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INFLUENCE OF ROLLING SHEAR MODULUS ON STRENGTH AND STIFFNESS OF STRUCTURAL BONDED TIMBER ELEMENTS

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Influence of rolling shear modulus on strength and stiffness of structural bonded timber elements

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1 Introduction

Rolling shear is defined as shear stress leading to shear strains in a plane perpendicular to the grain direction. Due to the very low rolling shear stiffness of timber significant shear deformations may occur. Fig. 1 shows a schematic representation of rolling shear stresses.

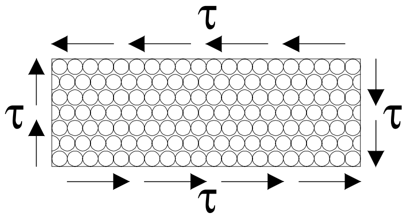


Fig. 1: Stress due to rolling shear

In prEN 1995-1-1 – Design of timber structures (final draft 2004) a ratio of $G_{R,mean}$ / G_{mean} = 0,10 is defined for softwood. For the rolling shear strength a common characteristic value of $f_{R,k}$ = 1,0 N/mm² is given independent of the strength class.

Neuhaus [9] determined the rolling shear modulus of spruce as 48 N/mm² for a moisture content of 9 % through torsion tests. *Aicher et al.* [1] analysed the rolling shear modulus for different annual ring orientations in the cross-section using the Finite Element Method. Depending on the annual ring orientation he found values between about 50 N/mm² and 200 N/mm². Experiments by *Aicher et al.* [2] resulted in a rolling shear modulus of 50 N/mm².

Fig. 2 shows rolling shear failure due in structural bonded timber elements.

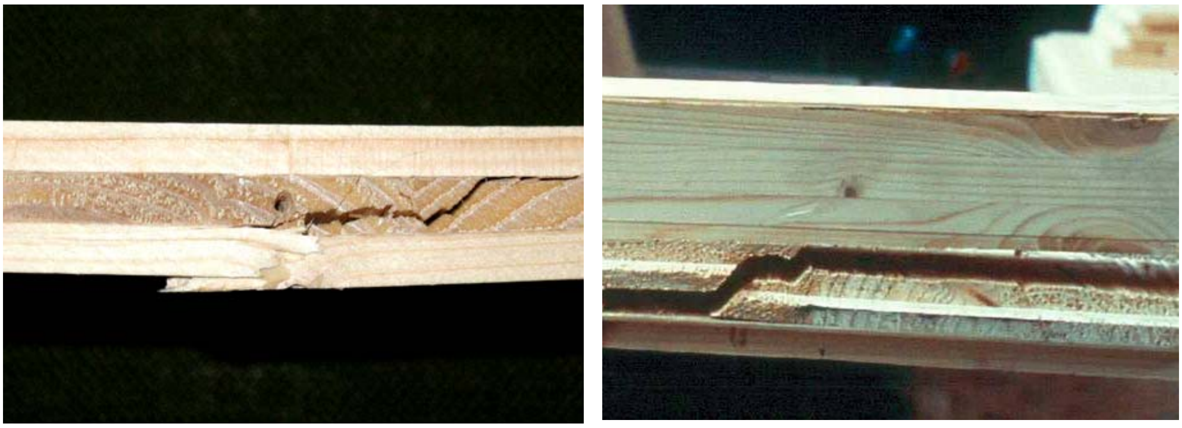


Fig. 2: Failure due to rolling shear

2 Determination of rolling shear modulus

2.1 Experimental investigations

For determining the rolling shear modulus of spruce specimens, the dynamic method of measuring the frequencies of a bending vibration was used. A method for the determination of the modulus of elasticity perpendicular to the grain and the rolling shear modulus was derived from the method for determining the modulus of elasticity parallel to the grain.

Görlacher describes in [5] the determination of the modulus of elasticity parallel to the grain direction via measuring the frequencies of a bending vibration. Fig. 3 shows the schematic representation of the experimental set-up. An approximate solution of the differential equation of a flexural vibration is given taking into account the shear modulus.

