



BSI Standards Publication

GRP tanks and vessels for use above ground

Part 5: Example calculation of a GRP-vessel

National foreword

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English Version

GRP tanks and vessels for use above ground - Part 5: Example calculation of a GRP-vessel

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CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

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European foreword

This document (CEN/TR 13121-5:2017) has been prepared by Technical Committee CEN/TC 210 “GRP tanks and vessels”, the secretariat of which is held by SFS.

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Introduction

EN 13121 consists of the following parts:

- EN 13121-1, *GRP tanks and vessels for use above ground — Part 1: Raw materials — Specification and acceptance conditions*
- EN 13121-2, *GRP tanks and vessels for use above ground — Part 2: Composite materials — Chemical resistance*
- EN 13121-3, *GRP tanks and vessels for use above ground — Part 3: Design and workmanship*
- EN 13121-4, *GRP tanks and vessels for use above ground — Part 4: Delivery, installation and maintenance*
- CEN/TR 13121-5, *GRP tanks and vessels for use above ground — Part 5: Example calculation of a GRP-tank (this report)*

These five parts together define the responsibilities of the tank or vessel manufacturer and the materials to be used in their manufacture.

EN 13121-1 specifies the requirements and acceptance conditions for the raw materials - resins, curing agents, thermoplastics linings, reinforcing materials and additives. These requirements are necessary in order to establish the chemical resistance properties determined in EN 13121-2 and the mechanical, thermal and design properties determined in EN 13121-3. Together with the workmanship principles determined in Part 3, requirements and acceptance conditions for raw materials ensure that the tank or vessel will be able to meet its design requirements. EN 13121-4 of this standard specifies recommendations for delivery, handling, installation and maintenance of GRP tanks and vessels. This part of EN 13121 gives guidance in use of the standard. CEN/TC 210 has found it necessary to publish an example calculation of a vessel according to EN 13121-3 due to the standards complexity, and for the understanding of how the standard complies with EN 1990:s principles and requirements for safety, serviceability and durability of structures.

The design and manufacture of GRP tanks and vessels involve a number of different materials such as resins, thermoplastics and reinforcing fibres and a number of different manufacturing methods. It is implicit that vessels and tanks covered by this standard are made only by manufacturers who are competent and suitably equipped to comply with all the requirements of this standard, using materials manufactured by competent and experienced material manufacturers.

Metallic vessels, and those manufactured from other isotropic, homogeneous materials, are conveniently designed by calculating permissible loads based on measured tensile and ductility properties. GRP, on the other hand, is a laminar material, manufactured through the successive application of individual layers of reinforcement. As a result there are many possible combinations of reinforcement type that will meet the structural requirement of any one-design case. This allows the designer to select the laminate construction best suited to the available manufacturing facilities and hence be most cost effective.

1 Scope

This Technical Report gives guidance for the design of a vessel using the standard EN 13121-3 GRP tanks and vessels for use above ground. The calculation is done according to the advanced design method given in EN 13121-3:2016, 7.9.3 with approved laminates and laminate properties.

2 General

Vessels or vessel structures may contain such structural elements or solutions for which this standard does not provide sufficient guidance. In that case, other methods shall be used in order to obtain a safe structure.

