Compression perpendicular to the grain

Univ.-Prof. Dr.-Ing.
Hans Joachim Blass

Dr.-Ing.
Rainer Görlacher

Universität Karlsruhe
Kaiserstr. 12
76128 Karlsruhe

Blass@holz.uka.de
Goerlacher@holz.uka.de

Summary

Compression perpendicular to the grain design in different codes is considered. Based on a literature review and a number of test series, a simple mechanical model is derived and a reliable and economic design method for partial loading situations in compression perpendicular to the grain is proposed.

1. Introduction

Contact joints where loads are introduced by compression perpendicular to the grain are easy to produce and assemble and therefore are widely used in timber structures. Contrary to most types of timber connection, the load-deformation behaviour of contact joints is generally very ductile.

However, different design codes contain very different rules for compression perpendicular to the grain. Especially since the test method for the compression strength perpendicular to the grain in EN 1193 was changed from a partial area to a full area loading test, the strength values for softwood in EN 338 were significantly reduced. Consequently, a change in design rules was necessary to maintain the resistance level in compression perpendicular to the grain joints where partial loading prevails. The latest version of Eurocode 5 contains e.g. very detailed design rules for compression perpendicular to the grain depending on a number of geometry parameters and loading situations.

In the following, different design methods and recent research results regarding compression perpendicular to the grain are presented. Subsequently, a simple, reliable and economic design method is proposed, based on test results and a simple mechanical model.

2. Existing design Rules

Generally, design rules for supports or concentrated loads take into account the higher load-carrying-capacity in partial loading situations and for projecting member ends by factors $k_{c,90}$ increasing the basic design compression strength perpendicular to the grain.

DIN 1052, Timber structures - Design and construction, 1988:

This design code follows the permissible stress format. In order to be able to compare the design results with the results of partial factor design, characteristic values are assumed to be 2,4-times the permissible stress values. For contact lengths between 15 mm and 150 mm and under the condition of sufficiently projecting member ends the design values of the compression strength perpendicular to the grain may be increased by up to 80 %. If the contact area reaches the member end, however, the resistance is decreased by 20 %. If larger deformations are acceptable, the design resistance may be increased by another 20 % to 25 %.

Eurocode 5 – Design of timber structures – Part 1-1: General rules and rules for buildings; German National Application Document.

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prEN 1995-1-1 - Design of timber structures, final draft 2004

The new version of Eurocode 5 enables an increase of design strength values depending on contact length and member depth. Further parameters influencing compression perpendicular to the grain capacity are load situation (support, sill with continuous or concentrated support).

Basic and modified characteristic compression strength values according to different codes are summarised in Table 1. Even though the different design approaches are based on very different basic strength values, the resulting load-carrying-capacities for partial area loading are similar.

Tab. 1: Compression perpendicular to the grain design for C24 and GL36h

	$f_{c,90,k}$ (N/mm^2)		max $k_{c,90}$	max $f_{c,90,k}$ (N/mm^2)	
	C24	GL36		C24	GL36
DIN 1052: 1988	4,8 6,0 1)	6,0 7,2 1)	1,8 1,8	8,6 10,8 1)	10,8 13,0 1)
Eurocode 5 and German NAD	5,0	6,0	1,8	9,0	10,8
prEN 1995-1-1 (EN 338 or EN 1194)	2,5	3,6	4,0	10,0	14,4

1) significant deformations are expected

3. Literature review

Thelandersson [1] proposes to distinguish between ultimate and serviceability limit states in compression perpendicular to the grain design. Situations, where local compression failure may lead to structural failure represent ultimate limit states. Examples are the intermediate support of a continuous beam where compression perpendicular to the grain failure may result in bending failure or sills continuously loaded in compression perpendicular to the grain sliding sideways. In these cases an ultimate limit state design is necessary.

At supports or in sills protruding at the end, however, even significant deformations do not cause structural failure. Hence, a serviceability limit state design is sufficient.

Gehri [2] presents a comprehensive literature review and describes possible design approaches.

Damkilde et. al [3] determined strength values according to EN 1193 for solid timber and glulam. The compression strength perpendicular to the grain ranged between 2 und 4 N/mm^2. The 5-percentile resulted in 2,3 to 2,4 N/mm^2 and the mean modulus of elasticity was 300 N/mm^2.

