EOTA

TECHNICAL REPORT

Calculation models for prefabricated wood-based Loadbearing stressed skin panels for use in roofs

TR 019

Edition February 2005

EUROPEAN ORGANISATION FOR TECHNICAL APPROVALS

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Foreword

This EOTA Technical Report (TR) has been adopted by EOTA WG 03.04/03 “Prefabricated wood-based loadbearing stressed skin panels” and endorsed by the EOTA Technical Board.

The Technical Report specifies the theoretical background of the several models for the calculation of prefabricated wood-based loadbearing stressed skin panels for use in roofs.
The requirements for these stressed skin panels are incorporated in the ETA Guideline Nr. 019 for prefabricated wood-based loadbearing stressed skin panels.

No existing EOTA Technical Report is superseded by this TR.

NOTES

The calculation models, described in annexes A, B and D, are included on behalf of the German mirror committee. Model “Kreuzinger” (see annex C) is included on behalf of the Dutch mirror committee.

As far as the calculation model “Kreuzinger” is concerned, the model has been developed (on behalf of UNIDEK Bouwelementen B.V. - Gemert - The Netherlands) by H.E. Lüning Adviesbureau voor technische houtconstructies B.V. - Doetinchem - The Netherlands, consultants in engineered timber and has been based on the Eurocodes as well on both the general model of Prof. Dr.-Ing. H. Kreuzinger and an applied model of Prof. Dr.-Ing. H.J. Blass.

The “Kreuzinger” model was specifically developed for wood-based stressed skin panels for use in roofs. The model can also be used for the calculation of other composite panels for use in roofs (e.g. according to ETA Guideline Nr. 016 - Part 2 - for self-supporting composite lightweight panels). In that case the specific product characteristics of wood-based stressed skin panels have to be replaced by those of the composite panels.

In future the model can also be made applicable for the calculation of prefabricated wood-based loadbearing stressed skin panels for use in walls and floors.

1 List of symbols

Main symbols

A	area (of cross-section)
E	modulus of elasticity
G	shear modulus
I	second moment of area
K	modulus of subgrade reaction
M	bending moment
N	axial force
Q	shear force
R	reaction force at support
S	section modulus
W	moment of resistance
a	distance between the centers of the two outer layers; variable concerning effective flange width
b	width of certain layer; width of support
c	factor of co-operation; variable concerning effective flange width
d	thickness
f	strength of a material; factor
h	height
i	certain layer in stressed skin panel
k	factor
λ	span; length
n	total of layers in stressed skin panel
z	distance from the center of a certain layer to the neutral axis
α	factor for EPS core at support; angle
γ	partial factor
λ	slenderness ratio; variable concerning effective flange width
μ	Poisson's ratio
ρ	mass density
σ	stress
τ	shear stress

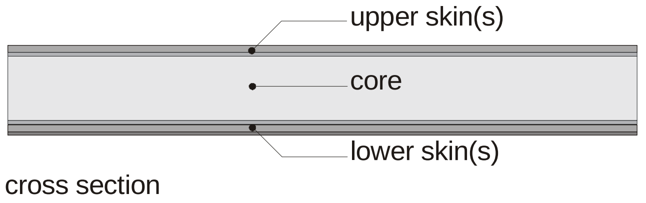
Subscripts

A	virtual beam A
B	virtual beam B
M	material
c	compression
d	design
f	flange
i	i^{th} layer in stressed skin panel
k	characteristic
m	bending
n	enlarging
o	at support
t	tension
v	shear
def	deformation
ef	effective concerning flange width
eff	effective
mean	mean
mod	modification
red	reduction
0	along the grain (timber); along the grain of face veneer (wood-based skin)
90	perpendicular to the grain (timber); perpendicular to the grain of face veneer (wood-based skin)
$\perp$	planar
//	in-plane

2 Introduction

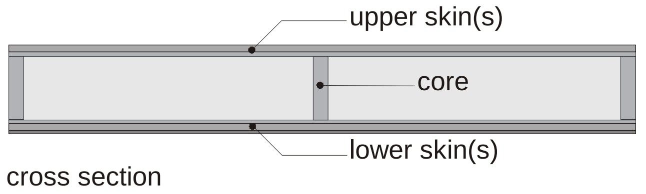
The models are capable of calculating stressed skin panels of the following types, to be used in roofs:

Type A
Stressed skin panels, closed box type double-skin, *without* wooden ribs, *with* loadbearing insulation:



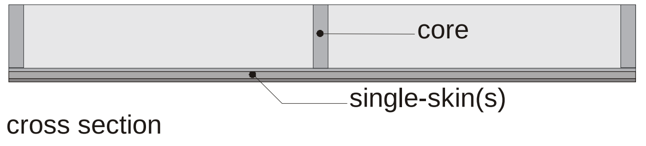
upper skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)
core : loadbearing insulation (e.g. expanded/extruded polystyrene, polyurethane)
lower skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)

Type B1
Stressed skin panels, closed box type double-skin, *with* wooden ribs and loadbearing insulation:



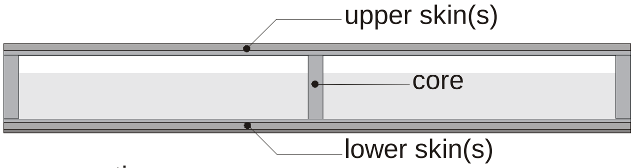
upper skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)
core : wooden ribs and loadbearing insulation (e.g. expanded/extruded polystyrene, polyurethane)
lower skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)

Type B2
Stressed skin panels, open box type single-skin, *with* wooden ribs and loadbearing insulation:



core : wooden ribs and loadbearing insulation (e.g. expanded/extruded polystyrene, polyurethane)
single-skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood); could be beneath or above the wooden ribs

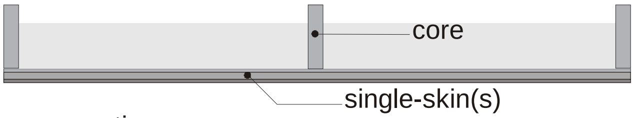
Type C1
Stressed skin panels, closed box type double-skin, *with* wooden ribs and non-loadbearing insulation or without insulation:



cross section

upper skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)
core : wooden ribs and non-loadbearing insulation (e.g. mineral wool) or without insulation
lower skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood)

Type C2
Stressed skin panels, open box type single-skin, *with* wooden ribs and non-loadbearing insulation or without insulation:



cross section

core : wooden ribs and non-loadbearing insulation (e.g. mineral wool) or without insulation
single-skin(s) : wood-based skin(s) (e.g. particleboard, oriented strand board, plywood); could be beneath or above the wooden ribs

3 Material properties

3.1 Skins

Timber products according to prEN 1995-1-1

3.2 Bond between core and skins

The bond between core and skins shall be tested by means of tensile tests (bonding capacity). The durability of the bond shall be verified by tests.

3.3 The mechanical properties of the core

Shall be determined and declared by the manufacturer (according to annex E, clause E.3).

4 Requirements for stresses and safety levels

4.1 General

The product shall be of sufficient mechanical resistance, in order to be able to resist to the stresses resulting from self-weight, snow, wind and walking-on as well as from temperature gradients, shrinkage or swelling. These loads shall be weighted such, that they do not affect – neither individually nor in combination – the serviceability of the product. In the case of mere timber constructions temperature gradients need normally not be taken into account. In the case of sandwich panels, however, temperature differences which are no longer to be neglected may possibly occur.

$$S_d \leq R_d$$

S_d = design value of load

R_d = design value of load-carrying capacity

$$S_d = \sum \gamma_i \psi_i S_{ki}$$

$$X_d = k_{\text{mod}} \frac{X_k}{\gamma_M}$$

γ_i = decisive loading factor

ψ_i = combination factor

S_{ki} = characteristic load

X_k = characteristic value of strength property

γ_M = decisive partial factor for material property

k_{mod} = modification factor for duration of load and moisture content

4.2 Ultimate limit state

The ultimate limit state, which corresponds to the maximum load-carrying capacity of the panel, shall be characterized by the most critical of the following failure modes either individually or in combination:

- Wrinkling (local buckling) of a face of the panel with consequential failure.
- Shear failure of the core.
- Shear failure of the bond between the face and the core.
- Crushing of the core at a support.
- Failure of the panels at the points of attachment to the supporting structure.
- A combination of bending and compression failure of a face of the panel.
- A combination of bending and tension failure of a face of the panel.
- A combination of bending and compression failure of the core.
- A combination of bending and tension failure of the core.

4.3 Serviceability limit state

The verification of the serviceability limit state shall be sufficient to ensure the proper functioning of the panels under the serviceability loads. The serviceability limit state shall be characterized by one of the following:

- The attainment of a specified limiting deflection.

4.4 Actions and combinations of actions

4.4.1 General

Characteristic values of actions are specified in Eurocode 1 ‘Basis of design and actions on structures’ or in other relevant loading codes. These values are to be considered as standard values for the country where the designed structure are to be located.
They are also defined and described in the particular National Application Document of each Member State.

Design values of actions are defined by enlarging the characteristic load values with the partial safety factors (γ). Load combinations are defined by using the combination factors (ψ).
Partial safety factors and combination factors are also defined and described in the particular National Application Document of each Member State.

These numerical values are identified as ‘boxed’ or by [ ].

The actions in 4.4.2 to 4.4.4 shall be taken into account in the design for mechanical resistance. They shall be considered either individually or in combination using the “boxed” combination factors and the “boxed” partial safety factors.

4.4.2 Permanent actions

The permanent actions to be taken into account in the design for mechanical resistance shall include the following:

- Self-weight of the panel (calculating from the nominal dimensions and mean densities).
- Mass of any permanent components of the structure and installation that apply load to the element.

4.4.3 Variable actions

The variable actions shall include the following:

- Snow loads.
- Live loads (e.g. due to access to a roof or ceiling).
- Wind loads.
- Construction loads.

4.4.4 Actions due to long term effects

Deformations of sandwich panels of type A may increase with time as a consequence of creep of the core. Creep also causes a change in the stresses with time and this shall be taken into account in the design.

4.4.5 Combinations of actions in the ultimate limit state

The basis of design common to all Eurocodes, specifies different types of load combinations which may be used for verification in the ultimate limit state.
The load combinations are described in Eurocode 1 ‘Basis of design and actions on structures’.

- The fundamental combination is intended for use mainly in those cases where exceeding the limit state causes significant damage.
- The accidental combination is intended for use mainly in those cases where exceeding the limit state is caused by special events, e.g. explosion or fire.
- The seismic combination is intended for use in the case where exceeding the limit state is caused by the special seismic event.

4.4.6 Combinations of actions in the serviceability limit state

The basis of design common to all Eurocodes, specifies different types of load combinations which may be used for verification in the serviceability limit state.
The load combinations are described in Eurocode 1 ‘Basis of design and actions on structures’.

- The characteristic combination is intended for use mainly in those cases where exceeding the limit state causes unacceptable irreversible deformation or significant damage.
- The frequent combination is intended for use mainly in those cases where exceeding the limit state is associated with reversible deformations or minor damage.
- The quasi-permanent combination is intended for use mainly in those cases where exceeding the limit state is associated with unacceptable irreversible deformation in the long-term.

5 Calculation method for determining the characteristic loads

The action-effects of sandwich panels with loads uniformly distributed along the panel width can normally be calculated according to the elastic bond theory as beam structures. In the case of local loading due to man load the effective width used for the load transfer shall be considerably reduced (for loading at the panel edge to b_m<b/3), or the sandwich panels shall be designed for local loadings as surface elements by taking the flexible bond into account. A number of calculation methods is given in the Annex for the calculation of sandwich panels as beam structures, which can be used as a function of the type of the structural system of the sandwich panels and of the structure (single-span beam or multi-span beam).
All calculation methods can be approximately used, with a"creep modulus", for the calculation of the redistrubuted action-effects due to creep of the core under the action of the self-weight and of the snow loading.

a) The action-effects of sandwich panels of type A can be calculated by using the classical beam theory taking account of the shear deformation of the core, if the skins can be considered for themselves as rigid composite compound units (always given for one-piece floor layers). Annex A contains calculations formulas from prEN 14509:2002 for single-span beams and multi-span beams.

b) The action-effects of sandwich panels of type B1 can be calculated as single-span beam in good approximation and as multi-span beam approximately by using the flexible bond theory, which is proposed in Eurocode 5 for timber structures with flexible bond, if the skins can be considered for themselves as rigid composite compound units (always given for one-piece floor layers). For single-span beams and multi-span beams Annex B contains calculation methods from Eurocode 5 with an adaptation to the situation of the sandwich panel of type B1.

c) The action-effects of the sandwich panels of type A and type B1 can be calculated by using the Kreuzinger method, if the skins can be considered for themselves as rigid composite compound units (always given for one-piece floor layers). The calculation formulas are given in Annex C.

d) The action-effects of the sandwich panels of type A and type B1 can be calculated with the method using programmes for "statics of a lattice frame". This model can also be applied for multi-layer sandwich panels or for sandwich panels with skins being for themselves components with a flexible bond. This model is shown in Annex D, and can also be used for surface structures.

e) Furthermore, the solutions of the differential equations of the elastic bond or the differential method can be used for the calculation of the action-effects of the sandwich panels.

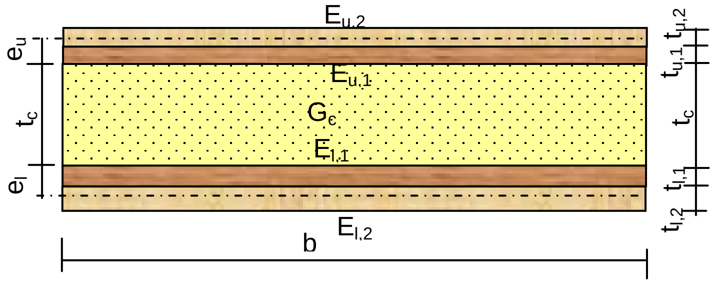
If shrinkage or swelling of the skins has to be taken into account, the resulting deformations or restraints can be calculated from an equivalent temperature gradient.

A partial safety factor of γ_M=1,5 is considered necessary for safeguarding the material properties of the core. The modification factors shall be determined experimentally.

5.1 Performance of the design

The design values of the actions shall be determined in accordance with prEN 1995-1-1. These actions shall be compared with the design values of the component resistances in accordance with prEN 1995-1-1. Due to the co-action of the core the following peculiarities result, which have to be considered in the design.
In the case of sandwich panel type A without wooden ribs and in the case of sandwich panel type B1 with wooden ribs with big spacing, which cannot be used for mere wood constructions because of the required buckling verification, the compressed skin is stabilized by the core. Because of the imperfections of the skin this stabilization is long-term-depending.
Sufficient stability can be approximately verified by establishing that the bond stress between core and skins does not exceed the time-depending design value.

Example bond stress between upper skin and core:



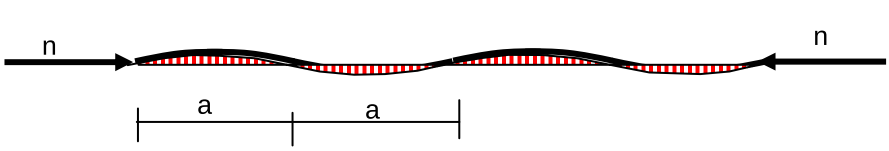
Bending stiffness of skin:

$$B_u = E_{u,1}\frac{t_{u,1}^3}{12} + E_{u,2}\frac{t_{u,1}^3}{12} + \frac{E_{u,1}t_{u,1}E_{u,2}t_{u,2}}{E_{u,1}t_{u,1} + E_{u,2}t_{u,2}}\frac{(t_{u,1}+t_{u,2})^2}{4}$$

$$a = \pi\sqrt[3]{\frac{2B_u}{\sqrt{E_c G_c}}}$$

$$n_{ki} = 1,8899\sqrt[3]{B_u E_c G_c}$$

$$\sigma_c = \frac{\pi}{a}\sqrt{E_c G_c}\, f_0 (1 + k_{def})\frac{n}{n_{ki} - n}$$



a =half of wrinkling wave length
n_{ki} =mathematical wrinkling load [N/mm]
n =normal force in the skin [N/mm]
f_0 =imperfection of the skin with a being half the wave length
σ_c =bond stress [N/mm²]

In the area of intermediate supports the skin has additionally to accept the transverse compression resulting from the reaction. This leads to a reduction of the acceptable longitudinal compression force. The bedding of the skin can be calculated with

$$c = \frac{\pi}{a}\sqrt{E_c G_c}$$

The calculation shall be carried out according to the second order theory.
The long term behaviour is to be taken into account.

The acceptance of the transverse reaction shall be verified without spreading in the core. For type A the reaction must be accepted by the core. For type B1 with wooden ribs almost the entire reaction must be accepted by the ribs by pressing vertically to the fibre direction.

If, for the system with wooden ribs, the verification of the acceptance of the bond stresses with long term loading is successful, the buckling verification may be omitted without taking the bedding by the core into account.
For mere wood constructions in panel system, which are designed only on the basis of prEN 1995-1-1, it is allowed to use the core for the stabilization of the skins, if the verification of the acceptance of the bond stresses is successful.

5.2 Wrinkling of the skin at a support

The wrinkling phenomenon of the skin is caused by the local influence of the shear force on the wood-based skin in combination with the compression force in the skin. A theory leading to a verification of stresses for this phenomenon is described in the SKH-Publication 94-02 [5]. A short description of this theory is given here.

