The Second Generation Eurocodes

Key changes and benefits through design examples

Online, 3-5 June 2025

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Design Example 2
Design of composite sandwich panels for building floors

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EUROCODES

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prCEN/TS 19101

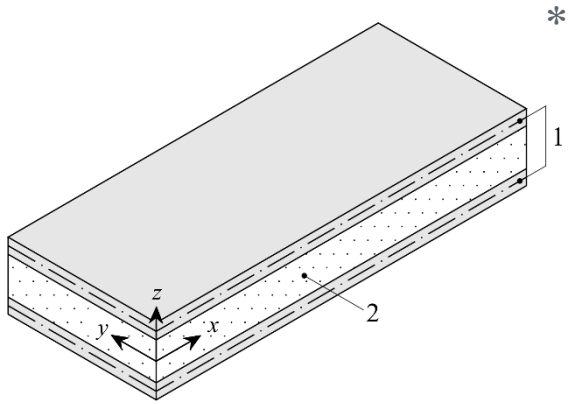
Design of fibre-polymer composite structures

OUTLINE

I. DATA OF THE PROBLEM

I. DATA OF THE PROBLEM

- Span L (x direction): 3750 mm
- Width b (y direction): calculations are performed per unit width
- Face sheet thickness (t_f): 5 mm
- Core thickness (t_c): 90 mm
- Distance between the centroid axes of the face sheets *(d)*: 95 mm
- Height of sandwich thickness *(h)*: 100 mm
- Support length (s_s): 120 mm (on each support)

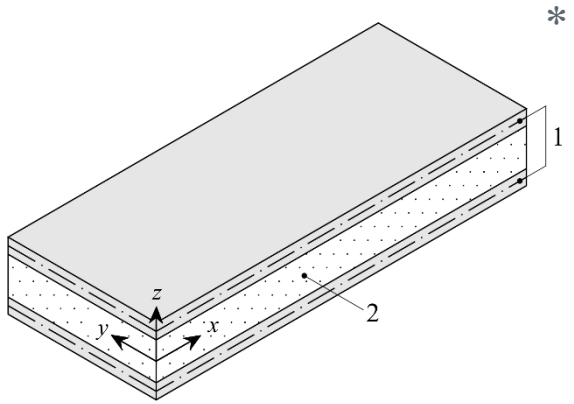


1 – faces

2 – core

I. DATA OF THE PROBLEM

- Face sheet fibre reinforcement: E-glass fibre fabrics ($[0/0/30/-30/90/0]_s$)
- Face sheet matrix: polyester resin
- Face sheet fibre volume fraction: 48%
- Density of composite face sheets: 1750 kg/m^3
- Core: rigid polyethylene terephthalate (PET) foam, 100 kg/m^3
- Manufacturing process: vacuum infusion
- Design service life: 50 years



1 – faces

2 – core

I. DATA OF THE PROBLEM

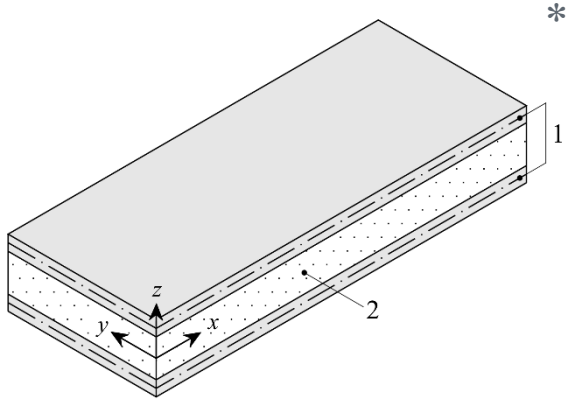
The sandwich panel is simply supported along its width (both edges parallel to y direction - cylindrical bending) and is submitted to the following set of uniformly distributed transverse loads (characteristic values), corresponding to a residential floor (building category A, prEN 1991-1-1, 5):

- Self-weight ($g_{sw,k}$): 0,27 kN/m^2 (calculated based on the previously-mentioned geometry and density)

- Other permanent loads ($g_{opl,k}$): 1,0 kN/m^2

Imposed loads (q_k) are 2,0 kN/m^2 (prEN 1991-1-1, 6, Table 6.1).