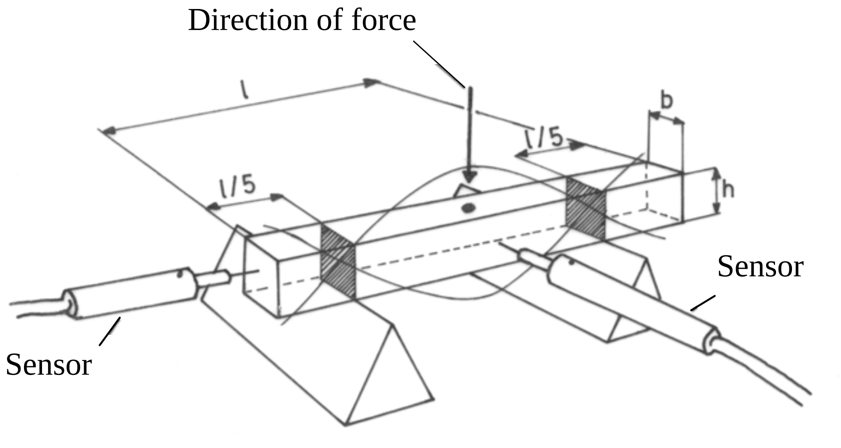


Fig. 3: Measuring the frequencies of a bending vibration

The modulus of elasticity may be determined from the frequency of a 1. order flexural mode using equation (1):

$$E=\frac{4\cdot\pi^2\cdot\ell^4\cdot f_0^2\cdot\rho}{500,6\cdot i^2}\cdot\left(1+\frac{i^2}{\ell^2}\cdot\left(49,48+12,3\cdot s\cdot\frac{E}{G}\right)-\frac{4\cdot\pi^2\cdot s\cdot i^2\cdot f_0^2\cdot\rho}{G}\right) \tag{1}$$

where

ℓ = length of test specimen
f_0 = frequency of bending vibration
ρ = density
i = radius of inertia
E = modulus of elasticity
G = shear modulus
s = form factor (according to *Hearmon* [7] for wood: s = 1,06)

For test specimens with large span to depth ratios (ℓ/h) and / or small modulus of elasticity to shear modulus ratios (E/G) the influence of shear modulus (or E/G, respectively) is small. In this case a rough estimate for the shear modulus is sufficient. Alternatively, the shear modulus may be determined for a known modulus of elasticity using specimens with small span to depth ratios and / or large ratios of modulus of elasticity to shear modulus.

First tests from *Görlacher* [6] showed that both, rolling shear modulus and modulus of elasticity perpendicular to the grain, significantly depend on the annual ring orientation. Based on these tests the rolling shear modulus and the modulus of elasticity perpendicular to the grain of spruce were determined in this study.

2.2 Test set-up and specimens

Different solid wood panels with cross layers (nominal thickness 21mm, 32 mm and 52 mm) were dismantled for testing. From every board of the middle layers a specimen (width 10 mm) was prepared. Consequently, three test series were performed depending on the thickness of the solid wood panels. The specimens were conditioned in a constant climate of 20° C and 65 % relative humidity. The average moisture content was 12,2 %.

Test series 1: L x B x H = 104 mm x 10 mm x 6 mm
Test series 2: L x B x H = 46 mm x 10 mm x 17 mm
Test series 3: L x B x H = 53 mm x 10 mm x 17 mm

The specimens were forced to bending vibrations in grain direction (see Fig. 4 left) and perpendicular to grain direction (see Fig. 4 right). For both bending vibrations the frequencies were measured.