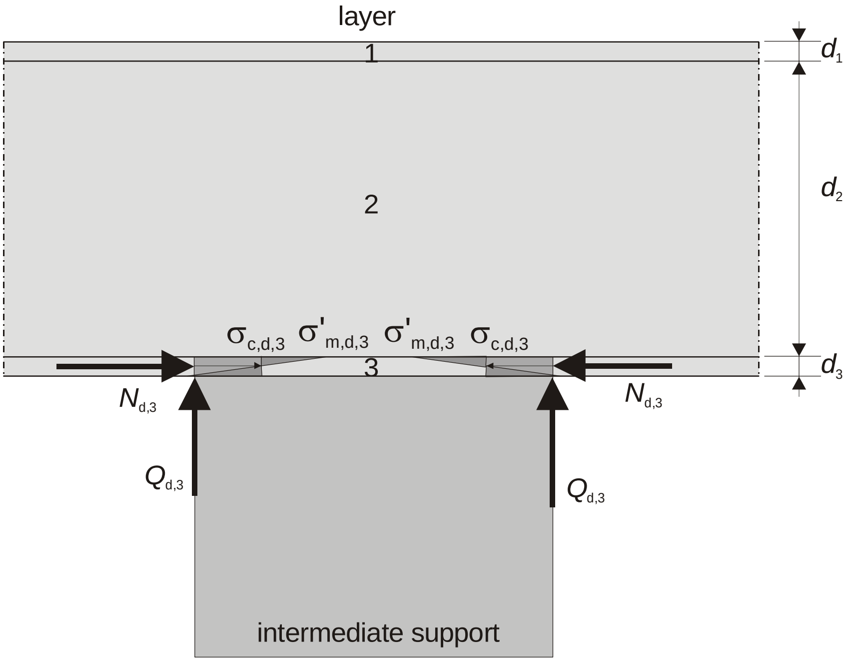


Figure 5.2 - E.g. local design ‘wrinkling’ stresses in the lower wood-based skin at an intermediate support

Modulus of subgrade reaction K underneath the lower wood-based skin:

$$K = \max\begin{cases} \dfrac{E_{t(c),fin,2}}{d_2} \\ 0{,}27 \cdot E_{t(c),fin,2} \cdot \sqrt[3]{\dfrac{E_{t(c),fin,2}}{E_{m,\perp,0,fin,3} \cdot I_3/b_3}} \end{cases}$$

where:

$$I_3 = \frac{b_3 \cdot d_3^3}{12}$$

concerning the loadbearing insulation core:

$E_{t(c),fin,2}$ the final modulus of elasticity for compression or tension.

concerning the lower wood-based skin:

$E_{m,\perp,0,fin,3}$ the planar final modulus of elasticity for bending along the grain of face veneer.

The local design moment $M'_{0,d}$ for an elastic supported wood-based skin with an own bending stiffness ($E_{m,\perp,0,fin,3} \cdot I_3$) and a modulus of subgrade reaction K, loaded by the design shear force $Q_{d,3}$ in layer 3:

$$\lambda = \sqrt[4]{\frac{K}{4 \cdot E_{m,\perp,0,fin,3} \cdot I_3/b_3}}$$

$$M'_{0,d} = \frac{Q_{d,3}}{4 \cdot \lambda}$$

The design compression force $N_{d,3}$ in the lower wood-based skin increases the design moment $M'_{0,d}$ with the factor f_n:

$$f_n = \frac{1}{\sqrt{1 - \frac{N_{d,3}}{4 \cdot E_{m,\perp,0,fin,3} \cdot I_3 \cdot \lambda^2}}}$$

$$M'_{d,3} = f_n \cdot M'_{0,d}$$

Local design compression and bending stress in layer 3 (lower wood-based skin) at a support:

$$\sigma_{c,d,3} = \frac{N_{d,3}}{A_3}$$

$$\sigma'_{m,d,3} = \frac{M'_{d,3}}{W_3}$$

The maximum design compression and bending stress must be compared to the design in-plane compression strength along the grain of face veneer and the design planar bending strength along the grain of face veneer of the lower wood-based skin.

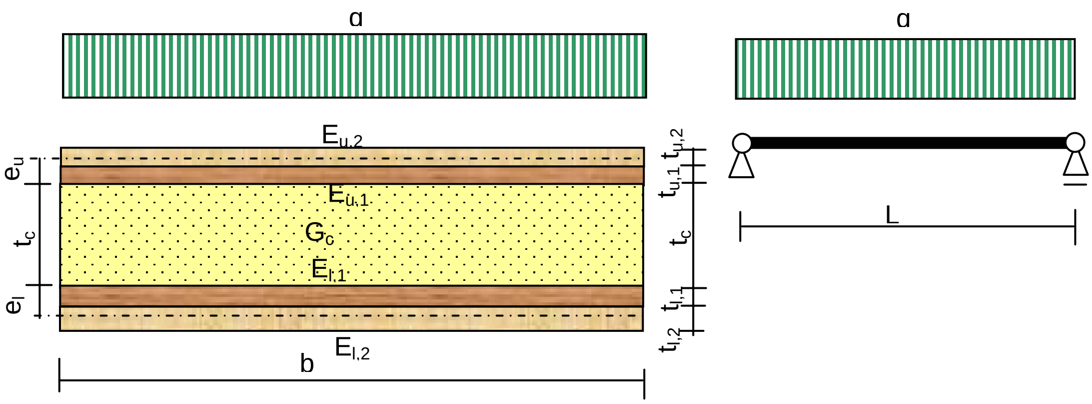
$$\frac{\sigma_{c,d,3}}{f_{c,//,0,d,3}} + \frac{\sigma'_{m,d,3}}{f_{m,\perp,0,d,3}} \leq 1{,}00$$

Annex A Model N

(Informative)

A.1 Beam theory by taking account of the shear deformations of the core

A.2 Single-span element



$$e_u = \frac{E_{u,1} b t_{u,1} \frac{t_{u,1}}{2} + E_{u,2} b t_{u,2} \left(t_{u,1} + \frac{t_{u,2}}{2} \right)}{E_{u,1} b t_{u,1} + E_{u,2} b t_{u,2}}$$

$$e_l = \frac{E_{l,1} b t_{l,1} \frac{t_{l,1}}{2} + E_{l,2} b t_{l,2} \left(t_{l,1} + \frac{t_{l,2}}{2} \right)}{E_{l,1} b t_{l,1} + E_{l,2} b t_{l,2}}$$

$$B_u = E_{u,1} b \frac{t_{u,1}^3}{12} + E_{u,2} b \frac{t_{u,1}^3}{12} + \frac{E_{u,1} b t_{u,1} E_{u,2} b t_{u,2}}{E_{u,1} b t_{u,1} + E_{u,2} b t_{u,2}} \frac{(t_{u,1} + t_{u,2})^2}{4}$$

$$B_l = E_{l,1} b \frac{t_{l,1}^3}{12} + E_{l,2} b \frac{t_{l,1}^3}{12} + \frac{E_{l,1} b t_{l,1} E_{l,2} b t_{l,2}}{E_{l,1} b t_{l,1} + E_{l,2} b t_{l,2}} \frac{(t_{l,1} + t_{l,2})^2}{4}$$

$$B_s = B_u + B_l + \frac{(E_{u,1} b t_{u,1} + E_{u,2} b t_{u,2})(E_{l,1} b t_{l,1} + E_{l,2} b t_{l,2})}{(E_{u,1} b t_{u,1} + E_{u,2} b t_{u,2}) + (E_{l,1} b t_{l,1} + E_{l,2} b t_{l,2})} (e_u + t_c + e_l)^2$$

$$Q = \frac{qbL}{2}$$

$$M = \frac{qbL^2}{8}$$

$$\max f = \frac{5qbL^4}{384 B_s} + \frac{qbL^2}{8 G_c b t_c}$$

$$N = \pm \frac{M}{(e_u + t_c + e_l)}$$

$$M_u = M \frac{B_u}{B_s}$$

$$M_l = M \frac{B_l}{B_s}$$

$$\theta = \frac{\alpha_l T_l - \alpha_u T_u}{(e_u + t_c + e_l)}$$

$$f_T = \frac{\theta L^2}{8}$$

A.3 Two-span element

$$f_3 = \frac{qb(L_1 + L_2)^4}{24 B_s} \left(\frac{a_3}{L_1 + L_2} - 2\left(\frac{a_3}{L_1 + L_2} \right)^3 + \left(\frac{a_3}{L_1 + L_2} \right)^4 \right) -$$

$$- \frac{R_2 (L_1 + L_2)^2 L_1}{6 B_s} \frac{a_3}{L_1 + L_2} \left(1 - \left(\frac{L_1}{L_1 + L_2} \right)^2 - \left(\frac{a_3}{L_1 + L_2} \right)^2 \right) + \frac{M_3}{G_c b t_c}$$

$$\theta = \frac{\alpha_l T_l - \alpha_u T_u}{(e_u + t_c + e_l)}$$

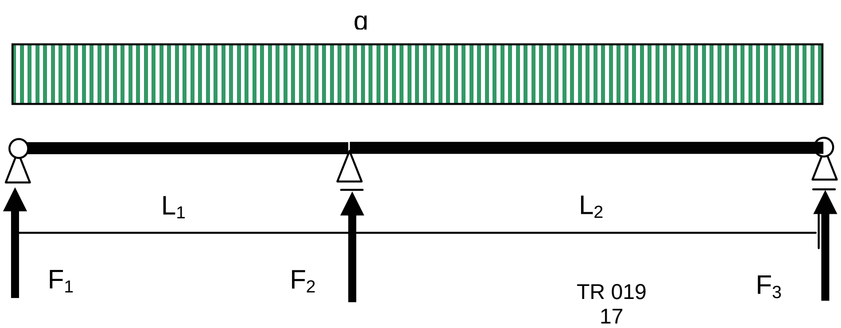
$$f_{2,T} = \frac{\theta (L_1 + L_2)^2}{2} \left(\frac{L_1}{L_1 + L_2} - \left(\frac{L_1}{L_1 + L_2} \right)^2 \right)$$

$$R_{2,T} = \frac{f_{2,T}}{f_{2,1}}$$

$$M_{2,T} = -R_{2,T} \frac{L_1 L_2}{L_1 + L_2}$$

$$F_{1,T} = -R_{2,T} \frac{L_2}{L_1 + L_2}$$

$$F_{3,T} = -R_{2,T} \frac{L_1}{L_1 + L_2}$$



$$f_{2,0} = \frac{qb(L_1+L_2)^4}{24B_s}\left(\frac{L_1}{L_1+L_2} - 2\left(\frac{L_1}{L_1+L_2}\right)^3 + \left(\frac{L_1}{L_1+L_2}\right)^4\right) + \frac{qbL_1L_2}{2G_cbt_c}$$

$$f_{2,1} = \frac{L_1^2L_2^2}{3(L_1+L_2)B_s} + \frac{L_1L_2}{(L_1+L_2)G_cbt_c}$$

$$R_2 = \frac{f_{2,0}}{f_{2,1}}$$

$$R_1 = \frac{qb(L_1+L_2)}{2} - R_2\frac{L_2}{(L_1+L_2)}$$

$$R_3 = \frac{qb(L_1+L_2)}{2} - R_2\frac{L_1}{(L_1+L_2)}$$

$$M_2 = R_1L_1 - \frac{qbL_1^2}{2}$$

$$\max M_1 = \frac{R_1^2}{2qb}$$

$$\max M_3 = \frac{R_3^2}{2qb}$$

$$a_1 = \frac{R_1}{qb}$$

$$a_3 = \frac{R_3}{qb}$$

$$f_1 = \frac{qb(L_1+L_2)^4}{24B_s}\left(\frac{a_1}{L_1+L_2} - 2\left(\frac{a_1}{L_1+L_2}\right)^3 + \left(\frac{a_1}{L_1+L_2}\right)^4\right) -$$

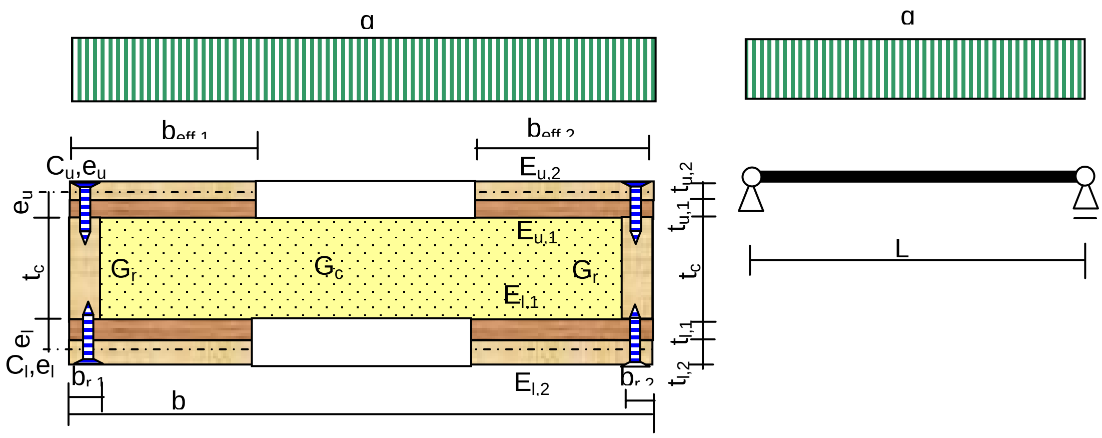
$$- \frac{R_2(L_1+L_2)^2L_2}{6B_s}\frac{a_1}{L_1+L_2}\left(1 - \left(\frac{L_2}{L_1+L_2}\right)^2 - \left(\frac{a_1}{L_1+L_2}\right)^2\right) + \frac{M_1}{G_cbt_c}$$

Annex B Model N

(Informative)

B.1 Approximation method for sandwich panels with wooden ribs according to prEN 1995-1-1

B.2 Single-span element



Schubfedersteifigkeiten:

$$Sf_{u,1} = \frac{1}{\frac{e_u}{C_u} + \frac{t_c}{G_r b_{r,1}}} + G_c \frac{b_{eff,1} - b_{r,1}}{t_c}$$

$$Sf_{l,1} = \frac{1}{\frac{e_l}{C_l} + \frac{t_c}{G_r b_{r,1}}} + G_c \frac{b_{eff,1} - b_{r,1}}{t_c}$$

$$Sf_{u,2} = \frac{1}{\frac{e_u}{C_u} + \frac{t_c}{G_r b_{r,2}}} + G_c \frac{b_{eff,2} - b_{r,2}}{t_c}$$

$$Sf_{l,2} = \frac{1}{\frac{e_l}{C_l} + \frac{t_c}{G_r b_{r,2}}} + G_c \frac{b_{eff,2} - b_{r,2}}{t_c}$$

$$\gamma_{u,1} = \frac{1}{1+\frac{\pi^2 b_{eff,1}\left(E_{u,1}t_{u,1}+E_{u,2}t_{u,2}\right)}{Sf_{u,1}L^2}}$$

$$\gamma_{l,1} = \frac{1}{1+\frac{\pi^2 b_{eff,1}\left(E_{l,1}t_{l,1}+E_{l,2}t_{l,2}\right)}{Sf_{l,1}L^2}}$$

γ

$$\gamma_{u,2} = \frac{1}{1+\frac{\pi^2 b_{eff,2}\left(E_{u,1}t_{u,1}+E_{u,2}t_{u,2}\right)}{Sf_{u,2}L^2}}$$

$$\gamma_{u,2} = \frac{1}{1+\frac{\pi^2 b_{eff,2}\left(E_{l,1}t_{l,1}+E_{l,2}t_{l,2}\right)}{Sf_{l,2}L^2}}$$

Effective bending stiffnesses

$$e_{u,1} = \frac{E_{u,1}b_{eff,1}t_{u,1}\frac{t_{u,1}}{2}+E_{u,2}b_{eff,1}t_{u,2}\left(t_{u,1}+\frac{t_{u,2}}{2}\right)}{E_{u,1}b_{eff,1}t_{u,1}+E_{u,2}b_{eff,1}t_{u,2}}$$

$$e_{l,1} = \frac{E_{l,1}b_{eff,1}t_{l,1}\frac{t_{l,1}}{2}+E_{l,2}b_{eff,1}t_{l,2}\left(t_{l,1}+\frac{t_{l,2}}{2}\right)}{E_{l,1}b_{eff,1}t_{l,1}+E_{l,2}b_{eff,1}t_{l,2}}$$

$$B_{u,1} = E_{u,1}b_{eff,1}\frac{t_{u,1}^3}{12}+E_{u,2}b_{eff,1}\frac{t_{u,1}^3}{12}+\frac{E_{u,1}b_{eff,1}t_{u,1}E_{u,2}b_{eff,1}t_{u,2}}{E_{u,1}b_{eff,1}t_{u,1}+E_{u,2}b_{eff,1}t_{u,2}}\frac{\left(t_{u,1}+t_{u,2}\right)^2}{4}$$

$$B_{l,1} = E_{l,1}b_{eff,1}\frac{t_{l,1}^3}{12}+E_{l,2}b_{eff,1}\frac{t_{l,1}^3}{12}+\frac{E_{l,1}b_{eff,1}t_{l,1}E_{l,2}b_{eff,1}t_{l,2}}{E_{l,1}b_{eff,1}t_{l,1}+E_{l,2}b_{eff,1}t_{l,2}}\frac{\left(t_{l,1}+t_{l,2}\right)^2}{4}$$

$$B_{s,w,1} = B_{u,1}+B_{l,1}+E_r\frac{b_{r,1}t_c^3}{12}+\frac{\gamma_{u,1}\left(E_{u,1}b_{eff,1}t_{u,1}+E_{u,2}b_{eff,1}t_{u,2}\right)\gamma_{l,1}\left(E_{l,1}b_{eff,1}t_{l,1}+E_{l,2}b_{eff,1}t_{l,2}\right)}{\gamma_{u,1}\left(E_{u,1}b_{eff,1}t_{u,1}+E_{u,2}b_{eff,1}t_{u,2}\right)+\gamma_{l,1}\left(E_{l,1}b_{eff,1}t_{l,1}+E_{l,2}b_{eff,1}t_{l,2}\right)}\left(e_u+t_c+e_l\right)^2$$

$$e_{r,1} = \frac{\gamma_{u,1}\left(E_{u,1}b_{eff,1}t_{u,1} + E_{u,2}b_{eff,1}t_{u,2}\right)\left(\frac{t_c}{2} + e_{u,1}\right) - \gamma_{l,1}\left(E_{l,1}b_{eff,1}t_{l,1} + E_{l,2}b_{eff,1}t_{l,2}\right)\left(\frac{t_c}{2} + e_{l,1}\right)}{\gamma_{u,1}\left(E_{u,1}b_{eff,1}t_{u,1} + E_{u,2}b_{eff,1}t_{u,2}\right) + \gamma_{l,1}\left(E_{l,1}b_{eff,1}t_{l,1} + E_{l,2}b_{eff,1}t_{l,2}\right) + E_r b_{r,1} t_r}$$

$$e_{r,2} = \frac{\gamma_{u,2}\left(E_{u,1}b_{eff,2}t_{u,1} + E_{u,2}b_{eff,2}t_{u,2}\right)\left(\frac{t_c}{2} + e_{u,2}\right) - \gamma_{l,2}\left(E_{l,1}b_{eff,2}t_{l,1} + E_{l,2}b_{eff,2}t_{l,2}\right)\left(\frac{t_c}{2} + e_{l,2}\right)}{\gamma_{u,2}\left(E_{u,1}b_{eff,2}t_{u,1} + E_{u,2}b_{eff,2}t_{u,2}\right) + \gamma_{l,2}\left(E_{l,1}b_{eff,2}t_{l,1} + E_{l,2}b_{eff,2}t_{l,2}\right) + E_r b_{r,2} t_r}$$