NOTE: The concentrated load defined in prEN 1991-1-1 was not considered in this design example, as a simplification.



*

1 – faces

2 – core

I. DATA OF THE PROBLEM

Fundamental design load for ULS (prEN 1990, Eq. (8.12)):

$$p_{Ed} = \gamma_G \left(g_{sw,k} + g_{opl,k} \right) + \gamma_Q \cdot q_k = 1{,}35 \cdot (0{,}27 + 1{,}0) + 1{,}5 \cdot 2{,}0 = 4{,}71 \text{ kN/m}^2$$

Bending moment and shear force:

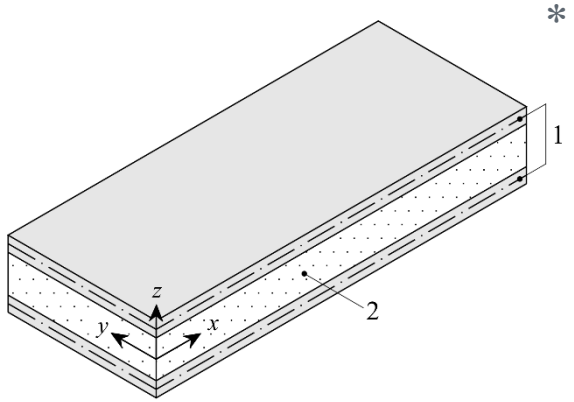
$$M_{Ed} = 8{,}28 \text{ kNm/m} = 8280 \text{ Nmm/mm}$$

$$V_{Ed} = 8{,}83 \text{ kN/m} = 8{,}83 \text{ N/mm}$$

The (i) frequent combination of actions (p_{freq}, short-term), and (ii) quasi-permanent combination of actions (p_{qp}, long-term) for SLS (prEN 1990, Eq. (8.31), Table A.1.7):

$$p_{freq} = \left(g_{sw,k} + g_{opl,k} \right) + \psi_{1,1} \cdot q_k = (0{,}27 + 1{,}0) + 0{,}5 \cdot 2{,}0 = 2{,}27 \text{ kN/m}^2$$

$$p_{qp} = \left(g_{sw,k} + g_{opl,k} \right) + \psi_{2,1} \cdot q_k = (0{,}27 + 1{,}0) + 0{,}3 \cdot 2{,}0 = 1{,}87 \text{ kN/m}^2$$



*

1 – faces

2 – core

I. DATA OF THE PROBLEM

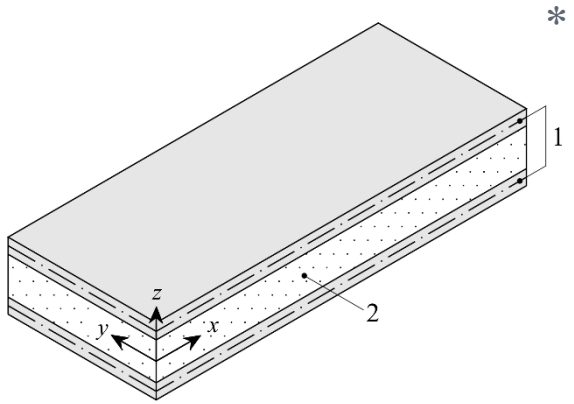
Other relevant data:

- Service temperature (T_s): 20 °C

- Glass transition temperatures: 95 °C for the composite face sheets and

90 °C for the PET foam

- Exposure class: I (indoor environment)



1 – faces

2 – core

II. CHARACTERISTIC VALUES OF MATERIAL PROPERTIES

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Characteristic values (X_k) of material properties determined by testing

Example

Average value of in-plane tensile strength in x direction (EN ISO 527):

$$\left(f_{x,t,m}\right)_f = 437 \text{ MPa } (V_{x,exp} = 6,4\%)$$

Characteristic value (5% fractile, prEN 1990, Annex D):

$$\left(f_{x,t,k}\right)_f = \left(f_{x,t,m}\right)_f \cdot \exp\left\{-k_n \cdot \sqrt{\ln\left(1+V_{x,exp}^2\right)} - \frac{\ln\left(1+V_{x,exp}^2\right)}{2}\right\}$$