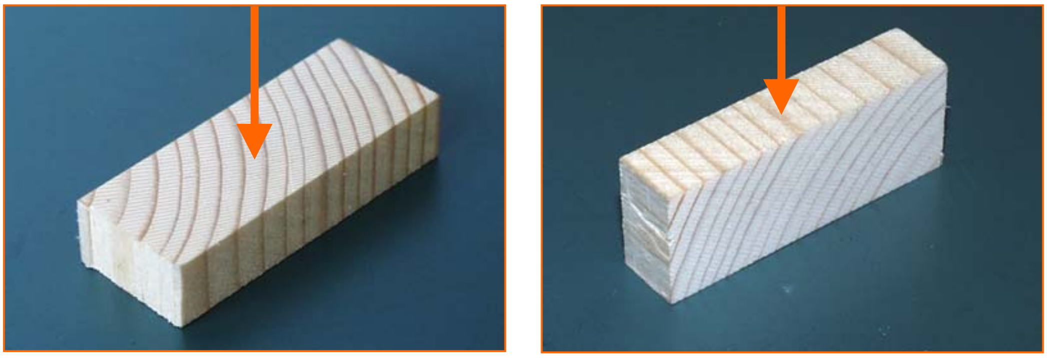


Fig. 4: Specimen with force in grain direction and perpendicular to grain direction

2.3 Results

For bending vibration in grain direction the shear modulus has a lower influence on the modulus of elasticity. Consequently a value of G = 500 N/mm² was assumed in equation (1). The modulus of elasticity perpendicular to grain may be determined using the measured frequency of bending vibration parallel to the grain (Fig. 4 left).

For bending vibration perpendicular to grain the influence of shear modulus is large. Rolling shear modulus may be calculated according to the following procedure: in equation (1) the modulus of elasticity from the bending vibration parallel to grain of the same specimen as well as the measured frequency from bending vibration perpendicular to grain is inserted and the rolling shear modulus is calculated.

For determining the rolling shear modulus of spruce 112 specimens were analysed using the dynamic method of measuring the frequencies of a bending vibration. Fig. 5 and Fig. 6 show the modulus of elasticity perpendicular to grain and the rolling shear modulus versus density. Four specimens were excluded from the analysis because of knots and marked in Fig. 5 and Fig. 6. Common values of rolling shear modulus of spruce are between 40 N/mm² and 80 N/mm². The results confirm specifications of prEN 1995-1-1 – Design of timber structures (final draft 2004) where a ratio of $G_{R,mean}$ / G_{mean} = 0,10 is defined for softwood.