Madsen [4] performed extensive tests with small contact areas and proposed a compression perpendicular to the grain design (see below). Further studies were performed by Leicester [5] and Korin [6].

4. Load carrying behaviour of perpendicular-to-grain joints

Four different loading situations leading to different stress distributions are distinguished.

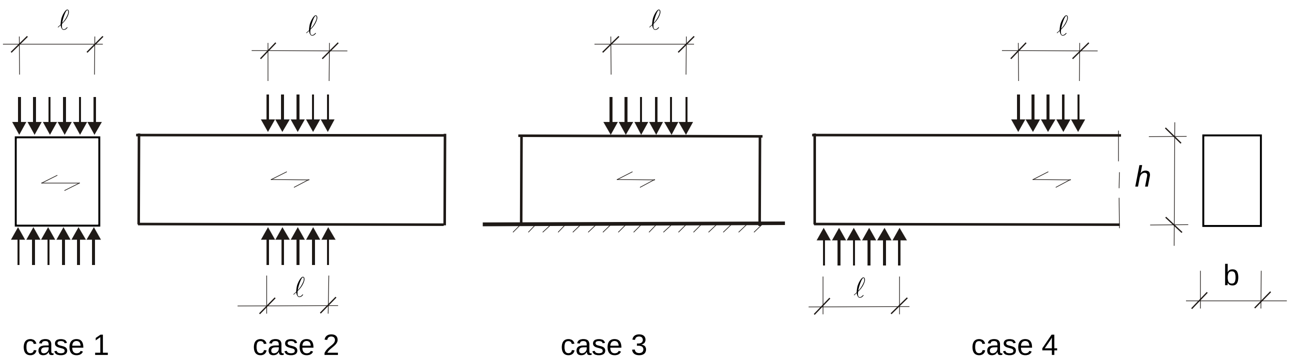


Figure 1: Different loading situations in compression perpendicular to the grain

Case 1: Assuming homogeneous material, a defined volume is uniformly stressed. Failure occurs at the weakest position by compression and lateral deformation. With increasing specimen depth stability failure governs.

Cases 2 to 4: Independent of the type of load distribution, local compression failure occurs. After local compression failure a load increase is possible. Protruding member ends have a favourable effect while the member depth has no influence on the load-carrying-capacity but on the deformation at failure.

5. Test results

Case 1: 18 glulam specimens with an average density of 470 kg/m^3 were tested:
b x ℓ x h = 120 x 100 x h mm (h = 50, 100 and 200 mm),
Loading area 120 x 100 mm by steel plates or timber parallel to the grain.

Cases 2 and 3: 36 glulam specimens with a density of the outer laminations of 420 kg/m^3 and 480 kg/m^3 (3 specimens) were tested:
b x ℓ x h = 120 x 300 x h mm (h = 50, 100 and 200 mm),
Loading area 120 x 100 mm, Member end projection 100 mm.

The deformation was measured over the complete specimen depth.

Typical test results are shown in Figure 2. Similar diagrams result for h = 100 and h = 50 mm.