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Example

Average value of in-plane tensile strength in x direction (EN ISO 527):

$$\left(f_{x,t,m}\right)_f = 437 \text{ MPa} \quad (V_{x,exp} = 6,4\%)$$

Characteristic value (5% fractile, prEN 1990, Annex D):

$$\left(f_{x,t,k}\right)_f = 437 \cdot \exp\left\{-2,33 \cdot \sqrt{\ln\left(1+0,064^2\right)} - \frac{\ln\left(1+0,064^2\right)}{2}\right\} \text{MPa} = 376 \text{ MPa}$$

Table D1:

test samples, n = 5

$k_n = 2,33$

(V_x previously unknown)

II. CHARACTERISTIC VALUES OF MATERIAL PROPERTIES

Summary of material properties (characteristic values)

Property	X_m(1)	$V_{x,exp}$(2)	X_k(3)
	[MPa]	[-]	[MPa]
$(f_{x,t})_f$	437	6,4%	376
$(f_{x,c})_f$	250	13,7%	180
$(f_{x,v})_c$	0,900	12,5%	0,668
$(f_{z,c})_c$	1,75	8,8%	1,42
$(E_{x,t})_f$	29400	2,7%	27598
$(E_{x,c})_f$	29400	2,7%	27598
$(E_{x,t})_c$	99,0	5,0%	88,0
$(E_{x,c})_c$	81,0	4,7%	72,5
$(E_z)_c$	110	4,0%	100
$(G_{xz})_c$	23,0	12,0%	17,3

(1) Mean value
(2) Experimental coefficient of variation
(3) Characteristic value

III. MATERIAL PARTIAL FACTOR

&

NOMINAL CONVERSION FACTOR

III. MATERIAL PARTIAL FACTOR & NOMINAL CONVERSION FACTOR

The partial factor for a material property (γ_m) depends on the coefficient of variation (Vx) and shall be determined from testing

Table 4.1 — Material partial factor γ_m as a function of V_x when V_x is known *

V_x	0,05	0,10	0,15	0,20	0,25	0,30	0,35	0,40	0,45
γ_m	1,07	1,15	1,23	1,32	1,41	1,51	1,61	1,71	1,82

NOTE These values are based on the design value method (see EN 1990:—, Annex C), a lognormal distribution of the material or product property, a sensitivity factor of 0,8, and a 50-year reliability index of 3,8.

Table 4.2 — Factor f_{V_x} to take into account the statistical uncertainty of V_x, as a function of the number of test results, n *

n	5	10	15	20	25	30	50	100	999
f_{V_x}	1,70	1,19	1,12	1,08	1,07	1,05	1,03	1,02	1,00

NOTE These values are based on the assumption that the material or product property is lognormally distributed.

$n = 5$

$f_{V_x} = 1{,}70$

$$\gamma_m = 1{,}16$$

Interpolated from Table 4.1

$$V_x = V_{x,exp} \cdot f_{V_x} = 1{,}70 \cdot 6{,}4\% = 0{,}109$$

4.4.5 (3)

III. MATERIAL PARTIAL FACTOR & NOMINAL CONVERSION FACTOR

The conversion factor (η_c) should be calculated from the following formula (Formula (4.4)):

$$\eta_c = \eta_{ct} \cdot \eta_{cm}$$

η_{ct} is the conversion factor for temperature effects

η_{cm} is the conversion factor for moisture effects

$T_s = 20\ °C$

$$\eta_{ct} = \min\left\{1{,}0 - 0{,}20 \cdot \frac{T_s - 20}{T_g - 20}; 1{,}0\right\} = 1{,}0$$

Fibre-dominated properties

$$\eta_{ct} = \min\left\{1{,}0 - 0{,}80 \cdot \frac{T_s - 20}{T_g - 20}; 1{,}0\right\} = 1{,}0$$