$$B_{u,2} = E_{u,1}b_{eff,2}\frac{t_{u,1}^3}{12} + E_{u,2}b_{eff,2}\frac{t_{u,1}^3}{12} + \frac{E_{u,1}b_{eff,2}t_{u,1}E_{u,2}b_{eff,2}t_{u,2}}{E_{u,1}b_{eff,2}t_{u,1} + E_{u,2}b_{eff,2}t_{u,2}}\frac{\left(t_{u,1} + t_{u,2}\right)^2}{4}$$

$$B_{l,2} = E_{l,1}b_{eff,2}\frac{t_{l,1}^3}{12} + E_{l,2}b_{eff,2}\frac{t_{l,1}^3}{12} + \frac{E_{l,1}b_{eff,2}t_{l,1}E_{l,2}b_{eff,2}t_{l,2}}{E_{l,1}b_{eff,2}t_{l,1} + E_{l,2}b_{eff,2}t_{l,2}}\frac{\left(t_{l,1} + t_{l,2}\right)^2}{4}$$

$$B_{s,w,2} = B_{u,2} + B_{l,2} + E_r\frac{b_{r,2}t_c^3}{12} + \frac{\gamma_{u,2}\left(E_{u,1}b_{eff,2}t_{u,1} + E_{u,2}b_{eff,2}t_{u,2}\right)\gamma_{l,2}\left(E_{l,1}b_{eff,2}t_{l,1} + E_{l,2}b_{eff,2}t_{l,2}\right)}{\gamma_{u,2}\left(E_{u,1}b_{eff,2}t_{u,1} + E_{u,2}b_{eff,2}t_{u,2}\right) + \gamma_{l,2}\left(E_{l,1}b_{eff,2}t_{l,1} + E_{l,2}b_{eff,2}t_{l,2}\right)}\left(e_u + t_c + e_l\right)^2$$

$$Q_{1,2} = \frac{1}{2}\frac{qbL}{2}$$

$$M_{1,2} = \frac{1}{2}\frac{qL^2}{8}$$

$$f = \frac{5qbL^4}{384\left(B_{s,w,1} + B_{s,w,2}\right)}$$

$$\min\sigma_{u,1} = -\frac{M_1}{B_{s,w,1}}\left[\gamma_{u,1}\left(\frac{t_c}{2} + e_{u,1} - e_{r,1}\right) + t_{u,1} + t_{u,2} - e_{u,1}\right]$$

$$max\,\sigma_{l,1} = \frac{M_1}{B_{s,w,1}}\left[\gamma_{l,1}\left(\frac{t_c}{2} + e_{l,1} + e_{r,1}\right) + t_{l,1} + t_{l,2} - e_{l,1}\right]$$

$$min\,\sigma_{u,2} = -\frac{M_2}{B_{s,w,2}}\left[\gamma_{u,2}\left(\frac{t_c}{2} + e_{u,2} - e_{r,2}\right) + t_{u,1} + t_{u,2} - e_{u,2}\right]$$

$$max\,\sigma_{l,2} = \frac{M_2}{B_{s,w,2}}\left[\gamma_{l,2}\left(\frac{t_c}{2} + e_{l,2} + e_{r,2}\right) + t_{l,1} + t_{l,2} - e_{l,2}\right]$$

This applies correspondingly to multi-span beams. The shear effect coefficients $\gamma_{u,1}$, $\gamma_{u,2}$, $\gamma_{l,1}$, $\gamma_{l,2}$ shall be calculated, instead with L, with 0.8 of the smaller one of two adjacent spans.

Annex C Calculation model by Kreuzinger

(Informative)

C.1 Model

Prof. Dr.-Ing. Kreuzinger of the University of München, Germany, has proposed a new and general model for calculating a composite element [1], consisting of several pliable cross-sections with different thickness and width, connected with each other.

Prof. Dr.-Ing. Blass of the University of Karlsruhe, Germany, has adapted the general model to a suitable model to calculate a timber-concrete composite floor system [2].
The following text is mainly based on the example given by Prof. Dr.-Ing. Blass.

C.1.1 Summary

The stiffness matrix takes into account equilibrium in the deformed state (linear static).

C.1.1.1 Shear deflection

The model Kreuzinger [1] contains the following assumptions for the shear deflections:
To determine the shear stiffness the shear stress line (product of shear stress and layer width) between the center of the two outer layers is assumed to have a constant course. The course of the shear deflection of the total cross-section is assumed to be linear (figure C.1). Thus the total shift u is related to the thickness of the composite beam, between the center of the two outer layers. Therefore, an effective shear modulus or shear stiffness for the whole cross-section can be given.

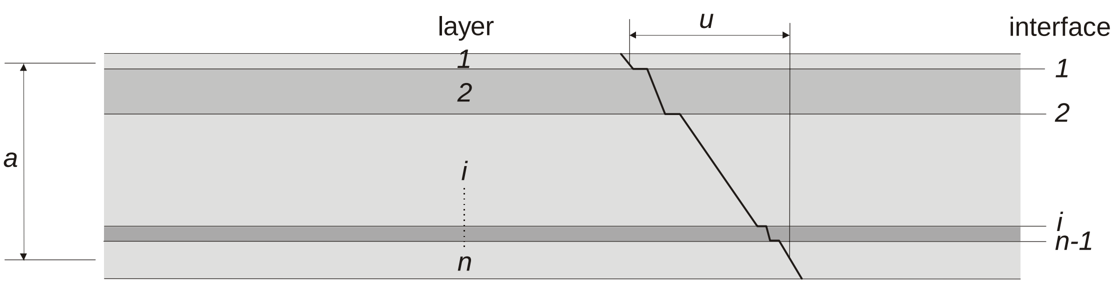


Figure C.1 - Linearity of the shear deflections

C.1.1.2 Stiffnesses

Besides the shear stiffness, the composite element also has two bending stiffnesses: the own bending stiffness and the Steiner bending stiffness.
These stiffnesses will be described by two virtual beams A en B.

C.1.1.3 Stresses

1. Axial forces cause axial stress in each layer *i*, which could be of a different thickness, width and material. The distance from the neutral axis to the layer center also influences the axial stress in each different layer. Therefore, the axial stress in each different layer also depends on the Steiner bending stiffness.
2. From the curvature of each layer a bending stress occurs in each different layer. The bending stress in each different layer depends on the own bending stiffness of each different layer *i* ($E_i \cdot I_i$).
3. Shear forces cause shear stresses in each layer *i*.
4. From the shear force transfer at the interface of the adjoining layers, each layer contains planar shear stresses at the interface of the adjoining layers. This results in a linear shear stress distribution over the depth of each layer due to the shear force transfer at the interface.

C.1.2 Analytical Kreuzinger model

C.1.2.1 Neutral axis

The neutral axis depends on the relation of the partial stiffness under axial load ($E_i \cdot A_i$) of each different layer *i* to the total stiffness under axial load $\left(\sum_{i=1}^{n} E_i \cdot A_i \right)$ of the cross section.

C.1.2.2 Virtual beam A

The own bending stiffness of *n* layers is represented by virtual beam A:

$$(EI)_A = \sum_{i=1}^{n} E_i \cdot I_i \qquad \text{(own bending stiffness)}$$

The shear stiffness of virtual beam A is assumed to be infinite. The shear stiffness of the composite element is described in virtual beam B.

C.1.2.3 Virtual beam B

The composite action of *n* cross-sections is represented by the Steiner bending stiffness in virtual beam B. Also represented in virtual beam B is the composite action at the interface of the adjoining layers and the finite shear stiffness.

The following assumptions are valid:

$$(EI)_B = \sum_{i=1}^{n} E_i \cdot A_i \cdot z_i^2 \qquad \text{(Steiner bending stiffness)}$$

$$\frac{1}{(GA)_B} = \frac{1}{S} = \frac{1}{a^2} \cdot \left(\sum_{i=1}^{n-1} \frac{1}{c_i} + \frac{d_1}{2 \cdot G_1 \cdot b_1} + \sum_{i=2}^{n-1} \frac{d_i}{G_i \cdot b_i} + \frac{d_n}{2 \cdot G_n \cdot b_n} \right) \qquad \text{(finite shear stiffness)}$$

The first term in parentheses deals with the slip deflection, depending on the connection between the layers. The last three terms in parentheses deal with the shear deflection, depending on the shear moduli of the layers. The two outer layers are only partially accounted for.

C.1.2.4 Kreuzinger beam

All the relevant stiffnesses are now systematic applied to two virtual beams A and B. In figure C.2 the model of this new virtual Kreuzinger beam is shown. Hereby the important requirement is: both virtual beams A and B must experience the same deflection, as, in reality, both beams are neither spatial nor substantially separated from each other. This can be achieved in the model by placing the beams parallel to each other and connecting them with mutual nodes.

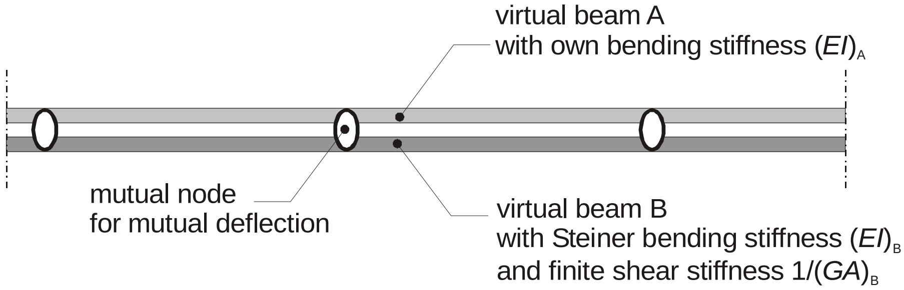


Figure C.2 - Model of the Kreuzinger beam

The Kreuzinger beam can now be loaded by action which results in deflection and internal virtual forces (M_A, Q_A, N_A, M_B, Q_B, N_B). Then these virtual forces are translated to the internal forces in each different layer of the composite element.
The forces M_A and Q_A of virtual beam A are divided among the different layers proportionally to the own bending stiffness of layer *i* ($E_i \cdot I_i$) and the total own bending stiffness $(EI)_A$. Each different layer takes into account a bending stress and a parabolic shear stress distribution.
The forces M_B and Q_B of virtual beam B deliver the constant axial stress in each layer *i* and the shear stress distribution at the interface of the adjoining layers, with which the total shear stress in layer *i* can be calculated.
In figure C.3 the axial, bending and shear stresses in a five layer composite element are shown. By the names A or B one can recognize the virtual beam and the stresses which belong to that beam.

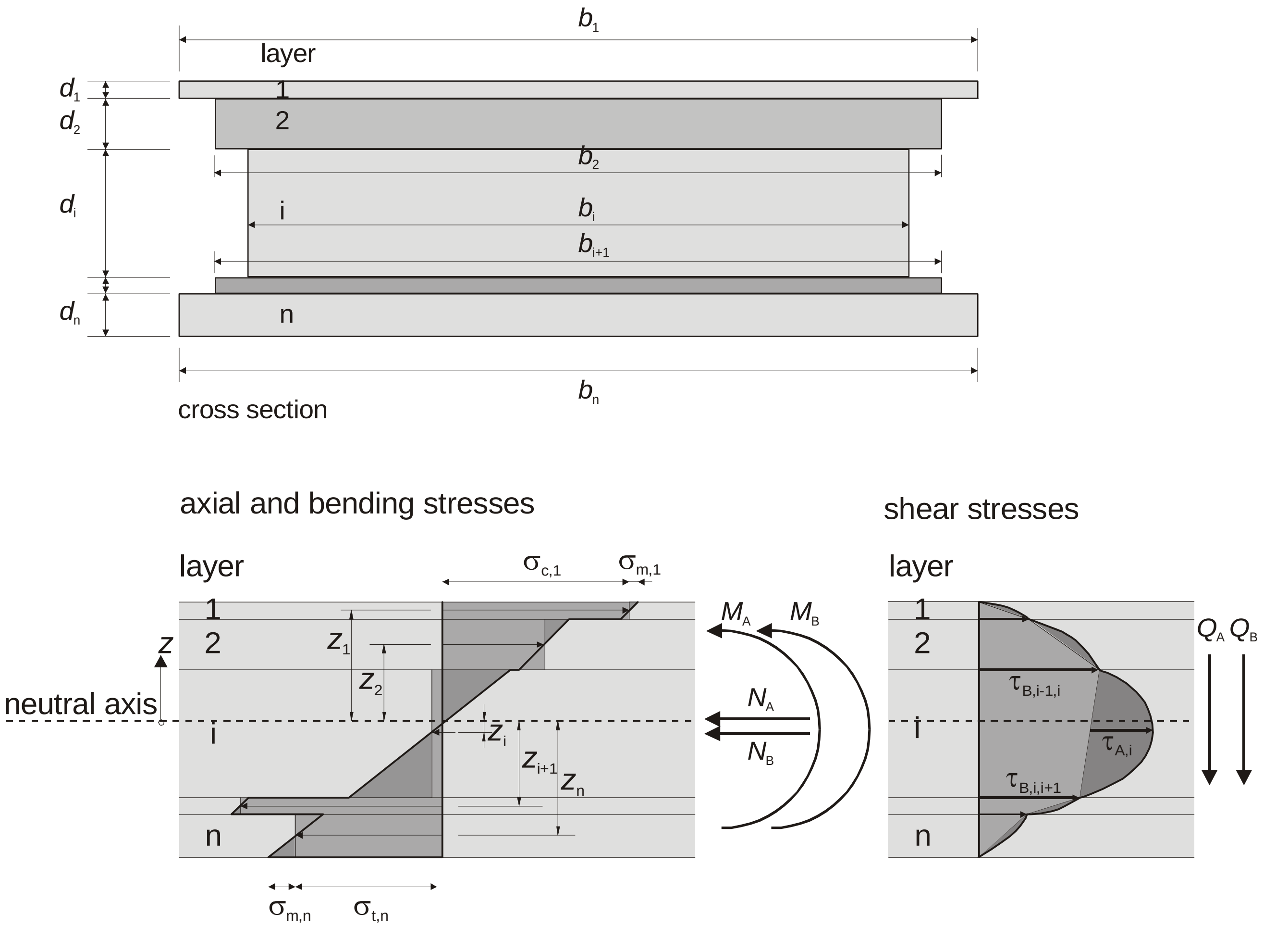


Figure C.3 - Stresses in the composite element

Bending stress in layer *i*:

$$M_A \Rightarrow M_i = \frac{E_i \cdot I_i}{(EI)_A} \cdot M_A \quad \Rightarrow \quad \sigma_{m,i} = \frac{M_i}{W_i}$$

(e.g. shown in figure C.3 as $\sigma_{m,n}$ or $\sigma_{m,1}$)

where:

$$I_i = \frac{b_i \cdot d_i^3}{12}$$

$$W_i = \frac{b_i \cdot d_i^2}{6}$$

b_i width of layer *i*
d_i thickness of layer *i*

Axial stress in layer *i*:

$$M_B \text{ and } N \Rightarrow N_i = \frac{E_i \cdot A_i \cdot z_i}{(EI)_B} \cdot M_B + \frac{E_i \cdot A_i}{\sum_{i=1}^{n} E_i \cdot A_i} \cdot N \Rightarrow \sigma_{c,i} \text{ or } \sigma_{t,i} = \frac{N_i}{A_i} \qquad \text{(e.g. shown in figure C.3 as } \sigma_{t,n} \text{ or } \sigma_{c,1}\text{)}$$

where:

$$N = N_A + N_B$$

$$A_i = b_i \cdot d_i$$

The axial force N from the actions on the structure is distributed on the partial cross-sections of the stressed skin panel according to the longitudinal stiffness values of the partial cross-sections.
Shear stress in layer *i*:

$$\tau_{max,i} = \tau_{A,i} + \tau_{1,i} + \frac{\tau_{2,i}}{2} + \frac{\tau_{2,i}^2}{16 \cdot \tau_{A,i}} \qquad \text{if } \tau_{A,i} > \frac{\tau_{2,i}}{4}$$

$$\tau_{max,i} = \tau_{1,i} + \tau_{2,i} \qquad \text{if } \tau_{A,i} \leq \frac{\tau_{2,i}}{4}$$

where:

$$Q_A \Rightarrow \tau_{A,i} = \frac{E_i \cdot I_i}{(EI)_A} \cdot Q_A \cdot \frac{3}{2} \cdot \frac{1}{d_i \cdot b_i} \qquad \text{(e.g. shown in figure C.3 as } \tau_{A,i}\text{)}$$

$$Q_B \Rightarrow \tau_{B,i\text{-}1,i} = \frac{Q_B}{(EI)_B} \cdot \frac{\sum_{i=1}^{i-1} E_i \cdot A_i \cdot z_i}{\min\begin{cases} b_{i-1} \\ b_i \end{cases}} \qquad \text{(e.g. shown in figure C.3 as } \tau_{B,i\text{-}1,i}\text{)}$$

$$Q_B \Rightarrow \tau_{B,i,i+1} = \frac{Q_B}{(EI)_B} \cdot \frac{\sum_{i=1}^{i} E_i \cdot A_i \cdot z_i}{\min\begin{cases} b_i \\ b_{i+1} \end{cases}} \qquad \text{(e.g. shown in figure C.3 as } \tau_{B,i,i+1}\text{)}$$

$$\tau_{1,i} = \min\begin{cases} \tau_{B,i\text{-}1,i} \\ \tau_{B,i,i+1} \end{cases}$$

$$\tau_{2,i} = \left|\tau_{B,i\text{-}1,i} - \tau_{B,i,i+1}\right|$$

Shear stress at the interface of the adjoining layers between layer *i* and *i+1*:

$$Q_B \Rightarrow \tau_{B,i,i+1} = \frac{Q_B}{(EI)_B} \cdot \frac{\sum_{i=1}^{i} E_i \cdot A_i \cdot z_i}{\min\begin{cases} b_i \\ b_{i+1} \end{cases}} \qquad \text{(e.g. shown in figure C.3 as } \tau_{B,i,i+1}\text{)}$$

The calculated deflection must not exceed the limiting values for the deflection and the design values of the calculated stresses must not exceed the design values of the material strengths.

