Design of solid wood panels with cross layers

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Summary

The objective of this paper is to present a method for the design of solid wood panels with cross layers. The stress distribution in and the deformation behaviour of solid wood panels were analysed using the composite theory. The shear influence in solid wood panels was determined using the shear analogy method. A strength class system is proposed for the design of solid wood panels with cross layers depending on the type of stress and the panel build-up.

Keywords: solid wood panels with cross layers, composite theory, shear analogy method, rolling shear modulus, shear influence, bending vibration, classification system

1. Introduction

Solid wood panels with cross layers consist of two outer skins oriented parallel to each other and at least one middle layer oriented crosswise to the grain direction of the outer skins. The layers themselves are composed of boards generally glued together at the edges. The build-up of the panels is symmetric to the middle layer (Fig. 1). The nominal thickness as well as the load bearing performance is determined by the build-up of the solid wood panel. The primary direction of the load-bearing capacity generally corresponds to the outer skin orientation.

Fig. 1 Build-up of solid wood panels with cross layer

Solid wood panels are used as plate and diaphragm members as well as skins in stressed skin panels. In Germany, the design rules for solid wood panels are presently given in technical approvals, where also strength and stiffness values based on tests are included.

Because of the increasing number of different types of solid wood panel a general design method and a classification system of solid wood panels is needed for practice. In the following, different design methods as well as a suggestion for the classification of solid wood panels with cross layers is presented.

2. Influence of shear deformation

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. Figure 2 shows a schematic representation of rolling shear stresses. Due to the very low rolling shear modulus, shear deformation increases significantly depending on the thickness of the rolling shear layer.

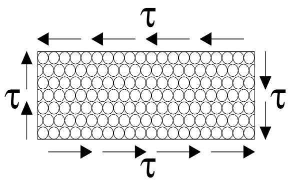


Fig. 2 Stress due to rolling shear

Only very few data are available regarding the rolling shear modulus which also depends on certain wood properties such as density and annual ring orientation. For rolling shear a ratio of $G_{R,mean}$ / G_{mean} = 0,10 is defined in [1]. In the present study the dynamic method of measuring the frequencies of a bending vibration was used for determining the rolling shear modulus. The method is accurately described in [2]. For the determination of modulus of elasticity perpendicular to the grain and rolling shear modulus small specimens from the middle layer of solid wood panels of spruce were prepared. Common values of the rolling shear modulus of spruce are between 40 N/mm² and 80 N/mm² depending significantly on the annual ring orientation. Additionally, the validity of the vibration method was checked by FE-simulation.

3. Design methods for solid wood panels

Blaß and Görlacher show in [3] the basics for the design of solid wood panels. There are two different types of stress for panels: loading perpendicular to the plane of the panel (load on panel) and loading in the plane of the panel (load in panel). Additionally, the strength and stiffness values of solid wood panels depend on the direction of the loading (parallel or perpendicular to the grain direction of the outer skins).

For the design of solid wood panels the composite theory may be used. The calculation method is based on the strength and stiffness properties of the single layers. Thereby both, layers loaded parallel to the grain and cross layers loaded perpendicular to the grain are taken into account. The strength and stiffness of solid wood panels is determined using the basic strength and stiffness values of the layers taking into account the different build-ups of the panels. However, the composite theory does not take into account shear deformation in bending members. Therefore, the composite theory may only be used for high span to depth ratios.

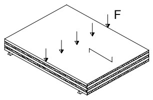
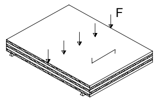
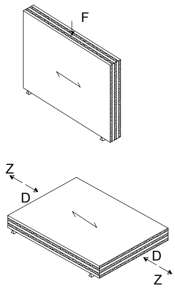
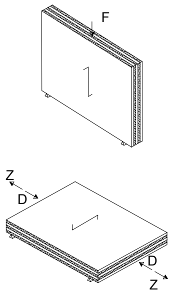
To take into account shear deformation, the theory of mechanically jointed beams may be used. The application is described in [3]. By calculating the effective bending stiffness and the resulting stresses, the normal stresses in cross layers may be disregarded. Instead of joint slip the shear deformation of cross layers is taken into account by the reduction factor γ_i. This calculation method according to Eurocode 5 only gives an accurate solution for simply supported beams with a sinusoidal load distribution. Because of the shear deformation in cross layers this calculation method also applies to small span to depth ratios.