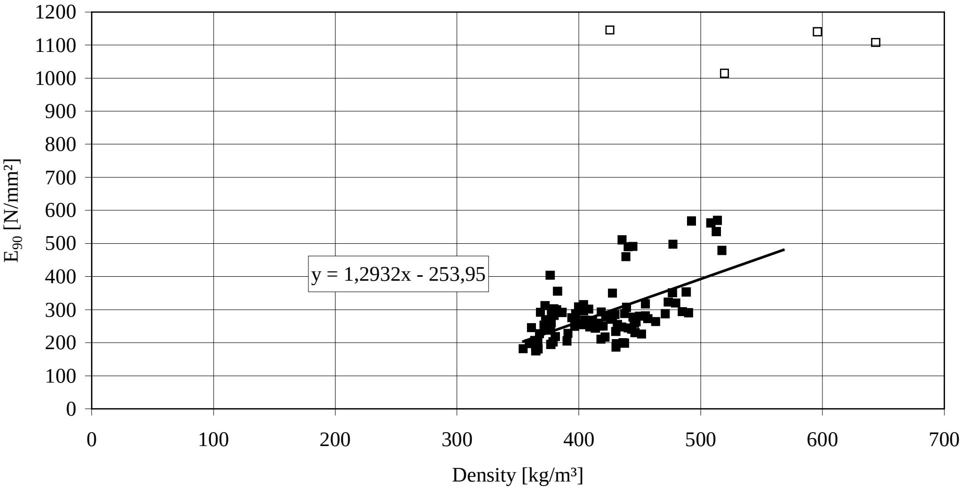


Fig. 5: Modulus of elasticity perpendicular to the grain versus density

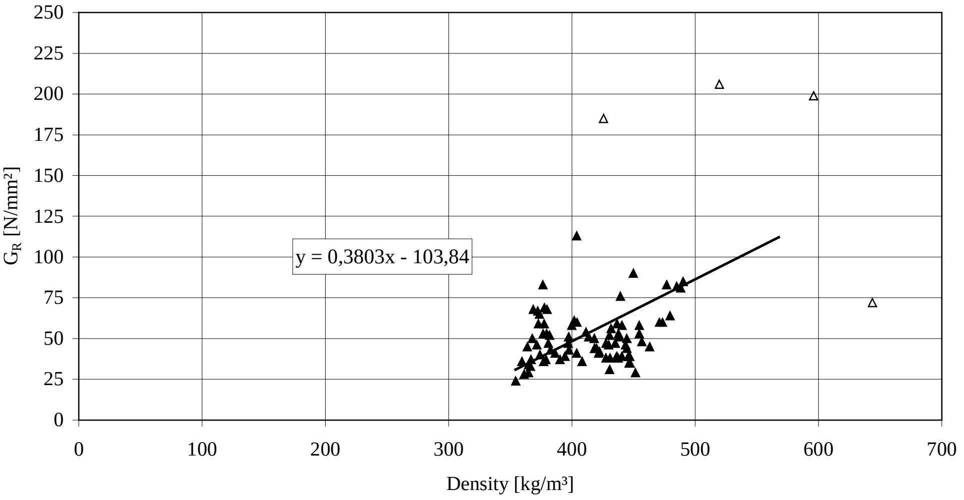


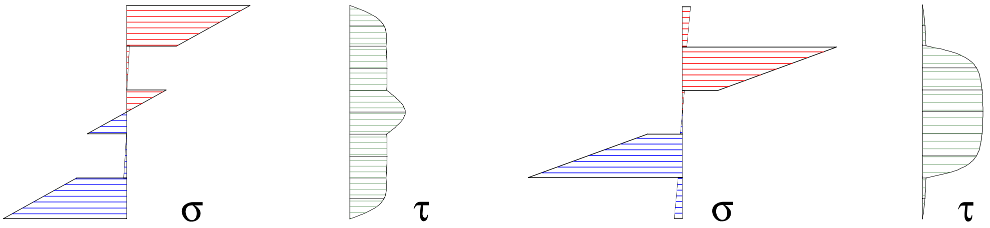
Fig. 6: Rolling shear modulus versus density

The influence of annual ring orientation on modulus of elasticity perpendicular to the grain and the rolling shear modulus was analysed by *Görlacher* [6] based on the Finite Element Method and on the transformation of constitutive equations. For small deviations of the annual ring orientation from 0° and 90°, respectively, the modulus of elasticity perpendicular to the grain is decreasing significantly and the rolling shear modulus remains almost constant. For an annual ring orientation of about 45° the rolling shear modulus is increasing significantly (up to a factor of about 4) and the modulus of elasticity perpendicular to the grain remains almost constant.

Because of curved annual rings in the specimens, the influence of annual ring orientation on the rolling shear modulus cannot be determined. Consequently, the theoretical results from FEM with straight annual rings in the cross-section cannot be confirmed by the method of measuring the frequencies of bending vibrations.

3 Design of solid wood panels with cross layers

The stress distribution in and the deformation behaviour of solid wood panels with cross layers loaded perpendicular to the plane both depend on the shear deformation. Due to the very low rolling shear modulus, shear deformation increases significantly depending on the thickness of the rolling shear layer. Bernoulli's hypothesis of plane cross-sections remaining plane and a linear stress-strain relationship may not be assumed because of shear deformations. Fig. 7 shows the normal and shear stress distribution in solid wood panels with 5 layers for bending perpendicular to the plane and parallel / perpendicular to the grain direction of outer skins.



a) b)

Fig. 7a and b: Bending stress and shear stress of solid wood panel with 5 layers when bending perpendicular to the plane a) parallel b) perpendicular to the grain direction of outer skins

The stress distribution in and the deformation behaviour of solid wood panels with cross layers were analysed using the shear analogy method by Kreuzinger [8]. Both different moduli of elasticity and shear moduli of single layers may be considered for any system configuration. Also the number of layers within a panel is unlimited in the shear analogy method.