C.2 Model for a glued stressed skin panel, closed box type double-skin, *without* wooden ribs, *with* loadbearing insulation (type A)

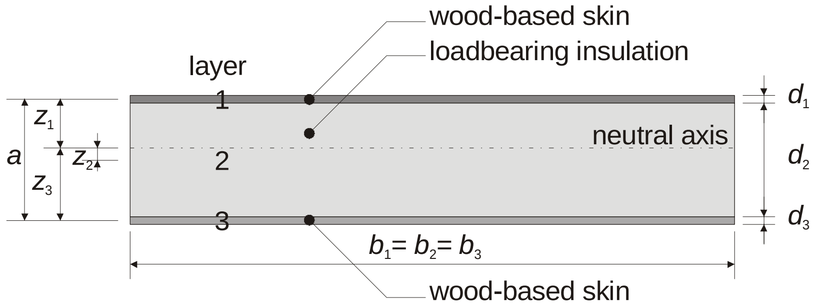


Figure C.4 - E.g. cross-section of the three layers stressed skin panel *without* wooden rib, *with* loadbearing insulation

In this example the main direction of the wood-based skin (the grain direction of face veneer) is parallel to the span direction. For wood-based skins like OSB or plywood the material properties parallel and perpendicular to the grain direction of face veneer are different.

C.2.1 Verification of ultimate limit states

The design strength values must be calculated according to prEN 1995-1-1 [12].
Some characteristic and mean values of the material properties are given in chapter 5.

C.2.1.1 Virtual beam A

The own bending stiffness, represented by virtual beam A, appears to be a factor of 100 to 200 times smaller than the Steiner bending stiffness, represented by virtual beam B. As there is no effect in the load distribution and singularity errors are caused by the large difference in stiffnesses, virtual beam A plays no part and is ignored.

C.2.1.2 Virtual beam B

Virtual beam B contains the Steiner bending stiffness and a finite shear stiffness resulting in a noticeable shear deflection:

$$(EI)_B = \sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i^2 \qquad \text{(Steiner bending stiffness)}$$

The wood-based skins are glued to the core. Therefore the connection between flange and web is assumed to be infinitely stiff. Because the factor of co-operation is assumed to be 1,00 the term $\sum_{i=1}^{n-1} \frac{1}{c_i}$ in the general equation for the shear stiffness (see also C.1.2.3) is neglected.

$$\frac{1}{(GA)_B} = \frac{1}{S} = \frac{1}{a^2} \cdot \left(\frac{d_1}{2 \cdot G_{\perp,0,mean,1} \cdot b_1} + \frac{d_2}{G_{mean,2} \cdot b_2} + \frac{d_3}{2 \cdot G_{\perp,0,mean,3} \cdot b_3} \right) \qquad \text{(finite shear stiffness)}$$

where:

$A_i = b_i \cdot d_i$

concerning the wood-based skin:

$E_{t(c),//,0,mean,i}$ the <u>in-plane</u> mean modulus of elasticity along the grain of face veneer for compression or tension.

$G_{\perp,0,mean,1(3)}$ the <u>planar</u> mean shear modulus along the grain of face veneer.

concerning the insulation core:

$E_{t(c),//,0,mean,i}$ the mean modulus of elasticity for compression or tension $E_{t(c),mean}$.

$G_{mean,2}$ the mean shear modulus.

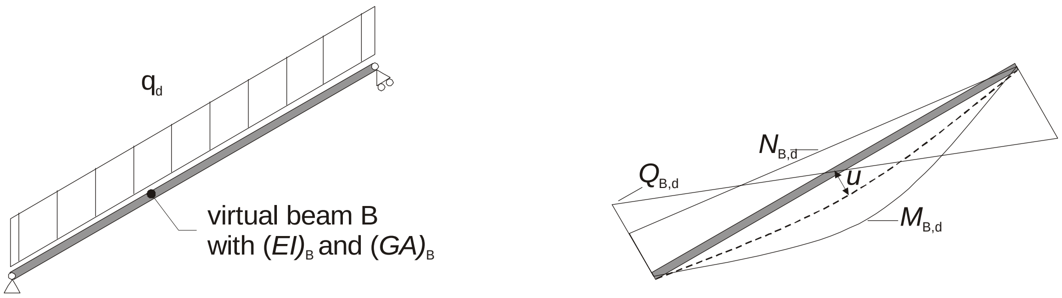


Figure C.5 - E.g. a simply supported Kreuzinger beam of type A

In figure C.5 a design example is given. The stressed skin panel of type A is now described as a virtual beam B with the Steiner bending stiffness $(EI)_B$ and a finite shear stiffness $(GA)_B$.

Virtual beam B can now be loaded by design combination of actions (see chapter 6) to determine the maximum design internal forces.
The calculated virtual design bending, shear and axial forces ($M_{d,B}$, $Q_{d,B}$, $N_{d,B}$) are then translated to the design axial and shear stresses in each different layer *i*. Bending stress in each layer *i* do not occur, because the own bending stiffness is neglected.

Virtual design bending moment $M_{d,B}$ is translated to design axial stress in each different layer *i* by ratio of the Steiner bending stiffness.

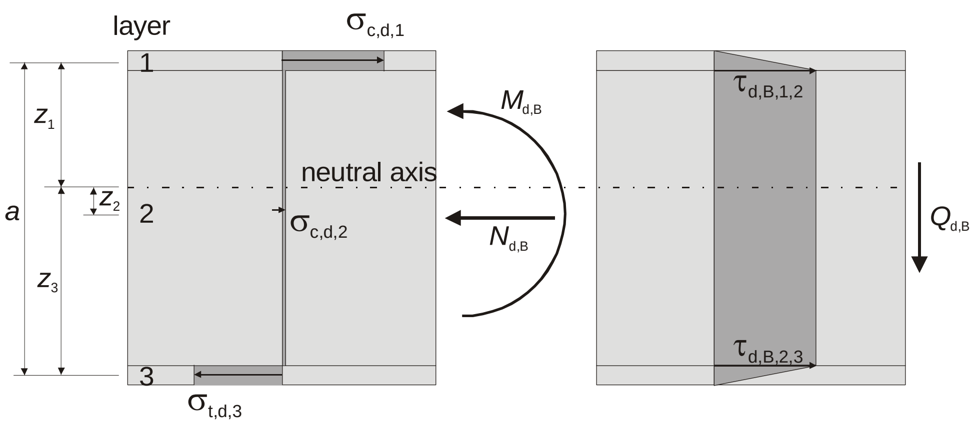


Figure C.6 - Design stresses in the stressed skin panel of type A

C.2.1.3 Design compression or tension stress

From the calculated virtual design bending and axial forces $M_{d,B}$ and $N_{d,B}$:

Depending on the direction of the moment $M_{d,B}$ and the axial force $N_{d,B}$ in the structure, each layer can experience compression or tension stress. In this example we assume that the upper wood-based skin and the loadbearing insulation core experience compression and the lower wood-based skin experiences tension.

<u>Design compression stress in layer 1 (upper wood-based skin):</u>

$$N_{d,1} = \frac{E_{t(c),//,0,mean,1} \cdot A_1 \cdot z_1}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),//,0,mean,1} \cdot A_1}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot N_{d,B} \Rightarrow \sigma_{c,d,1} = \frac{N_{d,1}}{A_1}$$ (shown in figure C.6 as $\sigma_{c,d,1}$)

The maximum design compression stress must be compared to the design in-plane compression strength along the grain of face veneer of the upper wood-based skin.

$$\sigma_{c,d,1} \leq f_{c,//,0,d,1}$$

Design compression stress in layer 2 (loadbearing insulation core):

$$N_{d,2} = \frac{E_{t(c),mean,2} \cdot A_2 \cdot z_2}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),mean,2} \cdot A_2}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot N_{d,B} \Rightarrow \sigma_{c,d,2} = \frac{N_{d,2}}{A_2}$$

(shown in figure C.6 as $\sigma_{c,d,2}$)

The maximum design compression stress must be compared to the design compression strength of the loadbearing insulation core.

$$\sigma_{c,d,2} \leq f_{c,d,2}$$

Design tension stress in layer 3 (lower wood-based skin):

$$N_{d,3} = \frac{E_{t(c),//,0,mean,3} \cdot A_3 \cdot z_3}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),//,0,mean,3} \cdot A_3}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot N_{d,B} \Rightarrow \sigma_{t,d,3} = \frac{N_{d,3}}{A_3}$$

(shown in figure C.6 as $\sigma_{t,d,3}$)

The maximum design tension stress must be compared to the design in-plane tension strength along the grain of face veneer of the lower wood-based skin.

$$\sigma_{t,d,3} \leq f_{t,//,0,d,3}$$

C.2.1.4 Design shear stress at interface of adjoining layers

From the calculated virtual design shear force $Q_{d,B}$:

Design shear stress at the interface of adjoining layers 1 and 2:

$$\tau_{d,B,1,2} = \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_1 \\ b_2 \end{cases}}$$

(shown in figure C.6 as $\tau_{d,B,1,2}$)

The maximum design shear stress at the interface of adjoining layers 1 and 2 must be compared to the minimum value of the design planar shear strength along the grain of face veneer of layer 1 (upper wood-based skin) or the design shear strength of layer 2 (loadbearing insulation core).

$$\tau_{d,B,1,2} \leq \min\begin{cases} f_{v,\perp,0,d,1} \\ f_{v,d,2} \end{cases}$$

Design shear stress at interface of adjoining layers 2 and 3:

$$\tau_{d,B,2,3} = \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_2 \\ b_3 \end{cases}}$$

(shown in figure C.6 as $\tau_{d,B,2,3}$)

The maximum design shear stress at interface of adjoining layers 2 and 3 must be compared to the minimum value of the design shear strength of layer 2 (loadbearing insulation core) or the design planar shear strength along the grain of face veneer of layer 3 (lower wood-based skin).

$$\tau_{d,B,2,3} \leq \min\begin{cases} f_{v,d,2} \\ f_{v,\perp,0,d,3} \end{cases}$$

C.2.1.5 Design shear stress

From the calculated virtual design shear force $Q_{d,B}$:
<u>Design shear stress in layer 1 (upper wood-based skin):</u>

$$\tau_{d,B,0,1} = 0$$

$$\tau_{d,B,1,2} = \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_1 \\ b_2 \end{cases}}$$ (shown in figure C.6 as $\tau_{d,B,1,2}$)

$$\tau_{1,d,1} = \min\begin{cases} \tau_{d,B,0,1} \\ \tau_{d,B,1,2} \end{cases} = 0$$

$$\tau_{2,d,1} = \left|\tau_{d,B,0,1} - \tau_{d,B,1,2}\right| = \tau_{d,B,1,2}$$

$$\tau_{max,d,1} = \tau_{1,d,1} + \tau_{2,d,1} = \tau_{d,B,1,2}$$

The maximum design shear stress must be compared to the design planar shear strength along the grain of face veneer of the upper wood-based skin.

$$\tau_{max,d,1} \leq f_{v,\perp,0,d,1}$$

<u>Design shear stress in layer 2 (loadbearing insulation core):</u>

$$\tau_{d,B,1,2} = \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_1 \\ b_2 \end{cases}}$$ (shown in figure C.6 as $\tau_{d,B,1,2}$)

$$\tau_{d,B,2,3} = \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_2 \\ b_3 \end{cases}}$$ (shown in figure C.6 as $\tau_{d,B,2,3}$)

$$\tau_{1,d,2} = \min\begin{cases} \tau_{d,B,1,2} \\ \tau_{d,B,2,3} \end{cases}$$

$$\tau_{2,d,2} = \left|\tau_{d,B,1,2} - \tau_{d,B,2,3}\right|$$

$$\tau_{max,d,2} = \tau_{1,d,2} + \tau_{2,d,2}$$

The maximum design shear stress must be compared to the design shear strength of the loadbearing insulation core.

$$\tau_{max,d,2} \leq f_{v,d,2}$$

Design shear stress in layer 3 (lower wood-based skin):

$$\tau_{d,B,2,3} = \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{(EI)_B} \cdot \frac{Q_{d,B}}{\min\begin{cases} b_2 \\ b_3 \end{cases}}$$ (shown in figure C.6 as $\tau_{d,B,2,3}$)

$$\tau_{d,B,3,4} = 0$$

$$\tau_{1,d,3} = \min\begin{cases} \tau_{d,B,2,3} \\ \tau_{d,B,3,4} \end{cases} = 0$$

$$\tau_{2,d,3} = \left|\tau_{d,B,2,3} - \tau_{d,B,3,4}\right| = \tau_{d,B,2,3}$$

$$\tau_{max,d,3} = \tau_{1,d,3} + \tau_{2,d,3} = \tau_{d,B,2,3}$$

The maximum design shear stress must be compared to the design planar shear strength along the grain of face veneer of the lower wood-based skin.

$$\tau_{max,d,3} \leq f_{v,\perp,0,d,3}$$

C.2.1.6 Local design compression stress in layer 2 (loadbearing insulation core) at a support

The verification is taken from the ECCS / CIB Report [13].

$$\sigma_{c,d,2} = \frac{R_d}{A_{eff}}$$

where:

R_d the maximum design reaction force at a support.
A_{eff} the effective support area of loadbearing insulation core at a support.

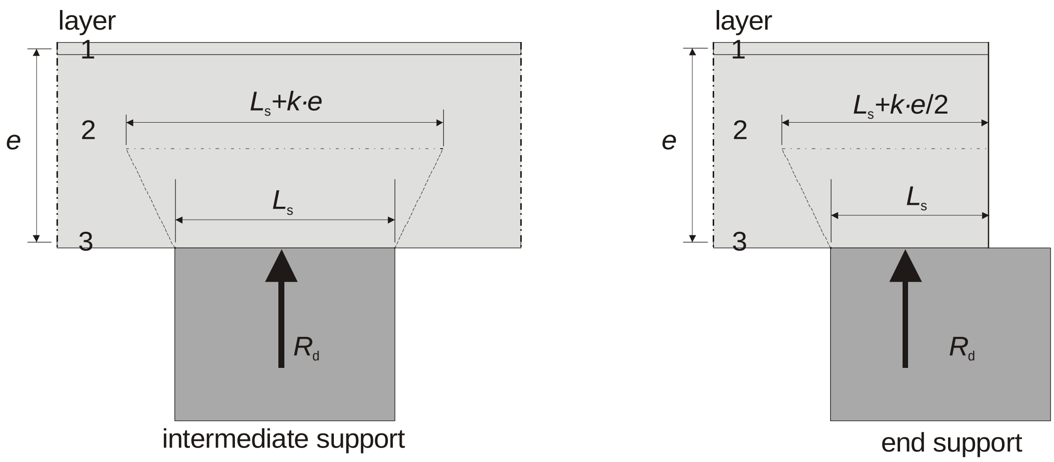


Figure C.7 – Effective support length of the loadbearing insulation core

Effective support area of the loadbearing insulation core:
Intermediate support:

$$A_{eff} = B \cdot (L_s + k \cdot e)$$

End support:

$$A_{eff} = B \cdot \left(L_s + k \cdot e/2\right)$$

where:

B the supported width of the loadbearing insulation core.

k a distribution parameter; k = 0,50 for loadbearing insulation core.

e the distance between the centers of the face layers; $e \leq 100$ mm.

For sandwich panels with $e > 100$ mm, $e = 100$ mm should be used.
The maximum design compression stress must be compared to the reduced design compression strength of the loadbearing insulation core.

$$\frac{\sigma_{c,d,2}}{f_{c,d,2}} \leq 1{,}00$$

C.2.1.7 Design wrinkling stress

The wrinkling phenomenon in the wood-based skin due to compression stress in the field or due to compression and bending stress at the support is described in chapter … and 5.2.

C.2.1.8 Influence of temperature

… needs brief research and a remark or recommendation here…

C.2.1.9 Fastening of the stressed skin panel to the supporting structure

In case the stressed skin panel is supported by a timber structure, metal fasteners can be used to connect the stressed skin panel to the supporting structure. The panel-to-timber connection must be calculated according to prEN 1995-1-1 [12].

C.2.2 Verification of serviceability limit states

As the loadbearing insulation core has a small finite shear stiffness, the shear deflection is of great influence. Besides a deflection caused by the elastic stiffness, an extra noticeable deflection caused by the small finite shear stiffness shall be calculated.

C.2.2.1 Design value of the stiffness properties of each layer *i*

Virtual beam B can now be loaded by combination of actions to be used for verification in the serviceability limit state (see also chapter 6) to determine the maximum total deflection.
The calculated deflection must not exceed the limiting values for the deflection. Some recommendations for limits of deflection are given in prEN 1995-1-1 [12] in absence of more precise information. Specific numerical limits of deflection or slope should in principle be decided by the structural engineer from case to case, depending on the actual situation and the demands of the client.

The final deformation of the stressed skin panel fabricated from members which have different creep properties should be calculated using modified final stiffness moduli ($E_{fin,i}$ and $G_{fin,i}$), which are determined by dividing the instantaneous values of the modulus for each member ($E_{mean,i}$ and $G_{mean,i}$) by the appropriate value of ($1+k_{def,i}$).
A load combination which consists of actions belonging to different load duration classes, the contribution of each action to the total deflection should be calculated separately using the appropriate k_{def} values.

Final stiffness properties of each action using the appropriate k_{def} values for <u>virtual beam B</u>:

$$E_{fin,i} = \frac{E_{mean,i}}{1 + \psi_2 \cdot k_{def,i}}$$

$$G_{fin,i} = \frac{G_{mean,i}}{1 + \psi_2 \cdot k_{def,i}}$$

concerning the wood-based skin with the grain of face veneer parallel to the span direction:

$E_{mean,i}$ the in-plane mean modulus of elasticity for compression or tension along the grain of face veneer $E_{t(c),//,0,mean}$.

$G_{mean,i}$ the planar mean shear modulus along the grain of face veneer $G_{\perp,0,mean}$.

concerning the loadbearing insulation core:

$E_{mean,i}$ the mean modulus of elasticity for compression or tension $E_{t(c),mean}$.

$G_{mean,i}$ the mean shear modulus G_{mean}.

ψ_2 a factor for the quasi-permanent value of a variable action. For permanent actions, ψ_2 should be taken equal to 1,00.