A more precise calculation method for solid wood panels with cross layers is the shear analogy method by Kreuzinger [4]. 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 not limited in the shear analogy method.

4. Calculation of solid wood panels with composite theory

Using the composite theory, strength and stiffness properties of single layers are taken into account by composition factors (Tab. 1). A linear stress-strain relationship and Bernoulli's hypothesis of plane cross-sections remaining plane are assumed. Shear deformation is not taken into account. The composition factor is the ratio between the strength or stiffness, respectively, of the considered cross section and the strength or stiffness, respectively, of a fictitious homogeneous cross section with the grain direction of all layers parallel to the direction of the stress. With these effective strength and stiffness values the stress distribution in and the deformation behaviour of solid wood panels with different build-ups is determined.

Tab. 1 Compositions factors k_i for solid wood panels with cross layers

	k_i
	$k_1 = 1 - \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2}^3 - a_{m-4}^3 + \ldots \pm a_1^3}{a_m^3}$
	$k_2 = \frac{E_{90}}{E_0} + \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2}^3 - a_{m-4}^3 + \ldots \pm a_1^3}{a_m^3}$
	$k_3 = 1 - \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2} - a_{m-4} + \ldots \pm a_1}{a_m}$
	$k_4 = \frac{E_{90}}{E_0} + \left(1 - \frac{E_{90}}{E_0}\right) \cdot \frac{a_{m-2} - a_{m-4} + \ldots \pm a_1}{a_m}$

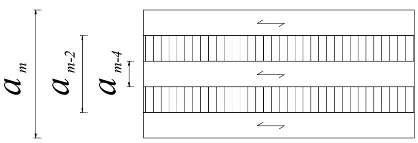


Fig. 3 Build-up and terms of solid wood panel with cross layers (m=5)

This calculation method is well known from the calculation of plywood. However, the cross layers loaded perpendicular to the grain are not taken into account when calculating plywood properties. This means that the modulus of elasticity perpendicular to the grain (E_{90}) is assumed to be zero. This assumption leads to large discrepancies between calculation and test results for some build-ups of solid wood panels with cross layers. Therefore the stiffness of cross layers will be regarded in the calculation of solid wood panels. Figure 3 shows the build-up and terms of solid wood panel with five layers.

The composition factors for different types of stress are given in table 1. The ratio of modulus of elasticity parallel to the grain (E_0) and perpendicular to the grain (E_{90}) is assumed as $E_0 / E_{90} = 30$. The effective values of strength and stiffness of solid wood panels may be determined using the composition factors (Tab. 1) and the strength properties and modulus of elasticity of the layers loaded parallel to the grain. Table 2 shows the effective values of strength and stiffness of solid wood panels with cross layers for different types of stress.

Tab. 2 Effective values of strength and stiffness for solid wood panels with cross layers

Loading	To the grain of outer skins	Effective strength value	Effective stiffness value
Perpendicular to the plane loading			
Bending	Parallel	$f_{m,0,ef} = f_{m,0} \cdot k_1$	$E_{m,0,ef} = E_0 \cdot k_1$
	Perpendicular	$f_{m,90,ef} = f_{m,0} \cdot k_2 \cdot a_m / a_{m-2}$	$E_{m,90,ef} = E_0 \cdot k_2$
In-plane loading			
Bending	Parallel	$f_{m,0,ef} = f_{m,0} \cdot k_3$	$E_{m,0,ef} = E_0 \cdot k_3$
	Perpendicular	$f_{m,90,ef} = f_{m,0} \cdot k_4$	$E_{m,90,ef} = E_0 \cdot k_4$
Tension	Parallel	$f_{t,0,ef} = f_{t,0} \cdot k_3$	$E_{t,0,ef} = E_0 \cdot k_3$
	Perpendicular	$f_{t,90,ef} = f_{t,0} \cdot k_4$	$E_{t,90,ef} = E_0 \cdot k_4$
Compression	Parallel	$f_{c,0,ef} = f_{c,0} \cdot k_3$	$E_{c,0,ef} = E_0 \cdot k_3$
	Perpendicular	$f_{c,90,ef} = f_{c,0} \cdot k_4$	$E_{c,90,ef} = E_0 \cdot k_4$

Generally, the single layers of solid wood panels mainly consist of boards of strength class C24. Consequently, the strength and stiffness values of C24 could be used as input values to determine the characteristic values of solid wood panels. However, this procedure disregards the lamination effect leading to a considerable improvement of solid wood panel compared with the boards representing the base material. Numerous test results show, that the strength and stiffness values of solid wood panels composed of boards of strength class C24 may be calculated based on board properties of strength class GL28h.