The following properties were used as input for modelling solid wood panels with cross layers:

Modulus of elasticity parallel to the grain: $E_0 = 12.500$ N/mm²
Modulus of elasticity perpendicular to the grain: $E_{90} = E_0 / 30$
Shear modulus: $G = 500$ N/mm²
Rolling shear modulus: $G_R = 50$ N/mm²

Tab. 1 summarises the build-up of the solid wood panels with cross layers that were analysed using the shear analogy method.

Tab. 1: Build-up of analysed solid wood panels with cross layers

Type of solid wood panel	Nominal thickness	Build-up
3 layers	21 mm	6,9 / 7,2 / 6,9
3 layers	60 mm	6,9 / 46,2 / 6,9

The span was varied for the modelling of the solid wood panels and the calculation of the effective modulus of elasticity when bending perpendicular to the plane. The effective modulus of elasticity is the effective bending stiffness over the second moment of inertia. The influence of the span on the effective modulus of elasticity of solid wood panels is shown in Fig. 8. The solid wood panels with a nominal thickness of 21 mm and 60 mm were analysed for bending perpendicular to the plane and parallel to the grain direction of the outer skins.

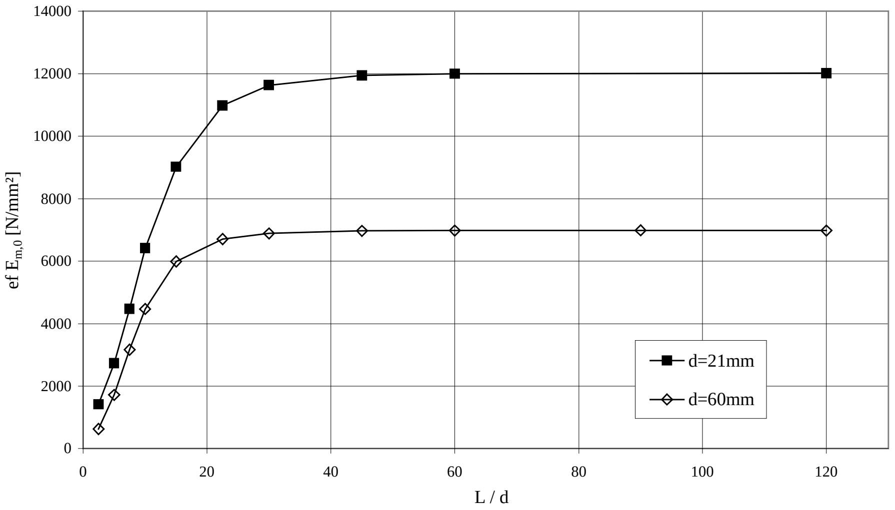


Fig. 8: Effective modulus of elasticity versus span to depth ratio for bending perpendicular to the plane and parallel to the grain direction of outer skins

Shear influence was observed for span to depth ratios smaller than 30 when bending perpendicular to the plane and parallel to the grain direction of outer skins: for decreasing span to depth ratios shear influence is increasing. Consequently the effective modulus of elasticity is decreasing.

For bending perpendicular to the plane and perpendicular to the grain direction of outer skins shear influence is not as distinctive as for loading parallel to the grain direction of outer skins. Shear influence was observed for span to depth ratios smaller than 20 for bending perpendicular to the plane and perpendicular to the grain direction of outer skins.

Fig. 9 shows the ratios of shear and bending deformation for a solid wood panel (nominal thickness 60 mm) for bending perpendicular to the plane and parallel to the grain direction of outer skins. Due to the very low rolling shear modulus, the proportion of shear deformation increases significantly for decreasing span to depth ratios. For small span to depth ratios shear deformation in cross layers hence have to be taken into account.