C.3 Model for a stressed skin panel, closed box type double-skin, *with* wooden ribs and (non)-loadbearing insulation (type B1 and C1)

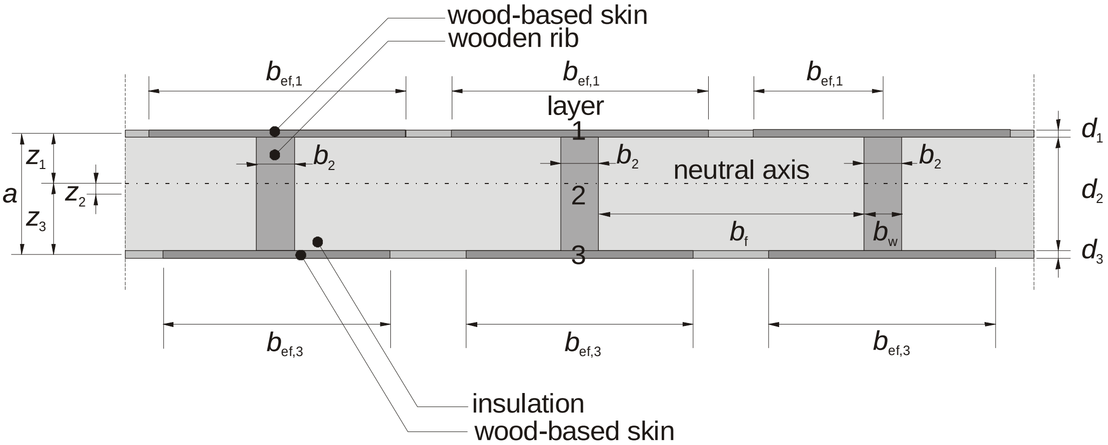


Figure C.8 - E.g. cross-section of the three layers stressed skin panel *with* wooden ribs and (non)-loadbearing insulation

In this example the main direction of the wood-based skin (the grain direction of face veneer) is parallel to the span direction. For wood-based skins like OSB or plywood the material properties parallel and perpendicular to the grain direction of face veneer are different.

C.3.1 Verification of ultimate limit states

The design strength values must be calculated according to prEN 1995-1-1 [12]. Some characteristic and mean values of the material properties are given in chapter 5.

C.3.1.1 Effective flange width b_{ef} of wood-based skins

C.3.1.1.1 With non-loadbearing (unstiff) insulation (type C1)

In case the space between the wooden ribs consists of non-loadbearing (unstiff) insulation the effective flange width should be taken from table 3.1 of the prEN 1995-1-1. The minimum value between the columns due to the shear lag and due to the plate buckling should be taken.

	$b_{ef,I}$	
Flange material	Shear lag[1]	Plate buckling[2]
Plywood, with grain direction in the outer plies:		
• parallel to the webs	$0{,}10 \cdot \lambda$	$20 \cdot h_{f,I}$
• perpendicular to the webs	$0{,}10 \cdot \lambda$	$25 \cdot h_{f,I}$
OSB	$0{,}15 \cdot \lambda$	$25 \cdot h_{f,I}$
Particleboard	$0{,}20 \cdot \lambda$	$30 \cdot h_{f,I}$

Table C.1 - Maximum effective flange widths due to the effect of shear lag and plate buckling according to prEN 1995-1-1

The center-to-center distance of the wooden ribs should not exceed 600 mm.

Remark:
Type C1 can also be calculated by the EC 5 method.

---

[1] λ = span of beam
[2] $h_{f,i}$ = thickness of flange (of wood-based skin layer *i*)

C.3.1.1.2 With loadbearing (stiff) insulation, glued to the wood-based skins (type B1)

The space between the wooden ribs forms a stressed skin panel of type A. Therefore the wood-based skins of type B1 are supported by the loadbearing (stiff) insulation core. The effect of plate buckling may be disregarded. The analytical solution for the maximum effective flange widths due to the effect of shear lag is independent of the type of insulation because it only takes into account shear lag and no plate buckling and therefore may be used in all cases. Effective flange width of the wood-based skins:

$$\frac{b_{ef,i} - b_w}{b_f} = \frac{2 \cdot \lambda \cdot \left(\lambda_{1,i} \cdot \tanh\alpha_{1,i} - \lambda_{2,i} \cdot \tanh\alpha_{2,i}\right)}{\pi \cdot b_f \cdot \left(\lambda_{1,i}^2 - \lambda_{2,i}^2\right)}$$

where:

$$\alpha_{1,i} = \frac{\lambda_{1,i} \cdot \pi \cdot b_f}{2 \cdot \lambda}$$

$$\alpha_{2,i} = \frac{\lambda_{2,i} \cdot \pi \cdot b_f}{2 \cdot \lambda}$$

$$\lambda_{1,i} = \sqrt{a_i + \sqrt{a_i^2 - c_i}}$$

$$\lambda_{2,i} = \sqrt{a_i - \sqrt{a_i^2 - c_i}}$$

$$a_i = \frac{E_{t(c),//,90,mean,i}}{2 \cdot G_{//,mean,i}} - \mu_i$$

$$c_i = \frac{E_{t(c),//,90,mean,i}}{E_{t(c),//,0,mean,i}}$$

λ	the span of the beam.
b_f	the web spacing.
b_w	the rib width.
$E_{t(c),//,0,mean,i}$	the in-plane mean modulus of elasticity along the grain of face veneer for compression or tension of wood-based skin layer *i*.
$E_{t(c),//,90,mean,i}$	the in-plane mean modulus of elasticity perpendicular to the grain of face veneer for compression or tension of wood-based skin layer *i*.
$G_{//,mean,i}$	the in-plane mean shear modulus of wood-based skin layer *i*.
μ_i	the in-plane Poisson's ratio of wood-based skin layer *i*.

C.3.1.2 Virtual beam A

Virtual beam A contains the own bending stiffness of the three layers:

$$(EI)_A = \sum_{i=1}^{3} E_{m,\perp,0,mean,i} \cdot I_i$$

where:

$$I_i = \frac{b_{ef,i} \cdot d_i^3}{12} \qquad \text{(for the wood-based skins and } b_{ef,i} \text{ according to C.3.1.1)}$$

$$I_i = \frac{b_i \cdot d_i^3}{12} \qquad \text{(for the wooden rib core)}$$

concerning the wood-based skin:

$E_{m,\perp,0,mean,i}$ the planar mean modulus of elasticity along the grain of face veneer for bending.

concerning the wooden rib core:

$E_{m,\perp,0,mean,i}$ the mean modulus of elasticity along the grain $E_{0,mean}$.

The shear stiffness of virtual beam A is assumed to be infinite.

C.3.1.3 Virtual beam B

Virtual beam B contains the Steiner bending stiffness:

$$(EI)_B = \sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i^2 \qquad \text{(Steiner bending stiffness)}$$

The shear stiffness should also be taken into account for slender webs and small λ/h-ratios. In these cases, the shear stiffness might influence the stress distribution and the deformation.
In this example the wood-based skins are glued to the wooden ribs. Therefore the connection between flange and web is assumed to be infinitely stiff. Because the factor of co-operation is assumed to be 1,00 the term $\sum_{i=1}^{n-1} \frac{1}{c_i}$ in the general equation for the shear stiffness (see also C.1.2.3) is neglected.
If the connection between skin and wooden rib is made of mechanical fasteners, the factor of co-operation is less than 1,00 and the slip stiffness due to mechanical fastening has to be taken into account by the term $\sum_{i=1}^{n-1} \frac{1}{c_i}$. The slip stiffness can be calculated according to EC 5. The total number of layers should then not exceed 5.
Mechanical fasteners are only mentioned to complete the formulas. Mechanical fasteners are not allowed i

$$\frac{1}{(GA)_B} = \frac{1}{S} = \frac{1}{a^2} \cdot \left(\frac{d_1}{2 \cdot G_{\perp,0,mean,1} \cdot b_{ef,1}} + \frac{d_2}{G_{mean,2} \cdot b_2} + \frac{d_3}{2 \cdot G_{\perp,0,mean,3} \cdot b_{ef,3}} \right) \qquad \text{(finite shear stiffness)}$$

where:

$A_i = b_{ef,i} \cdot d_i$ (for the wood-based skins and $b_{ef,i}$ according to C.3.1.1)

$A_i = b_i \cdot d_i$ (for the wooden rib core)

concerning the wood-based skins:

$E_{t(c),//,0,mean,i}$ the in-plane mean modulus of elasticity along the grain of face veneer for compression or tension.

$G_{\perp,0,mean,1(3)}$ the planar mean shear modulus along the grain of face veneer.

concerning the wooden rib core:

$E_{t(c),//,0,mean,i}$ the mean modulus of elasticity along the grain $E_{0,mean}$.

$G_{mean,2}$ the mean shear modulus.

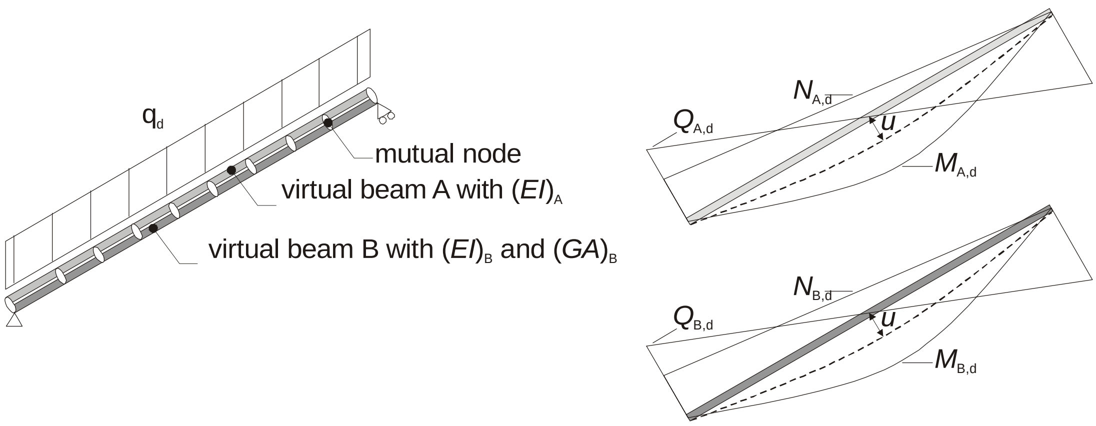


Figure C.9 - E.g. a simply supported Kreuzinger beam of type B1 or C1

In figure C.8 a design example is given. The stressed skin panel of type B1 or C1 is now described as a virtual beam A with the own bending stiffness $(EI)_A$ and a virtual beam B with the Steiner bending stiffness $(EI)_B$. Both beams are placed parallel to each other and they are connected with mutual nodes.

The combined virtual beams A and B can now be loaded by design combination of actions (see clause 4.4) to determine the maximum design internal forces.
The calculated virtual design bending, shear and axial forces ($M_{d,A}$, $Q_{d,A}$, $N_{d,A}$, $M_{d,B}$, $Q_{d,B}$, $N_{d,B}$) are then translated to the design bending, axial and shear stresses in each different layer *i*.

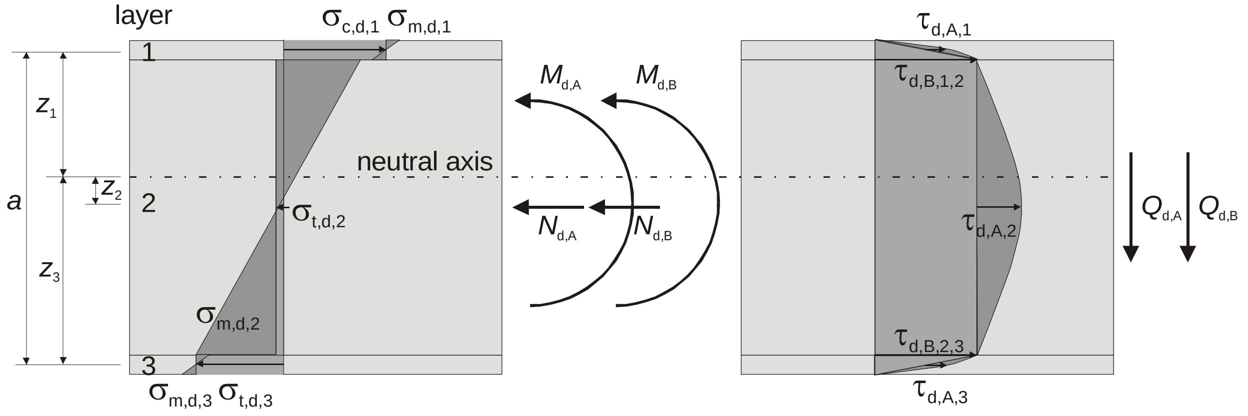


Figure C.10 - Stresses in the stressed skin panel of type B1 or C1

C.3.1.4 Design compression or tension stress in combination with bending stress

From the calculated virtual design bending and axial forces $M_{d,A}$; $N_{d,A}$; $M_{d,B}$ and $N_{d,B}$:

Depending on the direction of the moment $M_{d,B}$ and the axial forces $N_{d,A}$ and $N_{d,B}$ in the structure, every layer can experience compression or tension stress. In this example we assume that the upper wood-based skin experiences compression and the lower wood-based skin and the wooden rib core experience tension.

Design bending stress in layer 1 (upper wood-based skin):

$$M_{d,1} = \frac{E_{m,\perp,0,mean,1} \cdot I_1}{(EI)_A} \cdot M_{d,A} \quad \Rightarrow \quad \sigma_{m,d,1} = \frac{M_{d,1}}{W_1}$$ (shown in figure C.9 as $\sigma_{m,d,1}$)

where:

$$W_1 = \frac{b_{ef,1} \cdot d_1^2}{6}$$ (for the wood-based skins and $b_{ef,1}$ according to C.3.1.1)

Design compression stress in layer 1 (upper wood-based skin):

$$N_{d,1} = \frac{E_{t(c),//,0,mean,1} \cdot A_1 \cdot z_1}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),//,0,mean,1} \cdot A_1}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot \left(N_{d,A} + N_{d,B}\right) \Rightarrow \sigma_{c,d,1} = \frac{N_{d,1}}{A_1}$$ (shown in figure C.9 as $\sigma_{c,d,1}$)

The maximum combined design compression and bending stress must be compared to the combined design in-plane compression strength along the grain of face veneer and the design planar bending strength along the grain of face veneer of the upper wood-based skin.

$$\frac{\sigma_{c,d,1}}{f_{c,//,0,d,1}} + \frac{\sigma_{m,d,1}}{f_{m,\perp,0,d,1}} \leq 1{,}00$$

Design bending stress in layer *2* (wooden rib core):

$$M_{d,2} = \frac{E_{0,mean,2} \cdot I_2}{(EI)_A} \cdot M_{d,A} \quad \Rightarrow \quad \sigma_{m,d,2} = \frac{M_{d,2}}{W_2}$$ (shown in figure C.9 as $\sigma_{m,d,2}$)

where:

$$W_2 = \frac{b_2 \cdot d_2^2}{6}$$ (for the wooden rib core)

Design tension stress in layer 2 (wooden rib core):

$$N_{d,2} = \frac{E_{0,mean,2} \cdot A_2 \cdot z_2}{(EI)_B} \cdot M_{d,B} + \frac{E_{0,mean,2} \cdot A_2}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot \left(N_{d,A} + N_{d,B}\right) \Rightarrow \sigma_{t,d,2} = \frac{N_{d,2}}{A_2}$$ (shown in figure C.9 as $\sigma_{t,d,2}$)

The maximum combined design tension and bending stress must be compared to the combined design tension and bending strength along the grain of the wooden rib core.

$$\frac{\sigma_{t,d,2}}{f_{t,0,d,2}} + \frac{\sigma_{m,d,2}}{f_{m,d,2}} \leq 1{,}00$$

Design bending stress in layer 3 (lower wood-based skin):

$$M_{d,3} = \frac{E_{m,\perp,0,mean,3} \cdot I_3}{(EI)_A} \cdot M_{d,A} \quad \Rightarrow \quad \sigma_{m,d,3} = \frac{M_{d,3}}{W_3}$$ (shown in figure C.9 as $\sigma_{m,d,3}$)

where:

$$W_3 = \frac{b_{ef,3} \cdot d_3^2}{6}$$ (for the wood-based skins and $b_{ef,3}$ according to C.3.1.1)

Design tension stress in layer 3 (lower wood-based skin):

$$N_{d,3} = \frac{E_{t(c),//,0,mean,3} \cdot A_3 \cdot z_3}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),//,0,mean,3} \cdot A_3}{\sum_{i=1}^{3} E_{t(c),//,0,mean,i} \cdot A_i} \cdot \left(N_{d,A} + N_{d,B}\right) \Rightarrow \sigma_{t,d,3} = \frac{N_{d,3}}{A_3}$$ (shown in figure C.9 as $\sigma_{t,d,3}$)

The maximum combined design tension and bending stress must be compared to the combined design in-plane tension strength along the grain of face veneer and the design planar bending strength along the grain of face veneer of the lower wood-based skin.

$$\frac{\sigma_{t,d,3}}{f_{t,//,0,d,3}} + \frac{\sigma_{m,d,3}}{f_{m,\perp,0,d,3}} \leq 1{,}00$$

C.3.1.5 Design shear stress at interface of adjoining layers

From the calculated virtual design shear force $Q_{d,B}$:

Design shear stress at interface of adjoining layers 1 and 2:

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{Bmatrix} b_{ef,1} \\ b_2 \end{Bmatrix}}$$ (shown in figure C.9 as $\tau_{d,B,1,2}$)

The maximum design shear stress at interface of adjoining layers 1 and 2 must be compared to the minimum value of the design planar shear strength along the grain of face veneer of layer 1 (upper wood-based skin) or the design shear strength layer 2 (wooden rib core).

$$\tau_{d,B,1,2} \le \min\begin{cases} f_{v,\perp,0,d,1} \\ f_{v,d,2} \end{cases}$$

Design shear stress at interface of adjoining layers 2 and 3:

$$\tau_{d,B,2,3} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_2 \\ b_{ef,3} \end{cases}}$$ (shown in figure C.9 as $\tau_{d,B,2,3}$)

The maximum design shear stress at interface of adjoining layers 2 and 3 must be compared to the minimum value of the design shear strength of layer 2 (wooden rib core) or the design planar shear strength along the grain of face veneer of layer 3 (lower wood-based skin).

$$\tau_{d,B,2,3} \le \text{minimum of} \begin{cases} f_{v,d,2} \\ f_{v,\perp,0,d,3} \end{cases}$$

C.3.1.6 Design shear stress

From the calculated virtual design shear forces $Q_{d,A}$ and $Q_{d,B}$:

Design shear stress in layer 1 (upper wood-based skin):

$$\tau_{d,A,1} = \frac{E_{m,\perp,0,mean,1} \cdot I_1}{(EI)_A} \cdot Q_{d,A} \cdot \frac{3}{2} \cdot \frac{1}{d_1 \cdot b_{ef,1}}$$ (shown in figure C.9 as $\tau_{d,A,1}$)

$$\tau_{d,B,0,1} = 0$$

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_{ef,1} \\ b_2 \end{cases}}$$ (shown in figure C.9 as $\tau_{d,B,1,2}$)

$$\tau_{1,d,1} = \min\begin{cases} \tau_{d,B,0,1} \\ \tau_{d,B,1,2} \end{cases} = 0$$

$$\tau_{2,d,1} = \left|\tau_{d,B,0,1} - \tau_{d,B,1,2}\right| = \tau_{d,B,1,2}$$

$$\text{if } \tau_{d,A,1} > \frac{\tau_{2,d,1}}{4} \Leftrightarrow \text{if } \tau_{d,A,1} > \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,1} = \tau_{d,A,1} + \tau_{1,d,1} + \frac{\tau_{2,d,1}}{2} + \frac{\tau_{2,d,1}^2}{16 \cdot \tau_{d,A,1}} \Leftrightarrow \tau_{max,d,1} = \tau_{d,A,1} + \frac{\tau_{d,B,1,2}}{2} + \frac{\tau_{d,B,1,2}^2}{16 \cdot \tau_{d,A,1}}$$

$$\text{if } \tau_{d,A,1} \le \frac{\tau_{2,d,1}}{4} \Leftrightarrow \text{if } \tau_{d,A,1} \le \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,1} = \tau_{1,d,1} + \tau_{2,d,1} \Leftrightarrow \tau_{max,d,1} = \tau_{d,B,1,2}$$

The maximum design shear stress must be compared to the design planar shear strength along the grain of face veneer of the upper wood-based skin.

$$\tau_{max,d,1} \le f_{v,\perp,0,d,1}$$

Design shear stress in layer 2 (wooden rib core):

$$\tau_{d,A,2} = \frac{E_{0,mean,2} \cdot I_2}{(EI)_A} \cdot Q_{d,A} \cdot \frac{3}{2} \cdot \frac{1}{d_2 \cdot b_2}$$ (shown in figure C.9 as $\tau_{d,A,2}$)

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_{ef,1} \\ b_2 \end{cases}}$$ (shown in figure C.9 as $\tau_{d,B,1,2}$)

$$\tau_{d,B,2,3} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_2 \\ b_{ef,3} \end{cases}}$$ (shown in figure C.9 as $\tau_{d,B,2,3}$)

$$\tau_{1,d,2} = \min\begin{cases} \tau_{d,B,1,2} \\ \tau_{d,B,2,3} \end{cases}$$

$$\tau_{2,d,2} = \left|\tau_{d,B,1,2} - \tau_{d,B,2,3}\right|$$

if $\tau_{d,A,2} > \frac{\tau_{2,d,2}}{4}$:

$$\tau_{max,d,2} = \tau_{d,A,2} + \tau_{1,d,2} + \frac{\tau_{2,d,2}}{2} + \frac{\tau_{2,d,2}^2}{16 \cdot \tau_{d,A,2}}$$

if $\tau_{d,A,2} \le \frac{\tau_{2,d,2}}{4}$:

$$\tau_{max,d,2} = \tau_{1,d,2} + \tau_{2,d,2}$$

The maximum design shear stress must be compared to the design shear strength of the wooden rib core.

$$\tau_{max,d,2} \le f_{v,d,2}$$

Design shear stress in layer 3 (lower wood-based skin):

$$\tau_{d,A,3} = \frac{E_{m,\perp,0,mean,3} \cdot I_3}{(EI)_A} \cdot Q_{d,A} \cdot \frac{3}{2} \cdot \frac{1}{d_3 \cdot b_{ef,3}}$$ (shown in figure C.9 as $\tau_{d,A,3}$)

$$\tau_{d,B,2,3} = \frac{Q_{d,B}}{(EI)_B} \cdot \frac{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_2 \\ b_{ef,3} \end{cases}}$$ (shown in figure C.9 as $\tau_{d,B,2,3}$)

$$\tau_{d,B,3,4} = 0$$

$$\tau_{1,d,3} = \min\begin{cases} \tau_{d,B,2,3} \\ \tau_{d,B,3,4} \end{cases} = 0$$

$$\tau_{2,d,3} = \left|\tau_{d,B,2,3} - \tau_{d,B,3,4}\right| = \tau_{d,B,2,3}$$

if $\tau_{d,A,3} > \frac{\tau_{2,d,3}}{4} \Leftrightarrow$ if $\tau_{d,A,3} > \frac{\tau_{d,B,2,3}}{4}$:

$$\tau_{max,d,3} = \tau_{d,A,3} + \tau_{1,d,3} + \frac{\tau_{2,d,3}}{2} + \frac{\tau_{2,d,3}^2}{16 \cdot \tau_{d,A,3}} \Leftrightarrow \tau_{max,d,3} = \tau_{d,A,3} + \frac{\tau_{d,B,2,3}}{2} + \frac{\tau_{d,B,2,3}^2}{16 \cdot \tau_{d,A,3}}$$

if $\tau_{d,A,3} \le \frac{\tau_{2,d,3}}{4} \Leftrightarrow$ if $\tau_{d,A,3} \le \frac{\tau_{d,B,2,3}}{4}$:

$$\tau_{max,d,3} = \tau_{1,d,3} + \tau_{2,d,3} \Leftrightarrow \tau_{max,d,3} = \tau_{d,B,2,3}$$

The maximum design shear stress must be compared to the design planar shear strength along the grain of face veneer of the lower wood-based skin.

$$\tau_{d,max,3} \le f_{v,\perp,0,d,3}$$

The wood-based skins are supported by the relatively rigid wooden rib core. Therefore the local wrinkling effect of the skin doesn't occur in the stressed skin panel of type B1 or C1.

C.3.1.7 Fastening of the stressed skin panel to the supporting structure

In case the stressed skin panel is supported by a timber structure, metal fasteners can be used to connect the stressed skin panel to the supporting structure. The panel-to-timber connection must be calculated according to prEN 1995-1-1 [12].

C.3.2 Verification of serviceability limit states

C.3.2.1 Design value of the stiffness properties of each layer *i*

Both virtual beams A and B can now be loaded by combination of actions to be used for verification in the serviceability limit state to determine the maximum total deflection.
The calculated deflection must not exceed the limiting values for the deflection. Some recommendations for limits of deflection are given in prEN 1995-1-1 [12] in absence of more precise information. Specific numerical limits of deflection or slope should in principle be decided by the structural engineer from case to case, depending on the actual situation and the demands of the client.

The final deformation of the stressed skin panel fabricated from members which have different creep properties should be calculated using modified final stiffness moduli ($E_{fin,i}$ and $G_{fin,i}$), which are determined by dividing the instantaneous values of the modulus for each member ($E_{mean,i}$ and $G_{mean,i}$) by the appropriate value of ($1+k_{def,i}$). A load combination which consists of actions belonging to different load duration classes, the contribution of each action to the total deflection should be calculated separately using the appropriate k_{def} values.

Final stiffness properties of each action using the appropriate k_{def} values for <u>virtual beam A</u>:

$$E_{fin,i} = \frac{E_{mean,i}}{1 + \psi_2 \cdot k_{def,i}}$$

concerning the wood-based skin with the grain of face veneer parallel to the span direction:
$E_{mean,i}$ the <u>planar</u> mean modulus of elasticity for bending along the grain of face veneer $E_{m,\perp,0,mean}$.
concerning the wooden rib core:
$E_{mean,i}$ the mean modulus of elasticity along the grain $E_{0,mean}$.

Final stiffness properties of each action using the appropriate k_{def} values for <u>virtual beam B</u>:

$$E_{fin,i} = \frac{E_{mean,i}}{1 + \psi_2 \cdot k_{def,i}}$$

The shear moduli and the slip moduli of the connections should also be modified using the modification factor k_{def}.

$$G_{fin,i} = \frac{G_{mean,i}}{1 + \psi_2 \cdot k_{def,i}} \; ; \quad c_{fin,i} = \frac{\sum_{i=1}^{n-1} c_i}{1 + \psi_2 \cdot k_{def}}$$

concerning the wood-based skin:

$E_{mean,i}$ the <u>in-plane</u> mean modulus of elasticity for compression or tension along the grain of face veneer $E_{t(c),//,0,mean}$.

$G_{mean,i}$ the <u>planar</u> mean shear modulus along the grain of face veneer $G_{\perp,0,mean}$.

concerning the wooden rib core:

$E_{mean,i}$ the mean modulus of elasticity along the grain $E_{0,mean}$.

$G_{mean,i}$ the mean shear modulus G_{mean}.

ψ_2 a factor for the quasi-permanent value of a variable action. For permanent actions, ψ_2 should be taken equal to 1,00.

c_i the slip modulus between the layers of the stressed skin panel.

C.4 Model for a stressed skin panel, open box type single-skin, *with* wooden ribs and (non)-loadbearing insulation (type B2 and C2)

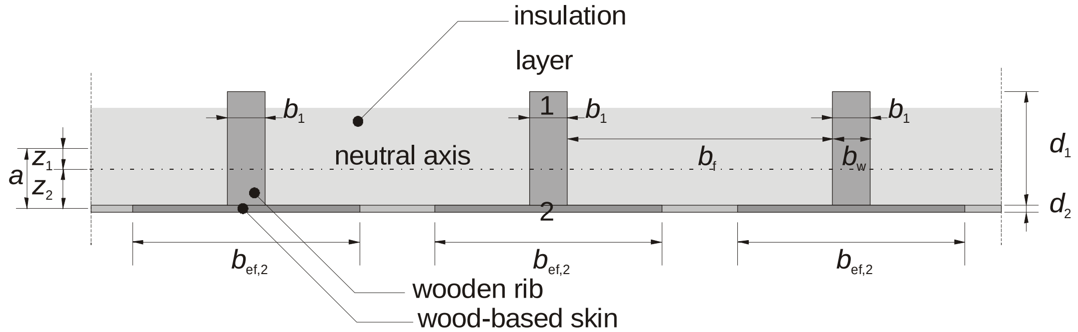


Figure C.11 - E.g. cross-section of the two layers single-skin stressed skin panel *with* wooden ribs and (non)-loadbearing insulation

In this example the main direction of the wood-based skin (the grain direction of face veneer) is parallel to the span direction. For wood-based skins like OSB or plywood the material properties parallel and perpendicular to the grain direction of face veneer are different.

C.4.1 Verification of ultimate limit states

The design strength values must be calculated according to prEN 1995-1-1 [12]. Some characteristic and mean values of the material properties are given in chapter 5.

C.4.1.1 Effective flange width b_{ef} of the wood-based skin

C.4.1.1.1 With non-loadbearing (unstiff) insulation (type C2)

In case the space between the wooden ribs consists of non-loadbearing (unstiff) insulation the effective flange width should be taken from table 3.1 of the prEN 1995-1-1. The minimum value between the columns due to the shear lag and due to the plate buckling should be taken.

	$b_{ef,l}$	
Flange material	Shear lag[3]	Plate buckling[4]
Plywood, with grain direction in the outer plies:		
• parallel to the webs	$0{,}10 \cdot \lambda$	$20 \cdot h_{f,l}$
• perpendicular to the webs	$0{,}10 \cdot \lambda$	$25 \cdot h_{f,l}$
OSB	$0{,}15 \cdot \lambda$	$25 \cdot h_{f,l}$
Particleboard	$0{,}20 \cdot \lambda$	$30 \cdot h_{f,i}$

Table C.2 - Maximum effective flange widths due to the effect of shear lag and plate buckling according to prEN 1995-1-1

The center-to-center distance of the wooden ribs should not exceed 600 mm.

Remark:
Type C2 can also be calculated by the EC 5 method.

[3] λ = span of beam
[4] $h_{f,i}$ = thickness of flange (of wood-based skin layer *i*)

C.4.1.1.2 With loadbearing (stiff) insulation, glued to the wood-based skins (type B2)

The wood-based skin is supported by the loadbearing (stiff) insulation core. The effect of plate buckling may be disregarded. The analytical solution for the maximum effective flange widths due to the effect of shear lag is independent of the type of insulation because it only takes into account shear lag and no plate buckling and therefore may be used also for open box type single-skin stressed skin panels. Effective flange width of the wood-based skins:

$$\frac{b_{\mathrm{ef,i}} - b_{\mathrm{w}}}{b_{\mathrm{f}}} = \frac{2 \cdot \lambda \cdot \left(\lambda_{1,\mathrm{i}} \cdot \tanh\alpha_{1,\mathrm{i}} - \lambda_{2,\mathrm{i}} \cdot \tanh\alpha_{2,\mathrm{i}}\right)}{\pi \cdot b_{\mathrm{f}} \cdot \left(\lambda_{1,\mathrm{i}}^2 - \lambda_{2,\mathrm{i}}^2\right)}$$

where:

$$\alpha_{1,\mathrm{i}} = \frac{\lambda_{1,\mathrm{i}} \cdot \pi \cdot b_{\mathrm{f}}}{2 \cdot \lambda}$$

$$\alpha_{2,\mathrm{i}} = \frac{\lambda_{2,\mathrm{i}} \cdot \pi \cdot b_{\mathrm{f}}}{2 \cdot \lambda}$$

$$\lambda_{1,\mathrm{i}} = \sqrt{a_{\mathrm{i}} + \sqrt{a_{\mathrm{i}}^2 - c_{\mathrm{i}}}}$$

$$\lambda_{2,\mathrm{i}} = \sqrt{a_{\mathrm{i}} - \sqrt{a_{\mathrm{i}}^2 - c_{\mathrm{i}}}}$$

$$a_{\mathrm{i}} = \frac{E_{\mathrm{t(c),//,90,mean,i}}}{2 \cdot G_{//,\mathrm{mean,i}}} - \mu_{\mathrm{i}}$$

$$c_{\mathrm{i}} = \frac{E_{\mathrm{t(c),//,90,mean,i}}}{E_{\mathrm{t(c),//,0,mean,i}}}$$

λ	the span of the beam.
b_{f}	the web spacing.
b_{w}	the rib width.
$E_{\mathrm{t(c),//,0,mean,i}}$	the <u>in-plane</u> mean modulus of elasticity along the grain of face veneer for compression or tension of wood-based skin layer *i*.
$E_{\mathrm{t(c),//,90,mean,i}}$	the <u>in-plane</u> mean modulus of elasticity perpendicular to the grain of face veneer for compression or tension of wood-based skin layer *i*.
$G_{//,\mathrm{mean,i}}$	the <u>in-plane</u> mean shear modulus of wood-based skin layer *i*.
μ_{i}	the <u>in-plane</u> Poisson’s ratio of wood-based skin layer *i*.

C.4.1.2 Virtual beam A

Virtual beam A contains the own bending stiffness of the two layers:

$$(EI)_{\mathrm{A}} = \sum_{\mathrm{i}=1}^{2} E_{\mathrm{m},\perp,0,\mathrm{mean,i}} \cdot I_{\mathrm{i}}$$

where:

$$I_1 = \frac{b_1 \cdot d_1^3}{12} \qquad \text{(for the wooden rib)}$$

$$I_2 = \frac{b_{\mathrm{ef},2} \cdot d_2^3}{12} \qquad \text{(for the wood-based skin and } b_{\mathrm{ef},2} \text{ according to C.4.1.1)}$$

concerning the upper wooden rib:

$E_{\mathrm{m},\perp,0,\mathrm{mean,i}}$ the mean modulus of elasticity along the grain $E_{0,\mathrm{mean}}$.

concerning the lower wood-based skin:

$E_{\mathrm{m},\perp,0,\mathrm{mean,i}}$ the <u>planar</u> mean modulus of elasticity along the grain of face veneer for bending.

The shear stiffness of virtual beam A is assumed to be infinite.

C.4.1.3 Virtual beam B

Virtual beam B contains the Steiner bending stiffness:

$$(EI)_B = \sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i^2 \qquad \text{(Steiner bending stiffness)}$$

The shear stiffness should also be taken into account for slender webs and small λ/h-ratios. In these cases, the shear stiffness might influence the stress distribution and the deformation.
In this example the wood-based skins are glued to the wooden ribs. Therefore the connection between flange and web is assumed to be infinitely stiff. Because the factor of co-operation is assumed to be 1,00 the term $\sum_{i=1}^{n-1} \frac{1}{c_i}$ in the general equation for the shear stiffness (see also C.1.2.3) is neglected.
If the connection between skin and wooden rib is made of mechanical fasteners, the factor of co-operation is less than 1,00 and the slip stiffness due to mechanical fastening has to be taken into account by the term $\sum_{i=1}^{n-1} \frac{1}{c_i}$. The slip stiffness can be calculated according to EC 5. The total number of layers should then not exceed 5.

$$\frac{1}{(GA)_B} = \frac{1}{S} = \frac{1}{a^2} \cdot \left(\frac{d_1}{2 \cdot G_{mean,1} \cdot b_1} + \frac{d_2}{2 \cdot G_{\perp,0,mean,2} \cdot b_{ef,2}} \right) \qquad \text{(finite shear stiffness)}$$

where:

$A_1 = b_1 \cdot d_1$ (for the wooden rib)

$A_2 = b_{ef,2} \cdot d_2$ (for the wood-based skin and $b_{ef,2}$ according to C.4.1.1)

concerning the upper wooden rib:

$E_{t(c),//,0,mean,i}$ the mean modulus of elasticity along the grain $E_{0,mean}$.

$G_{mean,1}$ the mean shear modulus.

concerning the lower wood-based skin:

$E_{t(c),//,0,mean,i}$ the in-plane mean modulus of elasticity along the grain of face veneer for compression or tension.

$G_{\perp,0,mean,2}$ the planar mean shear modulus along the grain of face veneer.