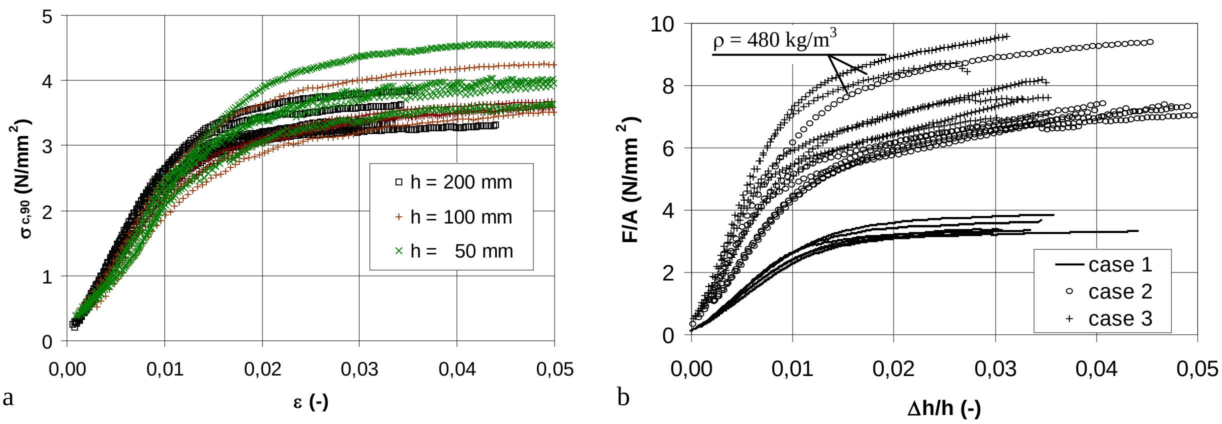


Figure 2: Stress-strain-diagrams, a) Case 1, h= 50, 100 and 200 mm
b) Cases 1, 2 and 3 with h = 200 mm

From the diagrams in Figure 2a an influence of specimen depth is hardly obvious. The results confirm the characteristic strength values for glulam between 2,7 to 3,6 N/mm^2 in EN 1194.

Figure 2b shows a significantly different load-deformation behaviour for the cases 1, 2 and 3. Here, the contact area was used to calculate the compression strength and the strain was calculated as the ratio between the vertical deformation of the loading plate and the member depth.

The further evaluation of the test results is based on the following assumptions:

Influence of member end projection:

Based on comprehensive compression tests using Douglas Fir and Spruce, Madsen [4] proposes the following design equation for compression perpendicular to the grain:

$$F_{ult} = A \cdot b \cdot \ell + C \cdot b \qquad (1)$$

where:

A and C are constant values depending on deformation and species,

b is the contact length perpendicular to the grain, and

ℓ is the contact length parallel to the grain.

Equation (1) may be transformed into:

$$F_{\text{ult}} = A \cdot b \cdot (\ell + \frac{C}{A}) \tag{2}$$

C/*A* may be interpreted as an increase of the contact length perpendicular to the grain at both sides of the contact area. The values of *A* and *C* according to Madsen [4] are summarised in Table 2:

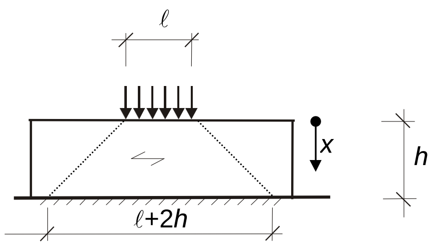
Tab. 2: Constants A and C according to Madsen

Deformation (mm)	*A* (N/mm²)	*C* (N/mm)	*C*/*A* (mm)
1	3,5	96	27,4
2	4,1	120	29,3
3	5,1	142	27,8
4	5,4	171	31,7

For the further evaluation a constant value of 30 mm is assumed for *C*/*A*.

Influence of load distribution cases 2 and 3:

The derivation for case 2 corresponds to case 3 with *h*/2.



Assumption: Load distribution under 45°:

$$\sigma(x) = \frac{F}{\ell \cdot b + 2 \cdot x \cdot b}$$

Total deformation Δ*h*

$$\Delta h = \int_0^h \frac{\sigma(x)}{E_{90}} dx$$

$$\Delta h = \frac{F}{2 \cdot b \cdot E_{90}} \ln\left(2 \cdot \frac{h}{\ell} + 1\right) = \frac{F \cdot h}{\ell \cdot b \cdot E_{90}} \left[\frac{\ell}{2 \cdot h} \ln\left(2\frac{h}{\ell} + 1\right)\right] = \Delta h_{(\text{Case 1})} \cdot \xi \tag{3}$$

$\Delta h_{(\text{Case 1})}$ corresponds to a deformation caused by a constant stress over the member depth. $\xi < 1$ takes into account the influence of the stress distribution on the deformation at the contact area. The results from the partial loading tests may be represented in a σ-ε-diagram by dividing the deformation by ξ. Case 3 corresponds to case 2 with *h*/2.

Tab. 3: ξ-values to take into account the stress distribution

ℓ (mm)	h (mm)	Case 2	Case 3
100	200	0,402 [1)]	0,549
100	100	0,549	0,693
100	50	0,693	0,811

[1)] Due to an incomplete load distribution, ξ = 0,441 was assumed in the evaluation

Figure 3 shows the stress-strain-diagrams for the tests with different specimen depths based on the assumptions listed above.