The effective values of strength and stiffness of solid wood panels according to table 2 can be determined with composition factors (Tab. 1) for different build-ups and type of stresses. The effective bending stiffness and effective axial stiffness can be directly determined using the modulus of elasticity:

- Bending perpendicular to the plane and parallel (perpendicular) to the grain of outer skins:

$$(EI)_{ef} = E_0 \cdot \frac{b \cdot a_m^3}{12} \cdot k_{1(2)} \tag{1}$$

where b = width of solid wood panel when loading perpendicular to the plane

- Bending, tension and compression in plane and parallel (perpendicular) to the grain of outer skins:

$$(EI)_{ef} = E_0 \cdot \frac{h^3 \cdot a_m}{12} \cdot k_{3(4)} \tag{2}$$

$$(EA)_{ef} = E_0 \cdot h \cdot a_m \cdot k_{3(4)} \tag{3}$$

where h = height of solid wood panel when loading in plane

The governing stresses in the layers loaded parallel to the grain can be determined using the effective stiffness values according to the following equations:

- Outer fibre bending stress, bending perpendicular to the plane and parallel to the grain direction of the outer skin:

$$\sigma_m = \frac{M}{(EI)_{ef}} \cdot E_0 \cdot \frac{a_m}{2} \tag{4}$$

- Outer fibre bending stress, bending perpendicular to the plane and perpendicular to the grain direction of the outer skin:

$$\sigma_m = \frac{M}{(EI)_{ef}} \cdot E_0 \cdot \frac{a_{m-2}}{2} \tag{5}$$

- Outer fibre bending stress, bending in plane and parallel or perpendicular, respectively, to the grain direction of the outer skin:

$$\sigma_m = \frac{M}{(EI)_{ef}} \cdot E_0 \cdot \frac{h}{2} \tag{6}$$

- Compression or tensile stress, compression or tension in plane and parallel or perpendicular, respectively, to the grain direction of the outer skin:

$$\sigma_{c(t)} = \frac{N}{(EA)_{ef}} \cdot E_0 \tag{7}$$

The governing stress when bending perpendicular to the plane and perpendicular to the grain direction of the outer skin is located in the outermost layers loaded parallel to the grain (m-2). Stresses in the outer skins (m) perpendicular to the grain do not cause failure and do not govern load-carrying-capacity.

The verification of the interaction between bending and tensile/compressive stress in the outer skins is not required for solid wood panels contrary to mechanically jointed beams. Solid wood panels are modified and homogenised building components like glued laminated timber. Therefore weak spots in single boards can be compensated by the neighbouring boards.

Because of disregarding the shear influence when using the composite theory, this calculation method can only be used for high span (L) to depth (d) ratios ($L/d \geq 30$ when loading perpendicular to the plane and parallel to the grain of outer skins and $L/d \geq 20$, respectively, when loading perpendicular to the plane and perpendicular to the grain of outer skins). Figure 4 shows the shear influence of an exemplary solid wood panel with 5 layers for bending perpendicular to the plane and parallel or perpendicular, respectively, to the grain of outer skins. The shear influence in solid wood panels was analysed by using the shear analogy method. The influence of shear deformation is increasing for decreasing span to depth ratios. Significant shear influence was observed for span to depth ratios smaller than 30 for loading perpendicular to the plane.