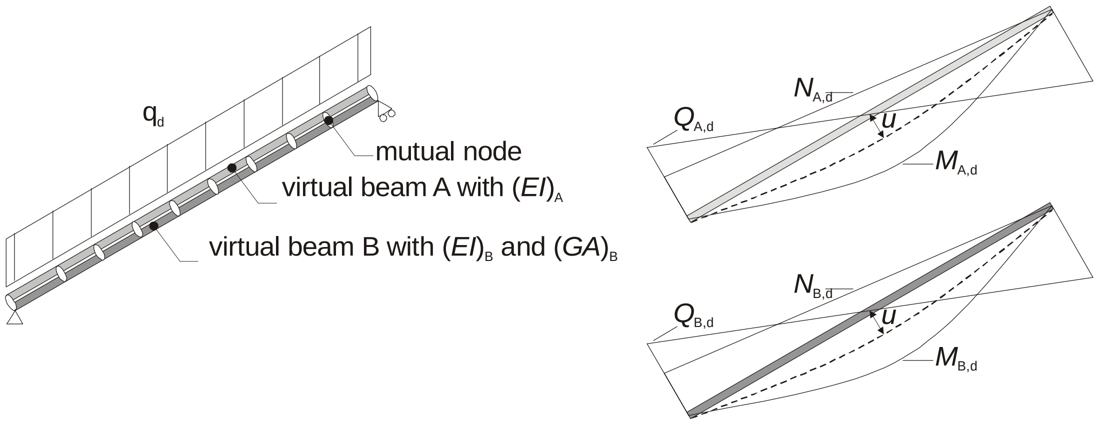


Figure C.12 - E.g. a simply supported Kreuzinger beam of type B2 or C2

In figure C.11 a design example is given. The stressed skin panel of type B2 or C2 is now described as a virtual beam A with the own bending stiffness $(EI)_A$ and a virtual beam B with the Steiner bending stiffness $(EI)_B$. Both beams are placed parallel to each other and they are connected with mutual nodes.

The combined virtual beams A and B can now be loaded by design combination of actions (see chapter 6) to determine the maximum design internal forces.
The calculated virtual design bending, shear and axial forces ($M_{d,A}$, $Q_{d,A}$, $N_{d,A}$, $M_{d,B}$, $Q_{d,B}$, $N_{d,B}$) are then translated to the design bending, axial and shear stresses in each different layer *i*.

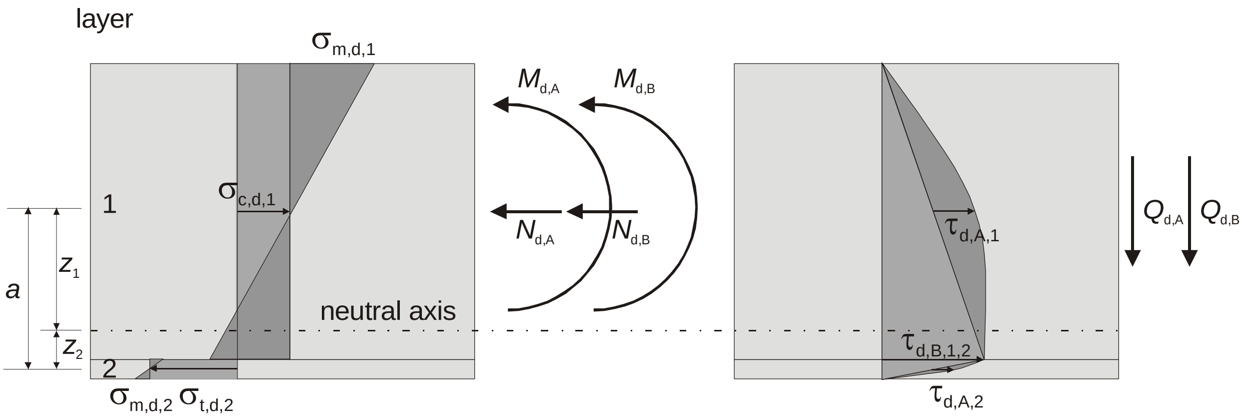


Figure C.13 - Stresses in the stressed skin panel of type B2 or C2

C.4.1.4 Design compression or tension stress in combination with bending stress

From the calculated virtual design bending and axial forces $M_{d,A}$; $N_{d,A}$; $M_{d,B}$ and $N_{d,B}$:

Depending on the direction of the moment $M_{d,B}$ and the axial forces $N_{d,A}$ and $N_{d,B}$ in the structure, every layer can experience compression or tension stress. In this example we assume that the upper wooden rib experiences compression and the lower wood-based skin experiences tension.

Design bending stress in layer 1 (upper wooden rib):

$$M_{d,1} = \frac{E_{0,mean,1} \cdot I_1}{(EI)_A} \cdot M_{d,A} \quad \Rightarrow \quad \sigma_{m,d,1} = \frac{M_{d,1}}{W_1}$$ (shown in figure C.12 as $\sigma_{m,d,1}$)

where:

$$W_1 = \frac{b_1 \cdot d_1^2}{6}$$ (for the wooden rib)

Design compression stress in layer 1 (upper wooden rib):

$$N_{d,1} = \frac{E_{0,mean,1} \cdot A_1 \cdot z_1}{(EI)_B} \cdot M_{d,B} + \frac{E_{0,mean,1} \cdot A_1}{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i} \cdot \left(N_{d,A} + N_{d,B}\right) \Rightarrow \sigma_{c,d,1} = \frac{N_{d,1}}{A_1}$$ (shown in figure C.12 as $\sigma_{c,d,1}$)

The maximum combined design compression and bending stress must be compared to the combined design compression and bending strength along the grain of the upper wooden rib.

$$\left(\frac{\sigma_{c,d,1}}{f_{c,0,d,1}}\right)^2 + \frac{\sigma_{m,d,1}}{f_{m,d,1}} \leq 1{,}00$$

Design bending stress in layer 2 (lower wood-based skin):

$$M_{d,2} = \frac{E_{m,\perp,0,mean,2} \cdot I_2}{(EI)_A} \cdot M_{d,A} \quad \Rightarrow \quad \sigma_{m,d,2} = \frac{M_{d,2}}{W_2}$$ (shown in figure C.12 as $\sigma_{m,d,2}$)

where:

$$W_2 = \frac{b_{ef,2} \cdot d_2^2}{6}$$ (for the wood-based skin and $b_{ef,2}$ according to §4.1.1)

Design tension stress in layer 2 (lower wood-based skin):

$$N_{d,2} = \frac{E_{t(c),//,0,mean,2} \cdot A_2 \cdot z_2}{(EI)_B} \cdot M_{d,B} + \frac{E_{t(c),//,0,mean,2} \cdot A_2}{\sum_{i=1}^{2} E_{t(c),//,0,mean,i} \cdot A_i} \cdot \left(N_{d,A} + N_{d,B}\right) \Rightarrow \sigma_{t,d,2} = \frac{N_{d,2}}{A_2}$$ (shown in figure C.12 as $\sigma_{t,d,2}$)

The maximum combined design tension and bending stress must be compared to the combined design in-plane tension strength along the grain of face veneer and the design planar bending strength along the grain of face veneer of the lower wood-based skin.

$$\frac{\sigma_{t,d,2}}{f_{t,//,0,d,2}} + \frac{\sigma_{m,d,2}}{f_{m,\perp,0,d,2}} \leq 1{,}00$$

C.4.1.5 Design shear stress at interface of adjoining layers

From the calculated virtual design shear force $Q_{d,B}$:

Design shear stress at interface of adjoining layers 1 and 2:

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{EI_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_1 \\ b_{ef,2} \end{cases}}$$ (shown in figure C.12 as $\tau_{d,B,1,2}$)

The maximum design shear stress at interface of adjoining layers 1 and 2 must be compared to the minimum value of the design shear strength of layer 1 (upper wooden rib) or the design planar shear strength along the grain of face veneer of layer 2 (lower wood-based skin).

$$\tau_{d,B,1,2} \leq \min\begin{cases} f_{v,d,1} \\ f_{v,\perp,0,d,2} \end{cases}$$

C.4.1.6 Design shear stress

From the calculated virtual design shear forces $Q_{d,A}$ and $Q_{d,B}$:

Design shear stress in layer 1 (upper wooden rib):

$$\tau_{d,A,1} = \frac{E_{0,mean,1} \cdot I_1}{(EI)_A} \cdot Q_{d,A} \cdot \frac{3}{2} \cdot \frac{1}{d_1 \cdot b_1}$$ (shown in figure C.12 as $\tau_{d,A,1}$)

$$\tau_{d,B,0,1} = 0$$

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{EI_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_1 \\ b_{ef,2} \end{cases}}$$ (shown in figure C.12 as $\tau_{d,B,1,2}$)

$$\tau_{1,d,1} = \min\begin{cases} \tau_{d,B,0,1} \\ \tau_{d,B,1,2} \end{cases} = 0$$

$$\tau_{2,d,1} = \left|\tau_{d,B,0,1} - \tau_{d,B,1,2}\right| = \tau_{d,B,1,2}$$

$$\text{if } \tau_{d,A,1} > \frac{\tau_{2,d,1}}{4} \Leftrightarrow \text{if } \tau_{d,A,1} > \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,1} = \tau_{d,A,1} + \tau_{1,d,1} + \frac{\tau_{2,d,1}}{2} + \frac{\tau_{2,d,1}^2}{16 \cdot \tau_{d,A,1}} \Leftrightarrow \tau_{max,d,1} = \tau_{d,A,1} + \frac{\tau_{d,B,1,2}}{2} + \frac{\tau_{d,B,1,2}^2}{16 \cdot \tau_{d,A,1}}$$

$$\text{if } \tau_{d,A,1} \le \frac{\tau_{2,d,1}}{4} \Leftrightarrow \text{if } \tau_{d,A,1} \le \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,1} = \tau_{1,d,1} + \tau_{2,d,1} \Leftrightarrow \tau_{max,d,1} = \tau_{d,B,1,2}$$

The maximum design shear stress must be compared to the design shear strength of the upper wooden rib.

$$\tau_{max,d,1} \le f_{v,d,1}$$

<u>Design shear stress in layer 2 (lower wood-based skin):</u>

$$\tau_{d,A,2} = \frac{E_{m,\perp,0,mean,2} \cdot I_2}{(EI)_A} \cdot Q_{d,A} \cdot \frac{3}{2} \cdot \frac{1}{d_2 \cdot b_2}$$ (shown in figure C.12 as $\tau_{d,A,2}$)

$$\tau_{d,B,1,2} = \frac{Q_{d,B}}{EI_B} \cdot \frac{\sum_{i=1}^{1} E_{t(c),//,0,mean,i} \cdot A_i \cdot z_i}{\min\begin{cases} b_1 \\ b_{ef,2} \end{cases}}$$ (shown in figure C.12 as $\tau_{d,B,1,2}$)

$$\tau_{d,B,2,3} = 0$$

$$\tau_{1,d,2} = \min\begin{cases} \tau_{d,B,1,2} \\ \tau_{d,B,2,3} \end{cases} = 0$$

$$\tau_{2,d,2} = \left|\tau_{d,B,1,2} - \tau_{d,B,2,3}\right| = \tau_{d,B,1,2}$$

$$\text{if } \tau_{d,A,2} > \frac{\tau_{2,d,2}}{4} \Leftrightarrow \text{if } \tau_{d,A,2} > \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,2} = \tau_{d,A,2} + \tau_{1,d,2} + \frac{\tau_{2,d,2}}{2} + \frac{\tau_{2,d,2}^2}{16 \cdot \tau_{d,A,2}} \Leftrightarrow \tau_{max,d,2} = \tau_{d,A,2} + \frac{\tau_{d,B,1,2}}{2} + \frac{\tau_{d,B,1,2}^2}{16 \cdot \tau_{d,A,2}}$$

$$\text{if } \tau_{d,A,2} \le \frac{\tau_{2,d,2}}{4} \Leftrightarrow \text{if } \tau_{d,A,2} \le \frac{\tau_{d,B,1,2}}{4}:$$

$$\tau_{max,d,2} = \tau_{1,d,2} + \tau_{2,d,2} \Leftrightarrow \tau_{max,d,2} = \tau_{d,B,1,2}$$

The maximum design shear stress must be compared to the design planar shear strength along the grain of face veneer of the lower wood-based skin.

$$\tau_{d,max,2} \le f_{v,\perp,0,d,2}$$

The wood-based skin is supported by the relatively stiff wooden rib. Therefore the local wrinkling effect of the skin doesn’t occur in the stressed skin panel of type B2 or C2.

C.4.1.7 Fastening of the stressed skin panel to the supporting structure

In case the stressed skin panel is supported by a timber structure, metal fasteners can be used to connect the stressed skin panel to the supporting structure. The stressed skin panel of type B2 or C2 should be fastened by connecting the wooden ribs to the supporting timber structure. The timber-to-timber connection must be calculated according to prEN 1995-1-1 [12].

C.4.2 Verification of serviceability limit states

C.4.2.1 Design value of the stiffness properties of each layer *i*

Both virtual beams A and B can now be loaded by combination of actions to be used for verification in the serviceability limit state to determine the maximum total deflection.
The calculated deflection must not exceed the limiting values for the deflection. Some recommendations for limits of deflection are given in prEN 1995-1-1 [12] in absence of more precise information. Specific numerical limits of deflection or slope should in principle be decided by the structural engineer from case to case, depending on the actual situation and the demands of the client.

The final deformation of the stressed skin panel fabricated from members which have different creep properties should be calculated using modified final stiffness moduli ($E_{fin,i}$ and $G_{fin,i}$), which are determined by dividing the instantaneous values of the modulus for each member ($E_{mean,i}$ and $G_{mean,i}$) by the appropriate value of ($1+k_{def,i}$).
A loadcombination which consists of actions belonging to different load duration classes, the contribution of each action to the total deflection should be calculated separately using the appropriate k_{def} values.

Final stiffness properties of each action using the appropriate k_{def} values for virtual beam A:

$$E_{fin,i} = \frac{E_{mean,i}}{1+\psi_2 \cdot k_{def,i}}$$

concerning the wood-based skin with the grain of face veneer parallel to the span direction:

- $E_{mean,i}$ — the planar mean modulus of elasticity for bending along the grain of face veneer $E_{m,\perp,0,mean}$.

concerning the wooden rib core:

- $E_{mean,i}$ — the mean modulus of elasticity along the grain $E_{0,mean}$.

Final stiffness properties of each action using the appropriate k_{def} values for virtual beam B:

$$E_{fin,i} = \frac{E_{mean,i}}{1+\psi_2 \cdot k_{def,i}}$$

The shear moduli and the slip moduli of the connections should also be modified using the modification factor k_{def}.

$$G_{fin,i} = \frac{G_{mean,i}}{1+\psi_2 \cdot k_{def,i}} \; ; \quad c_{fin,i} = \frac{\sum_{i=1}^{n-1} c_i}{1+\psi_2 \cdot k_{def}}$$

concerning the wood-based skin:

- $E_{mean,i}$ — the in-plane mean modulus of elasticity for compression or tension along the grain of face veneer $E_{t(c),//,0,mean}$.
- $G_{mean,i}$ — the planar mean shear modulus along the grain of face veneer $G_{\perp,0,mean}$.

concerning the wooden rib core:

- $E_{mean,i}$ — the mean modulus of elasticity along the grain $E_{0,mean}$.
- $G_{mean,i}$ — the mean shear modulus G_{mean}.
- ψ_2 — a factor for the quasi-permanent value of a variable action. For permanent actions, ψ_2 should be taken equal to 1,00.

- c_i — the slip modulus between the layers of the stressed skin panel.

C.5 Recommendations

C.5.1 General

The general theoretical model to calculate a composite element is developed by Prof. Dr.-Ing. H. Kreuzinger [1]. The Kreuzinger model describes the behaviour of the stressed skin panels when they are mainly loaded perpendicular to their plane, e.g. when they are used in roofs. Prof. Dr.-Ing. H.J. Blass [2] adapted the general model to a suitable model to calculate a timber-concrete composite floor element.
With the help of this example, several models have been developed for different types of prefabricated loadbearing wood-based stress skin panel, to be used in roofs. The general model has been adapted to avoid, for each type of stressed skin panel, the specific singularity problems[5] in the matrix operations.

In case one or more members of the composite stressed skin panel contains a finite shear stiffness, the shear deflection is taken into account by the Kreuzinger model. This is valid, when the stressed skin panel of type A is used.

The results of the calculations have been verified in two different ways:
1. Analytical calculations according to the Langlie method [4].
2. Independent F.E.M.[6]-calculations with the program ANSYS (version 5.3).

In comparison with experimental results the calculation results, based on the Kreuzinger model, are safe.

When the principle of the Kreuzinger beam is implemented in a F.E.M. calculation program, one can achieve very fast calculation of the stressed skin panel with the following advantages:

- A database of load cases and load combinations, with the relevant load factors.
- The freedom of the structure geometry.
- A material database with all relevant material properties and material factors.

In case of the stressed skin panel of type A the applied F.E.M. program must be able to calculate shear deflection.

The calculation of these stressed skin panels, to be used in roofs, is made with the consideration that partly the stressed skin panel is in the outside climate and partly it is in the inside climate.
The choice of the appropriate service class is recommended as follows:
Service class 2 for the outer wood-based skin and service class 1 for the remaining components.

C.5.2 Standards and codes

In general the characteristic and mean values of the material properties are defined in each Member State's National Application Document.

C.5.2.1 Concerning the wood-based skin

At this moment the characteristic and mean values of the material properties are also defined in the European Standard EN 12369-1: 2000.
The appropriate material factors (γ_M, k_{mod}, k_{def}) are now defined in the prEN 1995-1-1 [12]: Eurocode 5: 2002.

C.5.2.2 Concerning the wooden rib core

At this moment the characteristic and mean values of the material properties are also defined in the European Standard EN 338 and EN 1194.
The appropriate material factors (γ_M, k_{mod}, k_{def}) are defined in the prEN 1995-1-1 [12]: Eurocode 5: 2002.

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[5] Singularity problems occur when several stiffnesses are used in the model and the difference between the stiffnesses is so large that small values (almost zero) appear in the F.E.M. matrix.

[6] F.E.M.: Finite Element Method

C.5.2.3 Concerning the loadbearing insulation core

Characteristic values of the material properties are partly defined in the European Standards EN 13163 (EPS) and EN 13164 (XPS).
The appropriate material factors (γ_M, k_{mod}, k_{def}) are missing in the Eurocodes, so they are to be determined by testing according to prEN 14509.

C.5.2.4 Concerning the ultimate limit state

The general forces (bending, compression, tension, shear) can be verified according to the Design Code prEN1995-1-1 [12]: Eurocode 5: 2002.
In case of the stressed skin panel of type A: the verification of the local phenomena, as the wrinkling stress of the wood-based skin and the compression stress of the loadbearing insulation core at a support, is missing in the Eurocode.
For now, the verification of the wrinkling stress at a support is based on the theory of ir. H.P.v. Amstel, published by SKH [5] (the Netherlands) and the verification of the compression stress at a support is based on the ECCS / CIB Report Publication 257 [13] (Europe).
The wrinkling stress may be calculated by the wellknown formula of Plantema [3] too.