Matrix-dominated properties

III. MATERIAL PARTIAL FACTOR & NOMINAL CONVERSION FACTOR

The conversion factor (η_c) should be calculated from the following formula (Formula (4.4)):

$$\eta_c = \eta_{ct} \cdot \eta_{cm}$$

η_{ct} is the conversion factor for temperature effects

η_{cm} is the conversion factor for moisture effects

$$\eta_{cm} = 1{,}0$$

Table 4.6 — Values of η_{cm} for unprotected composite materials (glass, carbon or basalt fibres; thermoset polymer matrix of unsaturated polyester, vinylester or epoxy; fibre volume fraction of at least 35%) and epoxy adhesives *

Exposure classes	Conversion factor η_{cm}	Influence of moisture
I	1,00	Indoor exposure with service temperature according to 1.1(4)
II	0,85	Outdoors exposure with service temperature according to 1.1(4), without (i) continuous exposure to water, (ii) permanent immersion in water, (iii) permanent exposure to a relative humidity higher than 80%, (iv) combined UV-radiation and frequent freeze-thaw cycles
III	0,60	Continuous exposure to water (or seawater), or permanent immersion in water (or seawater), or permanent exposure to a relative humidity higher than 80% (material temperature up to 25 °C)

III. MATERIAL PARTIAL FACTOR & NOMINAL CONVERSION FACTOR

The conversion factor (η_c) should be calculated from the following formula (Equation (4.4)):

$$\eta_c = \eta_{ct} \cdot \eta_{cm}$$

η_{ct} is the conversion factor for temperature effects

η_{cm} is the conversion factor for moisture effects

$$\eta_c = \eta_{ct} \cdot \eta_{cm} = 1{,}0 \cdot 1{,}0 = 1{,}0$$

III. MATERIAL PARTIAL FACTOR & NOMINAL CONVERSION FACTOR

Summary of determined values

Property	X_m(1)	$V_{x,exp}$(2)	X_k(3)	f_{Vx}(4)	$V_{x,corr}$(5)	γ_m(6)	η_c(7)
	[MPa]	[-]	[MPa]	[-]	[-]	[-]	[-]
$(f_{x,t})_f$	437	6,4%	376	1,70	10,9%	1,16	1,00
$(f_{x,c})_f$	250	13,7%	180	1,70	23,3%	1,38	1,00
$(f_{x,v})_c$	0,900	12,5%	0,668	1,70	21,3%	1,34	1,00
$(f_{z,c})_c$	1,75	8,8%	1,42	1,70	15,0%	1,23	1,00
$(E_{x,t})_f$	29400	2,7%	27598	1,70	4,6%	1,07	1,00
$(E_{x,c})_f$	29400	2,7%	27598	1,70	4,6%	1,07	1,00
$(E_{x,t})_c$	99,0	5,0%	88,0	1,70	8,5%	1,13	1,00
$(E_{x,c})_c$	81,0	4,7%	72,5	1,70	8,0%	1,12	1,00
$(E_z)_c$	110	4,0%	100	1,70	6,8%	1,10	1,00
$(G_{xz})_c$	23,0	12,0%	17,3	1,70	20,4%	1,33	1,00

(1) Mean value
(2) Experimental coefficient of variation
(3) Characteristic value
(4) Factor to account for the statistical uncertainty of V_x
(5) Coefficient of variation corrected with (4)
(6) Material partial factor
(7) Conversion factor

IV. PRELIMINARY CHECKS

IV. PRELIMINARY CHECKS

The stress distributions among the sandwich panel's components depend on the geometry and mechanical properties of their constituent materials. In homogenous core sandwich panels, two notable aspects must be assessed: (i) thin vs. thick faces, and (ii) rigid vs. flexible core (7.1.4.1)

Thin faces if:

$$\frac{d}{t_f} > 5{,}8 \qquad \text{Eq. (7.1)}$$

d is the distance between face sheet centroids
t_f is the face sheet thickness

$t_f = 5$ mm and $d = 95$ mm, thus $d/t_f = 19{,}0 > 5{,}8$ → Faces are considered thin
(if thick, the stress distribution should be determined using FEM)

