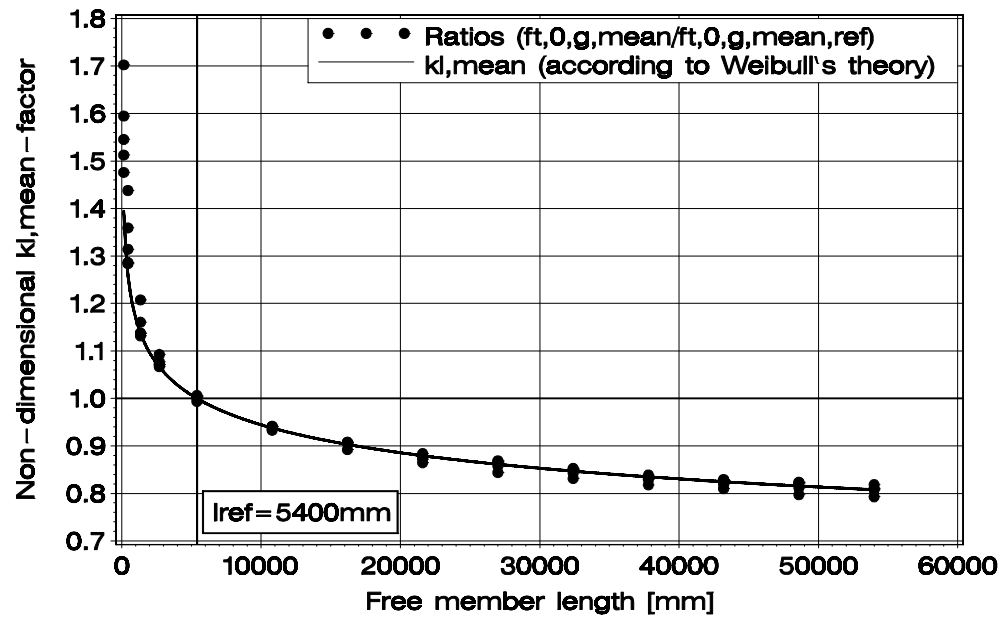


Fig. 9 $k_{l,mean}$ -factor (curve) and strength ratios (dots), calculated with the reference value 35.8 MPa, in dependence of free member length; reference length ($\ell_{ref} = 5400$ mm) and corresponding $k_{l,mean}$ -factor (= 1.0) highlighted by thick lines

Abb. 9 $k_{l,mean}$ -Faktor (Kurve) und Festigkeitsverhältnisse (Punkte), berechnet mit dem Referenzwert 35,8 MPa, in Abhängigkeit von der Bauteillänge; Referenzlänge ($\ell_{ref} = 5400$ mm) und entsprechender $k_{l,mean}$ -Factor (= 1.0) durch dicke Hilfslinien gekennzeichnet

Conclusion

An existing finite element based computer model was expanded to simulate glulam tensile tests. The computer model was originally used in a previous investigation to simulate glulam bending tests and to establish a new strength model. The present simulations were performed to look in more detail into the tensile strength of spruce glulam members.

First, comparative simulations of tensile and bending tests, respectively, were performed to revise the tensile-to-bending-strength ratio. In order to base this revision on a wide strength range simulated materials for glulam were graded according to nine different grading methods. They involve visual principles with lower and mechanical principles with higher requirements on the materials' strength. Consequently, this resulted in different strength levels. Second, 70 length-depth-

combinations were considered for simulated tension members to create a database describing the size effect in glulam members subject to tension.

According to the current study, the mean value of the tensile-to-bending-strength ratio is 0.88. The ratio applies to characteristic values of homogeneous glulam, is independent of the different grading methods and refers to standardised specimen dimensions for tensile and bending tests, respectively. The new found ratio is about 25 % higher than the value of about 0.70 in the European standard EN 1194 (1999). This difference may benefit the glulam industry by increasing the reference value for the characteristic tensile strength.

Instead of using all the nine grading methods the size effect was studied by means of a single method because in two previous studies it was found that differences in strength grading have almost no influence on the size effect. In the current study, the length but not the depth was found to be the dominant factor affecting the tensile strength. The influence of a member depth between 120 and 600 mm on the tensile strength is negligible. Based on Weibull's theory, non-dimensional length factors were obtained to fit the tensile-to-reference-tensile-strength ratio for characteristic and mean values each. The trend for both factors is similar. They decrease rapidly with increasing length for short members, meaning the tensile strength shows a strong dependence on the length of short members. For a quasi-infinite member length the size effect wears off. The effective strength of a tension member, 150 mm in length, is about 140% of the reference value whereas the remaining tensile strength for quasi-infinite member length is approximately 80% of the reference value. This applies to both characteristic and mean tensile strength.

The findings of the current study finally enable a consistent calculation of the length depending glulam tensile strength on the basis of its bending strength.

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