C.5.2.5 Confusing new prEN1995-1-1: Eurocode 5 with a different order of chapters

With the NVN-ENV 1995-1-1, version 1993 [9;10;11] by CEN a uniform layout has been used for all Member States. The latest prEN 1995-1-1, version 2002 [12] by CEN has a new order of chapters and there has been essential changes in calculation formulations.
The German draft E DIN 1052:2000 has combined the prEN 1995-1-1 and their N.A.D. [8] into one design code with another order of chapters.
Differences in the calculation formulations can be found when comparing the several versions of Eurocode 5 with each other.

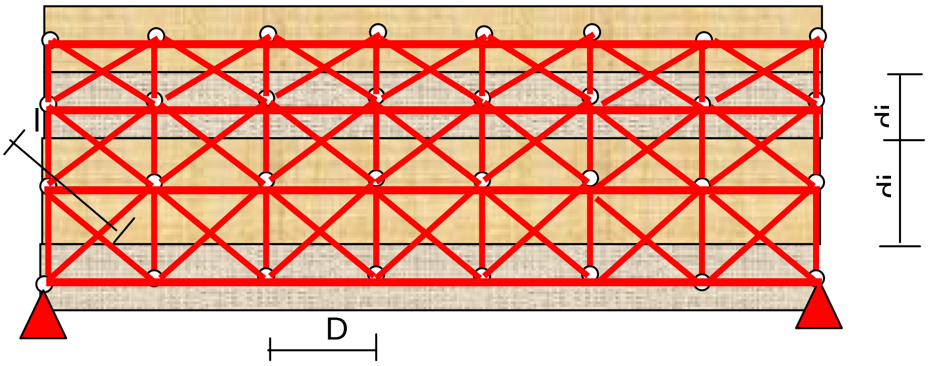
In this report we refer to the CEN-version prEN 1995-1-1, 09-10-2002 [12].
In the end the calculation must be made according to the definitive version of the CEN.

When using this calculation model in practice, the material properties should be used conforming the latest EN standards and codes, or by test results conforming EN standards and codes.

Annex D Model N

(Informative)

A somewhat more complicated, but universal calculation model for the composite cross-section could be as follows:



If the posts of this multi-member truss are designed to be rigid, for example by calculating with Ap=Dl*(di+di+1)/2, and if the influence of the expansions of the truss flanges on the shear stiffness is neglected, the shear stiffness between two layers is

$$S = G\frac{2t_{ideell}}{(d_i + d_{i+1})}$$

$$t_{ideell} = \frac{E}{G}\frac{\Delta l(d_i + d_{i+1})}{2\frac{l_d^3}{2A_d}}$$

$$S = E\frac{2\Delta l A_d}{l_d^3}$$

$$\frac{1}{S} = \frac{1}{C_{i,i+1}} + \frac{d_i}{2G_i b_i} + \frac{d_{i+1}}{2G_{i+1}b_{i+1}}$$

$$A_d = \frac{l_d^3}{2\Delta l E}\frac{1}{\frac{1}{C_{i,i+1}} + \frac{d_i}{2G_i b_i} + \frac{d_{i+1}}{2G_{i+1}b_{i+1}}}$$

l_d= length of diagonals
A_d= area of diagonals
E= E-modulus of the diagonals (free to chose)

By means of the area of the diagonals each truss plane can be adapted to the shear stiffness between two loadbearing layers of the composite cross-section. The skins pass through the entire length of the composite beam without intermediate hinge.

The fact that more time and work is needed for the system is partly compensated by the result, which means that the stresses calculated with this system are already the resulting stresses.

Further, by entering a shear stiffness of the "layered beams", it is possible to take account of the shear deformation resulting from the proportionate transverse force of the relevant layers.

It is pointed out that for all systems, where the flexibility of the bond does not affect the action-effects of the composite beam, or for sandwich beams with two skins having a small own bending stiffness, the complicated calculation with the equivalent truss system and the decomposition of the system into virtual beams can be omitted.

Annex E Material properties

(Informative)

E.1 In general

Three material types can be used in prefabricated wood-based loadbearing stressed skin panel:
1. Wood-based skins (e.g. particleboard, oriented stranded board, plywood)
2. Loadbearing insulation core (e.g. expanded/extruded polystyrene, polyurethane)
3. Wooden rib core (e.g. solid timber, glued laminated timber, laminated veneer lumber)

In common the prEN 1995-1-1 provides no data on strength and stiffness properties for structural materials. There are European standards which provide strength class systems, e.g. the EN 338 strength class system for solid timber and the EN 1194 strength class system for glued laminated timber.
Besides each Member State can use, in conjunction with the particular National Application Document, the local strength classes with their local names. These values are to be considered as standard values for the country where the designed structure are to be located.
New material can be used on condition that the characteristic and mean strength and stiffness values of the material property are known, which are necessary in the Kreuzinger model and that the material belongs to one of the three material types, which is mentioned above.
Strength and stiffness parameters can also be determined on the basis of tests, in accordance with the appropriate European standard or on well-established relations between the different properties.

The design value X_d of a material property with the characteristic strength value X_k in the ultimate limit state is defined as:

$$X_d = k_{mod} \cdot \frac{X_k}{\gamma_M}$$

where:

- γ_M the partial safety factor for the material property
- k_{mod} the modification factor taken into account the effect on the strength parameters of the duration of the actions and the moisture content.

The final value X_{fin} of a material property with the mean stiffness value X_{mean} in the serviceability limit state is defined as:

$$X_{fin} = \frac{X_{mean}}{1 + \psi_2 \cdot k_{def}}$$

where:

- k_{def} the modification factor, to calculate the creep influence, taken into account the effect on the stiffness parameters of the duration of the actions and the moisture content.
- ψ_2 a factor for the quasi-permanent value of a variable action. For permanent actions, ψ_2 should be taken equal to 1,00.

The values for the material properties in the following paragraphs are data which are available at this moment. They can be seen as boxed values, which in time can be replaced by more accurate values.
As soon as the missing factors and verifications are present in new Eurostandards and/or -codes, the calculation must be made according to these latest standards and/or codes.
It is also possible to measure the material properties of a certain product conforming existing European Standards (EN) to specify the specific characteristic and main values of this certain product.

When using this calculation model in practice, the material properties should be used conforming the latest EN standards and codes, or by test results conforming EN standards and codes.

E.2 Wood-based skins

Examples of wood-based skins are: particleboard, oriented stranded board / grade 3 and plywood.

E.2.1 Particleboard synthetic bonded according to EN 312-5

E.2.1.1 Material properties

Characteristic and mean values are taken from the EN 12369-1.
The particleboard is here classified according to EN 312 part 5.

Particleboard acc. EN 12369-1		Thickness range [mm]					
Material properties		> 6-13	> 13-20	> 20-25	>25-32	>32-40	> 40
Strength in N/mm²							
Planar (⊥)							
Bending	$f_{m,\perp,k}$	14,2	12,5	10,8	9,2	7,5	5,8
shear	$f_{v,\perp,k}$	1,8	1,6	1,4	1,2	1,1	1,0
In-plane (//)							
Tension	$f_{t,//,k}$	8,9	7,9	6,9	6,1	5,0	4,4
Compression	$f_{c,//,k}$	12,0	11,1	9,6	9,0	7,6	6,1
Stiffness in N/mm²							
Planar (⊥)							
E-modulus	$E_{m,\perp,mean}$	3200	2900	2700	2400	2100	1800
G-modulus	$G_{\perp,mean}$	200	200	200	100	100	100
In-plane (//)							
E-modulus	$E_{t(c),//,mean}$	1800	1700	1600	1400	1200	1100
G-modulus	$G_{//,mean}$	860	830	770	680	600	550
Density in kg/m³							
Density	ρ_k	650	600	550	550	500	500
In-plane (//)							
Poisson's ratio	μ	0,24	0,24	0,24	0,24	0,24	0,24

E.2.1.2 Ultimate limit states

Partial factor for material properties according to prEN 1995-1-1 [12]:

$\gamma_M = 1{,}30$

Strength modification factor: k_{mod} according to prEN 1995-1-1 [12], effecting the strength parameters and depending on the load duration and the moisture content in the structure for particleboard according to EN 312 part 5.

Load duration class	Service class	
	1	2
Permanent	0,30	0,20
Long-term	0,45	0,30
medium-term	0,65	0,45
short-term	0,85	0,60
instantaneous	1,10	0,80

E.2.1.3 Serviceability limit states

Deformation modification factor: k_{def} according to prEN 1995-1-1 [12], effecting the stiffness parameters to calculate the creep influence and depending on the load duration and the moisture content in the structure for particleboard according to EN 312 part 5.

Load duration class	Service class	
	1	2
Permanent	2,25	3,00

E.2.2 OSB/3 (Oriented Strand Board / grade 3)

E.2.2.1 Material properties

Characteristic and mean values are taken from the EN 12369-1.
The OSB is here classified according to EN 300 OSB/3.

OSB/3 acc. EN 300		**along grain of face veneer (0)** Thickness range [mm]				**perp. to grain of face veneer (90)** Thickness range [mm]		
Material properties		> 6-10	>10-18	> 18-25		> 6-10	>10-18	> 18-25
Strength in N/mm²								
Planar (⊥)								
Bending	$f_{m,\perp,0,k}$	18,0	16,4	14,8	$f_{m,\perp,90,k}$	9,0	8,2	7,4
shear	$f_{v,\perp,0,k}$	1,0	1,0	1,0	$f_{v,\perp,90,k}$	0,5	0,5	0,5
In-plane (//)								
Tension	$f_{t,//,0,k}$	9,9	9,4	9,0	$f_{t,//,90,k}$	7,2	7,0	6,8
Compression	$f_{c,//,0,k}$	15,9	15,4	14,8	$f_{c,//,90,k}$	12,9	12,7	12,4
Stiffness in N/mm²								
Planar (⊥)								
E-modulus	$E_{m,\perp,0,mean}$	4930	4930	4930	$E_{m,\perp,90,mean}$	1980	1980	1980
G-modulus	$G_{\perp,0,mean}$	100	100	100	$G_{\perp,90,mean}$	50	50	50
In-plane (//)								
E-modulus	$E_{t(c),//,0,mean}$	3800	3800	3800	$E_{t(c),//,90,mean}$	3000	3000	3000
G-modulus	$G_{//,mean}$	1080	1080	1080	$G_{//,mean}$	1080	1080	1080
Density in kg/m³								
Density	ρ_k	550	550	550	ρ_k	550	550	550
In-plane (//)								
Poisson's ratio	μ	0,24	0,24	0,24	μ	0,24	0,24	0,24

E.2.2.2 Ultimate limit states

Partial factor for material properties according to prEN 1995-1-1[12]:

γ_M = 1,20

Strength modification factor: k_{mod} according to prEN 1995-1-1 [12], effecting the strength parameters and depending on the load duration and the moisture content in the structure for OSB/3 according to EN 300.

Load duration class	Service class 1	2
Permanent	0,40	0,30
long-term	0,50	0,40
medium-term	0,70	0,55
short-term	0,90	0,70
instantaneous	1,10	0,90

E.2.2.3 Serviceability limit states

Deformation modification factor: k_{def} according to prEN 1995-1-1 [12], effecting the stiffness parameters to calculate the creep influence and depending on the load duration and the moisture content in the structure for OSB/3 according to EN 300.

Load duration class	Service class 1	2
Permanent	1,50	2,25

E.2.3 Plywood

E.2.3.1 Material properties

Characteristic and mean values are taken from the German standard, mentioned in the draft E DIN 1052 [8]. The plywood is here classified according to EN 636-2.

Plywood acc. DIN 68705-3 Material properties		**along grain of face veneer (0)**		**perpendicular to grain of face veneer (90)**
Strength in N/mm²				
Planar (⊥)				
Bending	$f_{m,\perp,0,k}$	32	$f_{m,\perp,90,k}$	12
shear	$f_{v,\perp,0,k}$	2,5	$f_{v,\perp,90,k}$	2,5
In-plane (//)				
Compression	$f_{c,//,0,k}$	18	$f_{c,//,90,k}$	9
Tension	$f_{t,//,0,k}$	18	$f_{t,//,90,k}$	9
Stiffness in N/mm²				
Planar (⊥)				
E-modulus	$E_{m,\perp,0,mean}$	5500	$E_{m,\perp,90,mean}$	1500
G-modulus	$G_{\perp,0,mean}$	250	$G_{\perp,90,mean}$	250
In-plane (//)				
E-modulus	$E_{t(c),//,0,mean}$	4500	$E_{t(c),//,90,mean}$	2500
G-modulus	$G_{//,mean}$	500	$G_{//,mean}$	500
Density in kg/m³				
Density	ρ_k	400	ρ_k	400
In-plane (//)				
Poisson's ratio	μ	0,07	μ	0,07

E.2.3.2 Ultimate limit states

Partial factor for material properties according to prEN 1995-1-1 [12]:

$\gamma_M = 1,20$

Strength modification factor: k_{mod} according to prEN 1995-1-1 [12], effecting the strength parameters and depending on the load duration and the moisture content in the structure for plywood according to EN 636 part 2.

Load duration class	Service class 1	 2
Permanent	0,60	0,60
long-term	0,70	0,70
medium-term	0,80	0,80
short-term	0,90	0,90
instantaneous	1,10	1,10

E.2.3.3 Serviceability limit states

Deformation modification factor: k_{def} according to prEN 1995-1-1 [12], effecting the stiffness parameters to calculate the creep influence and depending on the load duration and the moisture content in the structure for plywood according to EN 636 part 2.

Load duration class	Service class 1	 2
Permanent	0,80	1,00

E.3 Loadbearing insulation

An example of loadbearing insulation is expanded polystyrene (EPS). EPS is now classified in the European Standard EN 13163. Other (missing) values can be taken from the following tables.
When using this calculation model in practice, the material properties should be used conforming the latest EN standards and codes, or by test results conforming EN standards and codes.

E.3.1 Example of EPS (expanded polystyrene)

E.3.1.1 Properties

Characteristic values are taken from EN 13163.
EPS class names is based on the compression strength of the EPS.
The *G*-modulus can also be measured by tests, as it is described in prEN 14509: Annex A.3 "Shear test on the core material" or in prEN 12090: "Thermal insulating products for building applications - Determination of shear behaviour".

EPS acc. EN 13163		Strength class					
Material properties		EPS60	EPS80	EPS100	EPS120	EPS150	EPS200
Strength in N/mm²							
compression	$f_{c,k}$	0,060	0,080	0,100	0,120	0,150	0,200
tension	$f_{t,k}$	0,100	0,125	0,150	0,170	0,200	0,250
shear	$f_{v,k}$	0,050	0,060	0,075	0,085	0,100	0,125
Stiffness in N/mm²							
E-modulus	$E_{t(c),mean}$	4	5	6	7	9	11
G-modulus	G_{mean}	1,82	2,27	2,73	3,18	4,09	5,00
Density in kg/m³							
density	ρ_k	15	17,5	20	22,5	27,5	32,5

E.3.2 EPS (expanded polystyrene), XPS (extruded polystyrene), PUR (polyurethane)

E.3.2.1 Properties

Characteristic values are taken from EN 13163 or EN 13164.

EPS acc. EN 13163/ XPS acc. EN 13164 Material properties acc. prEN 14 509		Chapter
Strength in N/mm²		
Compression	$f_{c,k}$	A.2
Tension	$f_{t,k}$	A.1
Shear	$f_{v,k}$	A.3
Stiffness in N/mm²		
E-modulus	$E_{t(c),mean}$	A.2
G-modulus	G_{mean}	A.5.6
Density in kg/m³		
Density	ρ_k	A.8
Creep coefficient		A.6

E.3.2.2 Ultimate limit states

The partial factor for material properties is based on the indicative numbers given in prEN 14 509 and a consensus with the German mirror group.

Partial factor for material properties acc. to prEN 14 509 of EPS/ XPS/PUR:

$\gamma_M = 1,25$

if no more exact assessment according to ENV 1991-1 is made.
An assessment acc. to Eurocode is necessary in case of testresults with v>0,1.

Strength modification factor: k_{mod}, effecting the strength parameters and depending on the load duration and the moisture content in the structure.

Load duration class	Service class	
	1	2
permanent	0,25	0,25
long-term	0,50	0,50
medium-term	0,75	0,75
short-term	1,00	1,00
instantaneous	1,00	1,00

The values for the long-term and medium-term load duration classes are from the results of linear interpolation between the known values of the permanent and short-term load duration classes. For the instantaneous class, the value for short-term is used.
With the k_{mod}-value of 0,25 the maximum load on EPS, XPS and PUR in the permanent-term is limited to a maximum value equal to 25% of the characteristic failure load of EPS, XPS and PUR in the short-term.

E.3.2.3 Serviceability limit states

The deformation modification factor is based on the indicative numbers given in prEN 14 509.
Deformation modification factor: k_{def}, effecting the stiffness parameters to calculate the creep influence.

Deformation modification factor of EPS, XPS and PUR:

$k_{def} = 7,00$

E.4 Wooden rib

Example of wooden rib is solid timber.

E.4.1 Solid timber of coniferous species and poplar

E.4.1.1 Properties

Characteristic and mean values are according to EN 338

Solid timber acc. EN 338		Strength class			
Material properties		C16	C18	C22	C24
Strength in N/mm²					
bending	$f_{m,k}$	16	18	22	24
tension	$f_{t,0,k}$	10	11	13	14
compression	$f_{c,0,k}$	17	18	20	21
shear	$f_{v,k}$	1,8	2,0	2,4	2,5
Stiffness in N/mm²					
E-modulus	$E_{0,mean}$	8000	9000	10000	11000
G-modulus	G_{mean}	500	560	630	690
Density in kg/m³					
density	ρ_k	310	320	340	350

E.4.1.2 Ultimate limit states

Partial factor for material properties according to prEN 1995-1-1 [12]:
$\gamma_M = 1,30$

Strength modification factor: k_{mod} according to prEN 1995-1-1 [12], effecting the strength parameters and depending on the load duration and the moisture content in the structure.

Load duration class	Service class	
	1	2
permanent	0,60	0,60
long-term	0,70	0,70
medium-term	0,80	0,80
short-term	0,90	0,90
instantaneous	1,10	1,10

E.4.1.3 Serviceability limit states

Deformation modification factor: k_{def} according to prEN1995-1-1 [12], effecting the stiffness parameters to calculate the creep influence and depending on the load duration and the moisture content in the structure.

Load duration class	Service class	
	1	2
permanent	0,60	0,80

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