IV. PRELIMINARY CHECKS

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Flexible core if:

$$\frac{6\cdot\left(\eta_c\right)_f\cdot E_f\cdot t_f\cdot d^2}{\left(\eta_c\right)_c\cdot E_c\cdot t_c^{\,3}}>100 \qquad \text{Eq. (7.2)}$$

E_f and E_c are the elastic moduli of the face sheets and core, respectively
t_c is the thickness of the core
$(\eta_c)_f$ and $(\eta_c)_c$ are the relevant conversion factors for the face sheet and core moduli, respectively

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Flexible core if:

$$\frac{6\cdot(\eta_c)_f\cdot E_f\cdot t_f\cdot d^2}{(\eta_c)_c\cdot E_c\cdot t_c^{\,3}}>100$$

For the tensile case:

$$\frac{6\cdot 1\cdot 29400\cdot 5\cdot 95^2}{1\cdot 99{,}0\cdot 90^3}=110>100$$

For the compressive case:

$$\frac{6\cdot 1\cdot 29400\cdot 5\cdot 95^2}{1\cdot 81{,}0\cdot 90^3}=135>100$$

→ Flexible core

(simplified stress distributions given in Table 7.1 can be used, i.e., core contribution to axial stresses is neglected)

V. ULTIMATE LIMIT STATES VERIFICATIONS

V. ULTIMATE LIMIT STATES VERIFICATIONS

The following ULS verifications should be performed:

- Face sheet tensile failure (8.4.2.1)
- Face sheet crushing (8.4.2.2)
- Face sheet wrinkling (8.4.2.3)
- Core shear failure (8.4.3.1)
- Core indentation (8.4.3.4)

V. ULTIMATE LIMIT STATES VERIFICATIONS

Example: face sheet tensile failure (8.4.2.1)

Eq. (8.51):

$$\left(\sigma_{x,Ed}\right)_f \le \left(f_{x,t,d}\right)_f \Leftrightarrow \frac{\left(\sigma_{x,Ed}\right)_f}{\left(f_{x,t,d}\right)_f} \le 1{,}0$$

where (Eq. (8.53)):

$$\left(\sigma_{x,Ed}\right)_f = \cancel{\left(\sigma_{x,N,Ed}\right)_f} \pm \left(\sigma_{x,M,Ed}\right)_f \quad \xrightarrow{\text{Table 7.1}} \quad \left(\sigma_{x,Ed}\right)_f = \left(\sigma_{x,M,Ed}\right)_f = \frac{M_{Ed}}{t_f \cdot d} = \frac{8280}{5 \cdot 95} = 17{,}4\,\text{MPa}$$

$\left(\sigma_{x,N,Ed}\right)_f = 0$

and (Eq. (8.52)):

$$\left(f_{x,t,d}\right)_f = \frac{1}{\gamma_m \cdot \gamma_{Rd}} \cdot \eta_c \cdot \left(f_{x,t,k}\right)_f \quad \xrightarrow{\text{Table 4.4}} \quad \left(f_{x,t,d}\right)_f = \frac{1}{1{,}16 \cdot 1{,}4} \cdot 1{,}0 \cdot 376 = 231\ \text{MPa}$$

$\gamma_{Rd} = 1{,}4$
(composite material failure)

Verification:

$$\frac{\left(\sigma_{x,Ed}\right)_f}{\left(f_{x,t,d}\right)_f} = \frac{17{,}4}{231} = 0{,}08 \le 1{,}0$$

OK

VI. CREEP RUPTURE (ULS)

VI. CREEP RUPTURE (ULS)

Creep rupture is also a ULS verification – relevant for members subjected to sustained stresses

- Tensile creep rupture (8.5(2))
- Compressive creep rupture (8.5(5))

VI. CREEP RUPTURE (ULS)

Example: tensile creep rupture (8.5(2))