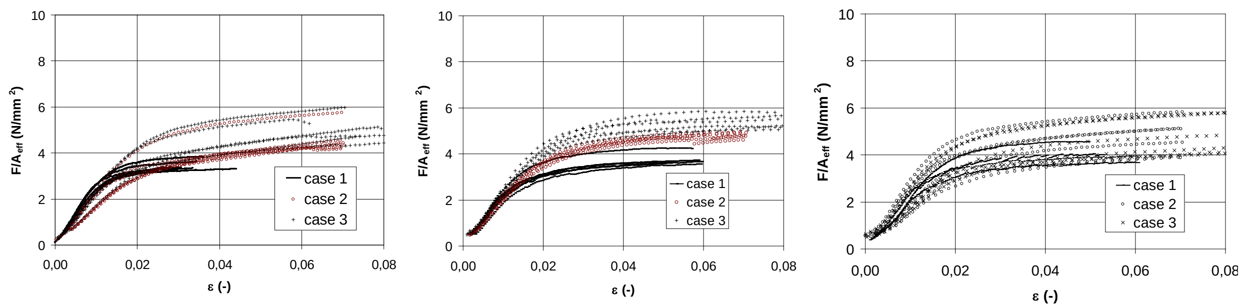


Figure 3: Stress-strain-diagrams for tests with h = 200 (left), 100 (middle) and 50 mm (right).

Taking into account the projecting member ends by an increased contact length and the stress distribution by ξ, the diagrams of the different cases become very similar. Especially the initial slope corresponding to the modulus of elasticity of 300 N/mm^2 shows the appropriateness of the ξ-values.

Case 4: Table 4 shows the different test series. The stress-strain-diagrams in Figure 4 take into account the projecting member end on one or both sides of the contact area. The stress distribution was assumed as constant over the measuring length (ξ=1). The initial slope of the curves corresponds to those of case 1 (constant stress distribution).

Tab. 4 Test series for case 4

	number of tests	*h* (mm)	*b* (mm)	*l* (mm)	measuring length (mm)
series 1	6	320	120	120	160
series 2	4	630	120	240	315
series 3	4	700	220	280	350
series 4	5	1000	100	80	150
series 5	10	540	120	90	160

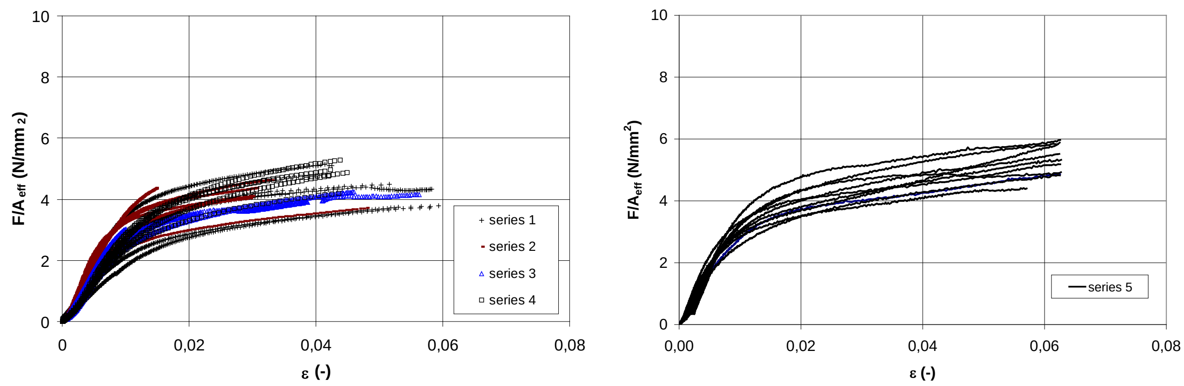


Figure 4: Stress-strain-diagrams for support loading (case 4).