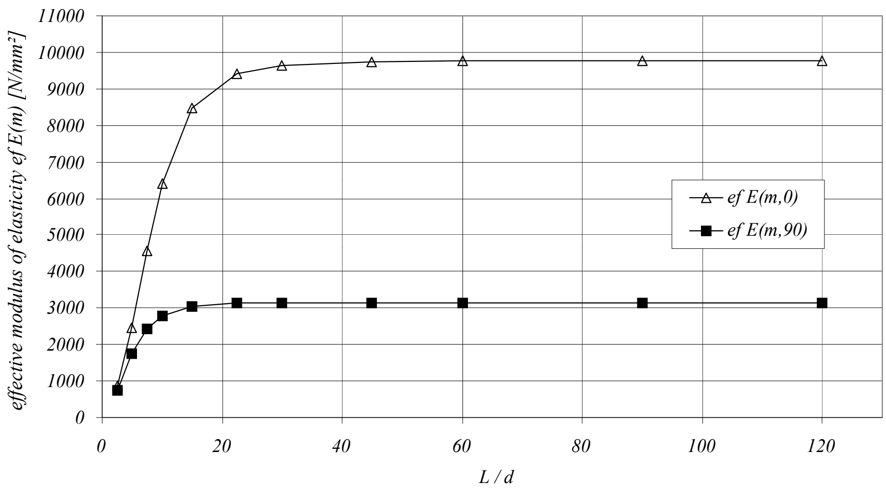


Fig. 4 Effective modulus of elasticity for bending perpendicular to the plane (m=5)

5. Classification of solid wood panels

In Germany the design rules for solid wood panels are presently given in technical approvals where strength and stiffness values based on tests are included. When strength and stiffness properties of solid wood panels from different producers are determined using the composite theory, characteristic strength and stiffness values of GL 28h are used for the board properties. The resulting values are still conservative when compared with test results. Table 3 shows a strength class system for solid wood panels comprising all build-ups presently used in Germany. The strength class of a solid wood panel is a combination of property sets for in plane and perpendicular to the plane loading, e.g. Class 6E.

Tab. 3 Characteristic values of strength, stiffness and density for solid wood panels

	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Loading	Perpendicular to the plane						In plane					
2	Class	1	2	3	4	5	6	A	B	C	D	E	F
	Parallel to the grain of outer skins [N/mm²]												
3	$f_{m,k}$	16	19	21	24	26,5	29	7	10,5	13,5	16,5	19	21,5
4	$f_{t,k}$	-	-	-	-	-	-	4,5	6,5	8,5	10,5	12	13,5
5	$f_{c,k}$	-	-	-	-	-	-	6	9	11,5	14,5	16,5	18,5
6	$f_{v,k}$	1,5						3,8					
7	E_{mean}	6900	7800	8700	9800	10800	11800	3100	4200	5400	6800	7800	8700
8	G_{mean}	90						780					
	Perpendicular to the grain of outer skins [N/mm²]												
9	$f_{m,k}$	17	15	13	10	7	5	21,5	18,5	15	12,5	10,5	8
10	$f_{t,k}$	-	-	-	-	-	-	13,5	11,5	9,5	8	6,5	4,5
11	$f_{c,k}$	-	-	-	-	-	-	18,5	16	13	11	9	6,5
12	$f_{v,k}$	1,5						3,8					
13	E_{mean}	5100	4300	3200	2100	1100	650	8700	7500	6200	5200	4200	3200
14	G_{mean}	90						780					
	Density [kg/m³]												
15	ρ_k	410											

6. Conclusion

The design rules for solid wood panels with cross layers in Germany are presently given in technical approvals. The aim of this study was to derive a general design method for solid wood panels. The rolling shear modulus significantly influences the load and deformation behaviour of solid wood panels with cross layers loaded perpendicular to the plane. For determining the rolling shear modulus, the dynamic method of measuring the frequencies of a bending vibration was used. Common values of the rolling shear modulus of spruce are between 40 N/mm² and 80 N/mm² and depend significantly on the annual ring orientation. The shear influence in solid wood panels was analysed using the shear analogy method. For span to depth ratios of at least 30, the influence of shear may be disregarded for loading perpendicular to the plane. In this case, the composite theory is taken as a basis for the design of solid wood panels. The calculation considers both, layers loaded parallel and perpendicular to the grain. Strength and stiffness of solid wood panels may be determined using basic strength and stiffness values of the single layers, taking into account the homogenisation caused by the parallel loading within a layer. Finally a strength class system for solid wood panels is given in order to simplify the design of solid wood panels. In this system characteristic strength, stiffness and density values of solid wood panels are given depending on type of stress and direction of stress with regard to the grain direction of the outer skins.

7. References

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