Eq. (8.110):

$$\sigma_{t,creep,Ed} \leq \sigma_{t,creep,Rd} \quad \Leftrightarrow \quad \frac{\sigma_{t,creep,Ed}}{\sigma_{t,creep,Rd}} \leq 1,0$$

where the design value of the tensile stress limit for creep rupture is given by (Eq. (8.111)):

$$\sigma_{t,creep,Rd} = \frac{\eta_c}{\gamma_{M,creep}} \cdot k_{t,creep} \cdot f_{x,t,k} \longrightarrow \sigma_{t,creep,Rd} = 0,4 \cdot \frac{1,0 \cdot 376}{1,5} = 100\,\text{MPa}$$

$\gamma_{M,creep}$ = 1,50 (8.5(2) NOTE 4)
$k_{t,creep}$ = 0,4 (Table 8.3, glass fibre, 50 years)

VI. CREEP RUPTURE (ULS)

Example: tensile creep rupture (8.5(2))

Eq. (8.110):

$$\sigma_{t,creep,Ed} \leq \sigma_{t,creep,Rd} \quad \Leftrightarrow \quad \frac{\sigma_{t,creep,Ed}}{\sigma_{t,creep,Rd}} \leq 1,0$$

and the design value of the maximum sustained tensile stress caused by the quasi-permanent combination of actions is determined for the bottom face sheet:

$$\sigma_{t,creep,Ed} = \frac{M_{qp}}{t_f \cdot d}$$ Table 7.1

$$\sigma_{t,creep,Ed} = \frac{M_{qp}}{t_f \cdot d} = \frac{3290}{5 \cdot 95} = 6,9\,\text{MPa}$$

$$M_{qp} = \frac{p_{qp} \cdot L_{tot}^2}{8} = \frac{1,87 \cdot 3,75^2}{8} = 3,29\,\text{kN} \cdot \text{m/m}$$

Verification:

$$\frac{\sigma_{t,creep,Ed}}{\sigma_{t,creep,Rd}} = \frac{6,9}{100} = 0,07 \leq 1,0$$

OK

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

SLS verifications include the following:

- Deflections for the quasi-permanent load combination (appearance) (prEN 1990, Annex A, A.1.8.2.2(1))
- Deflections for the frequent load combination (comfort of users) (prEN 1990, Annex A, A.1.8.2.2(1))
- Matrix cracking (9.4(1))

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

Example: deflections for the quasi-permanent load combination (appearance) (prEN 1990, Annex A, A.1.8.2.2(1))

For the quasi-permanent load combination:

$$w_1 + w_2 - w_c \leq L/250$$

w_1 initial part of the deflection under permanent loads
w_2 long-term part of the deflection under permanent loads including quasi-permanent loads
w_c precamber in unloaded structural member (not applicable in our example)

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

Example: deflections for the quasi-permanent load combination (appearance) (prEN 1990, Annex A, A.1.8.2.2(1))

Initial deflection of simply supported beam under uniformly distributed loading (Timoshenko beam theory):

$$w(0) = w_{\text{bend}}(0) + w_{\text{shear}}(0) = \frac{5}{384} \cdot \frac{p \cdot L^4}{D(0)} + \frac{1}{8} \cdot \frac{p \cdot L^2}{S(0)}$$

$D(0)$ mean value, at time 0, of flexural stiffness per unit width
$S(0)$ mean value, at time 0, of shear stiffness per unit width

Eqs. (7.3) and (7.5)
$$D(0) \approx D_0(0) = \frac{(\eta_c)_f \cdot E_{x,t,m} \cdot t_f \cdot d^2}{2} = \frac{1{,}0 \cdot 29400 \cdot 5 \cdot 95^2}{2} = 663338\,\text{N} \cdot \text{m} = 663\,\text{kN} \cdot \text{m}$$

Eq. (7.8)
$$S(0) = \frac{(G_{xz,m})_c \cdot d^2}{t_c} = \frac{23{,}0 \cdot 95^2}{90} = 2306389\,\text{N/m} = 2306\,\text{kN/m}$$

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

Example: deflections for the quasi-permanent load combination (appearance) (prEN 1990, Annex A, A.1.8.2.2(1))

Long-term (creep) deflection estimated by multiplying initial deformations by the creep coefficients:

$$w_{creep}(t=50\,\text{years}) = \frac{5}{384}\cdot\frac{p\cdot L^4}{D(0)}\cdot\phi_{E_{x,t}}(t=50\,\text{years}) + \frac{1}{8}\cdot\frac{p\cdot L^2}{S(0)}\cdot\phi_{G_{xz}}(t=50\,\text{years})$$