6. Design proposal

The compression stress perpendicular to the grain is calculated using an effective contact length ℓ_{ef} parallel to the grain. If the timber member protrudes over the end of the contact area, the actual contact length ℓ may be extended on both sides by the member end projection length *a*, but not more than the minimum of 30 mm or ℓ.

$$A_{ef} = (\ell + \min\{a_{left}; \ell; 30\text{ mm}\} + \min\{a_{right}; \ell; 30\text{ mm}\}) \cdot b \tag{4}$$

If an ultimate limit state design is necessary, the following condition should be fulfilled:

$$f_{c,90,d} \geq \frac{F_{c,90,d}}{A_{ef}} \tag{5}$$

If a serviceability limit state is considered, a compression strain of 1 % to 2 % is considered acceptable. Exceeding this strain limit corresponding to the compression strength values according to EN 338 and EN 1194, respectively, leads to disproportionately increasing deformation. Since a compression strain of 1 % to 2 % causes local damage, the characteristic load combination for the serviceability limit state design applies:

$$E_d(serv.) = \sum G_{k,j} + Q_{k,1} + \sum_{i>1} \psi_{0,i} Q_{k,1} \tag{6}$$

Taking into account equation (6), the compression perpendicular to the grain design reads:

$$\frac{f_{c,90,k} \cdot k_{mod}}{1{,}0} \geq \frac{F_{c,90,d}(serv.)}{A_{ef}} \quad \text{since } \gamma_M = 1{,}0 \tag{7}$$

Equation (7) may expressed as an ultimate limit state design:

$$E_d(ult) = 1{,}35 \cdot \sum G_{k,j} + 1{,}5 \cdot Q_{k,1} + \sum_{i>1} 1{,}5 \cdot \psi_{0,i} \cdot Q_{k,1} \approx 1{,}35 \cdot E_d(serv.) \tag{8}$$

$$\frac{f_{c,90,k} \cdot k_{mod}}{\gamma_M} = f_{c,90,d} \geq \frac{F_{c,90,d}(ult.)}{1{,}35 \cdot \gamma_M \cdot A_{ef}} \quad \text{where } \gamma_M = 1{,}3 \tag{9}$$

$$f_{c,90,d} \cdot k_{c,90} \geq \frac{F_{c,90,d}(ult.)}{A_{ef}} \quad \text{where } k_{c,90} = 1{,}35 \cdot 1{,}3 = 1{,}75 \tag{10}$$

Expressing the serviceability limit state design as an ultimate limit state design requires a modification factor $k_{c,90}$ = 1,75. This value is based on the tests with glulam. Because of the influence of annual ring orientation in the cross-section, the compression perpendicular to the grain behaviour of solid timber is more unfavourable than for glulam. Consequently, it is proposed to limit the value of the factor $k_{c,90}$ for solid timber to 1,5. Since the total deformation in sills is larger than in support loading situations, a further distinction is made: The $k_{c,90}$-values of 1,75 and 1,5 for glulam and solid timber, respectively, are used for supports. If sills are considered, both values are decreased by a value of 0,25. This leads to the following values of $k_{c,90}$:

$k_{c,90}$ = 1,0 for ultimate limit states

$k_{c,90}$ = 1,25 for solid timber in sills (cases 2 and 3) in serviceability limit states (SLS)

$k_{c,90}$ = 1,5 for solid timber at supports (case 4) and for glulam in sills (cases 2 and 3) in SLS

$k_{c,90}$ = 1,75 for glulam at supports (case 4) in SLS

In order to allow the stress distribution leading to the ξ-values in paragraph 5, the clear distance l_1 between neighboured partial loading areas should fulfill the condition $l_1 \geq 2\,h$. Due to limited test results, the contact length l parallel to the grain should not exceed 400 mm.

7. References

[1] Thelandersson S. and Mårtensson A., "Design Principles for Timber in Compression Perpendicular to Grain" *Proceedings of the CIB-W-18,* Paper -30-20-1

[2] Gehri E. "Timber in compression perpendicular to the grain", *International Conference of IUFRO S 5.02 Timber Engineering*, Copenhagen, Denmark 1997

[3] Damkilde L., Hoffmeyer P. and Pedersen T.N., "Compression Strength Perpendicular to Grain of Structural Timber and Glulam", *Proceedings of the CIB-W-18,* Paper 31-6-4

[4] Madsen B., "Behaviour of Timber Connections", *Timber Egnineering Ltd.* Vancouver, Canada, 2000

[5] Leicester R.H., Fordham H. and Breitinger H., "Bearing Strength of Timber Beams" *Proceedings of the CIB-W-18,* Paper 31-6-5

[6] Korin U., "Timber in Compression Perpendicular to Grain", *Proceedings of the CIB-W-18,* Paper - 23-6-1