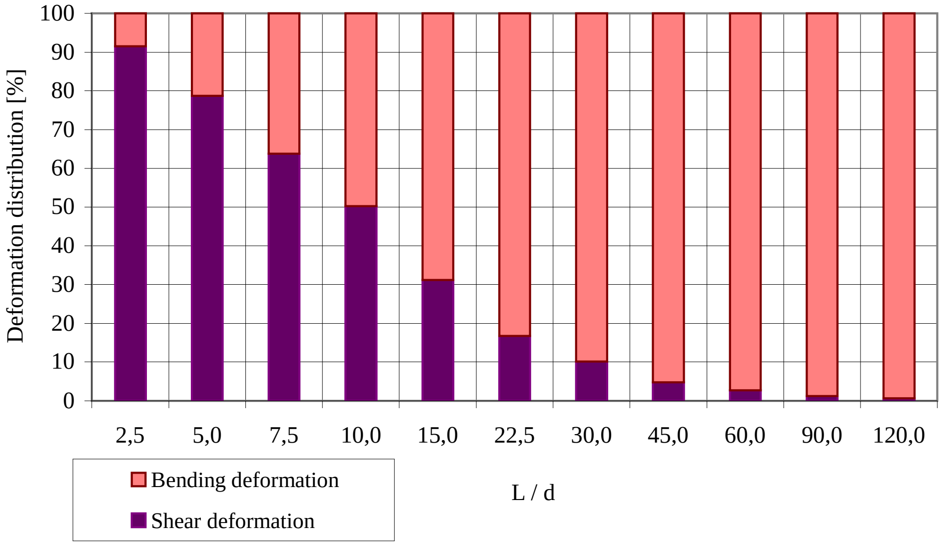


Fig. 9: Proportion of shear and bending deformation versus span to depth ratio for solid wood panel (nominal thickness 60 mm) when bending perpendicular to the plane and parallel to the grain direction of outer skins

In [3] and [4] different methods for the design of solid wood panels with cross layers are presented. The theory of mechanically jointed beams may be used for the design of solid wood panels with cross layers taking into account shear deformations. Instead of joint slip the shear deformation of cross layers is taken into account by the reduction factor γ_i when calculating the effective bending stiffness and the resulting stresses. The shear analogy method is a more precise calculation method for the design of solid wood panels with cross layers taking into account shear deformations. Both different moduli of elasticity and shear moduli of single layers may be considered. Using the composite theory for the design of solid wood panels with cross layers, shear deformations are not taken into account. Consequently the composite theory may only be used for high span to depth ratios for the design of solid wood panels with cross layers.

4 Summary

The stress distribution in and the deformation behaviour of solid wood panels with cross layers loaded perpendicular to the plane both depend on shear deformation. Due to the very low rolling shear modulus, shear deformation increases significantly depending on the thickness of the rolling shear layer.

The dynamic method of measuring the frequencies of a bending vibration was used for determining the rolling shear modulus of spruce. From the well known method for determining the modulus of elasticity parallel to the grain, a method to determine the modulus of elasticity perpendicular to the grain and the rolling shear modulus was derived. Rolling shear modulus and modulus of elasticity perpendicular to the grain both depend on annual ring orientation. Common values for the rolling shear modulus of spruce are between 40 N/mm² and 80 N/mm².

The load bearing performance of solid wood panels with cross layers loaded perpendicular to the plane was analysed using the shear analogy method. Shear influence was determined for different build-ups of solid wood panels depending on the type of stress and span to depth ratio. For decreasing span to depth ratios, shear deformation increases significantly due to the very low rolling shear modulus. Significant shear influence was observed for span to depth ratios smaller than 30 for bending perpendicular to the plane and parallel to the grain direction of outer skins and for span to depth ratios smaller than 20 for bending perpendicular to the plane and perpendicular to the grain direction of outer skins.

5 Literature

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