Table 4.8 woven (0/90°) $\phi_{E_{x,t}}(t=50\,\text{years}) = 0{,}68$

Table 4.9 PET foam $\phi_{G_{xz}}(t=50\,\text{years}) = 0{,}65$

VII. SERVICEABILITY LIMIT STATES VERIFICATIONS

Example: deflections for the quasi-permanent load combination (appearance) (prEN 1990, Annex A, A.1.8.2.2(1))

Deflection calculations:

$$w_1 = \frac{5}{384}\cdot\frac{\left(g_{sw,k}+g_{opl,k}\right)\cdot L^4}{D(0)}+\frac{1}{8}\cdot\frac{\left(g_{sw,k}+g_{opl,k}\right)\cdot L^2}{S(0)}$$

$$w_1 = \frac{5}{384}\cdot\frac{1{,}27\cdot 3{,}75^4}{663}+\frac{1}{8}\cdot\frac{1{,}27\cdot 3{,}75^2}{2306} = 4{,}93\cdot 10^{-3}+1{,}43\cdot 10^{-3} = 6{,}36\,\text{mm}$$

$$w_2 = \frac{5}{384}\cdot\frac{\left(g_{sw,k}+g_{opl,k}+\psi_{2,1}\cdot q_k\right)\cdot L^4}{D(0)}\cdot\phi_{E_{x,t,m}}\left(t=50\,\text{years}\right)+\frac{5}{384}\cdot\frac{\left(\psi_{2,1}\cdot q_k\right)\cdot L^4}{D(0)}+$$
$$+\frac{1}{8}\cdot\frac{\left(g_{sw,k}+g_{opl,k}+\psi_{2,1}\cdot q_k\right)\cdot L^2}{S(0)}\cdot\phi_{G_{xz}}\left(t=50\,\text{years}\right)+\frac{1}{8}\cdot\frac{\left(\psi_{2,1}\cdot q_k\right)\cdot L^2}{S(0)}$$

$$w_2 = \frac{5}{384}\cdot\frac{1{,}87\cdot 3{,}75^4}{663}\cdot 0{,}68+\frac{5}{384}\cdot\frac{(0{,}3\cdot 2{,}0)\cdot 3{,}75^4}{663}+\frac{1}{8}\cdot\frac{1{,}87\cdot 3{,}75^2}{2306}\cdot 0{,}65$$
$$+\frac{1}{8}\cdot\frac{(0{,}3\cdot 2{,}0)\cdot 3{,}75^2}{2306}=$$
$$=7{,}27\cdot 10^{-3}+1{,}38\cdot 10^{-3}=8{,}65\,\text{mm}$$

$$w_1+w_2-w_c = 6{,}36+8{,}65-0 = 15{,}0\,\text{mm} \le L/250 = 3750/250 = 15{,}0\,\text{mm}$$

Verification:

$$\frac{w_1+w_2-w_c}{L/250}=\frac{15{,}0}{15{,}0}=1{,}00$$

OK

VIII. CONCLUDING REMARKS

VIII. CONCLUDING REMARKS

Summary of ULS verifications performed:

Type of verification	E_d/R_d	Check
Face sheet tensile failure	0,08	✓
Face sheet crushing	0,19	✓
Face sheet wrinkling	0,12	✓
Core shear failure	0,28	✓
Core indentation	0,09	✓
Tensile creep rupture	0,07	✓
Compressive creep rupture	0,19	✓

VIII. CONCLUDING REMARKS

Summary of SLS verifications performed:

Type of verification		Ratio	Check
Deflections			
Vertical mid-span deflection for quasi-permanent combination of actions ($L/250$)		1,00	✓
Vertical mid-span deflection for frequent combination of actions ($L/300$)		0,84	✓
Matrix cracking			
Limit	Matrix cracking tensile strain	0,15	✓

Thank you!

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CORE Group: https://coregroup.tecnico.ulisboa.pt