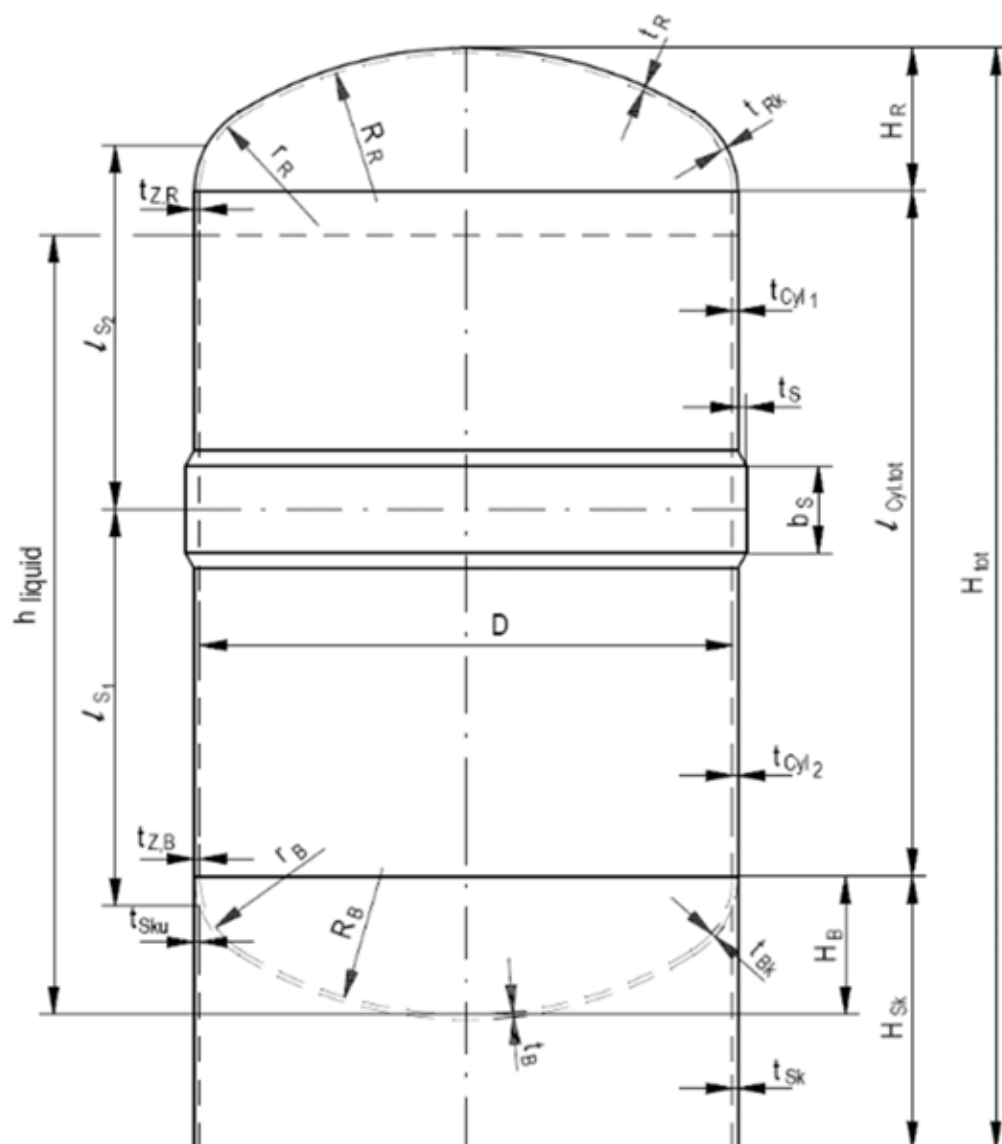
This example calculation is based on a pressurized GRP vessel with an internal diameter of $D = 3000$ mm. The cylindrical parts of the vessel are filament wound. Its bottom and roof are torispherical dished ends that are hand laid up using mixed laminates. Protection against medium attack is obtained by a chemical resistance layer (CRL).

The tank is located outdoors in a seismic area.

IMPORTANT – This example doesn't cover all necessary verifications for the calculation of the GRP tank. Additional verifications have to be performed for the roof, the upper cylinder, etc.

3 Dimensions of the tank

Sketch of the tank dimensions:



General Dimensions:

Diameter: $D = 3\,000\text{ mm}$

Total height: $H_{tot} = 8\,000\text{ mm}$

Cylinder:

Thickness cylinder 1: $t_{Cyl,1} = t_{c1} = 9,2\text{ mm}$

Thickness cylinder 2: $t_{Cyl,2} = t_{c2} = 11,7\text{ mm}$

Thickness cylinder at roof: $t_{Z,R} = 30,0\text{ mm}$

Thickness cylinder at bottom: $t_{Z,B} = 46,1\text{ mm}$

Total cylinder length: $l_{Cyl,tot} = 6\,610\text{ mm}$

Distance between stiffeners: $l_{s,1} = 3\,700\text{ mm}$ $l_{s,2} = 3\,303\text{ mm}$

Thickness of the stiffener: $t_s = 20\text{ mm}$

Width of the stiffener: $b_s = 260 \text{ mm}$

Skirt:

Thickness skirt: $t_{sk} = 17,0 \text{ mm}$

Thickness overlay laminate: $t_{02} = 7,0 \text{ mm}$

Height of the skirt: $H_{sk} = 890 \text{ mm}$

Roof:

Thickness calotte: $t_R = 13,0 \text{ mm}$

Radius calotte: $R_R = 3000 \text{ mm}$

Thickness knuckle roof: $t_{Rk} = 30,0 \text{ mm}$

Radius knuckle: $r_{Rk} = 300 \text{ mm}$

Height of the roof: $H_R = 590 \text{ mm}$

Bottom:

Thickness calotte: $t_B = 16,5 \text{ mm}$

Radius calotte: $R_B = 3\,000 \text{ mm}$

Thickness knuckle: $t_{Bk} = 45,0 \text{ mm}$

Radius knuckle: $r_{Bk} = 300 \text{ mm}$

Height of the bottom: $H_B = 590 \text{ mm}$

4 Building materials

Resin type: UP-resin, Resin group 4

5 Loadings (9)

LC 1: Dead load

The assumed dead loads for the separate tank parts are:

Roof: $W_{R,k} = 4 \text{ kN}$ Area load: $w_{R,k} = 0,57 \text{ kN/m}^2$

Cylinder + rings: $W_{C,k} = 19 \text{ kN}$

Bottom: $W_{B,k} = 4 \text{ kN}$ Area load: $w_{B,k} = 0,57 \text{ kN/m}^2$

Skirt: $W_{sk} = 3 \text{ kN}$

Total dead load of the vessel: $W_{tot} = 30 \text{ kN}$

LC 2: Liquid filling

Density of the medium $\rho_{liquid} = 1,30 \text{ kg/dm}^3$

Filling height $h_{liquid} = 7\,000 \text{ mm}$

Volume $V = 52,0 \text{ m}^3$

LC 3: Long time design overpressure

Design pressure

$PS_{op,l} = 2,000 \text{ bar} \equiv 0,20 \text{ N/mm}^2$

LC 4: Short time design overpressure

Design pressure $PS_{op.s} = 2,500 \text{ bar} \equiv 0,25 \text{ N/mm}^2$

LC 5: Long time design negative pressure

Design pressure $PS_{ep.l} = 0,000 \text{ bar} \equiv 0,00 \text{ N/mm}^2$

LC 6: Short time design negative pressure

Design pressure $PS_{ep.s} = 0,050 \text{ bar} \equiv 0,005 \text{ N/mm}^2$

LC 7: Wind (9.2.2)

Peak velocity pressure $q_p = 0,8 \text{ kN/m}^2$ (EN 1991-1-4)

Force coefficient (cylindrical vessel) $c_f = 0,8$

External pressure arising from wind load: $p_{wind} = 0,6 \cdot q_p = 0,6 \cdot 0,8 = 0,48 \text{ kN/m}^2$

LC 8: Snow (9.2.1)

Characteristic snow load $s_k = 0,85 \text{ kN/m}^2$ (EN 1991-1-3)

Shape coefficient $\mu = 0,80$

Snow load $p_{snow} = s_k \cdot \mu = 0,85 \cdot 0,8 = 0,68 \text{ kN/m}^2$

LC 9: Personnel loading (9.2.8)

Live load on the roof $p_{access} = 1,5 \text{ kN/m}^2$

LC 10: Temperature

Design temperature $TS = 50^\circ\text{C}$

Difference in temperature $\Delta T = 20 \text{ K}$

LC 11: Earthquake (9.2.3.4)

Reference peak ground acceleration $a_{gR} = 1,00 \text{ m/s}^2$

Importance factor $\gamma_1 = 1,4$

Design ground acceleration $a_g = a_{gR} \cdot \gamma_1 = 1,00 \cdot 1,4 = 1,40 \text{ m/s}^2$

Ground type according to EN 1998-1 D

Viscous damping 5 %

Control periods of the response spectrum $T_B = 0,20 \text{ s}$ $T_C = 0,8 \text{ s}$ $T_D = 2,0 \text{ s}$

Soil factor $S = 1,35$

Behaviour factor $q = 1,5$

Bending modulus cylinder tangential $E_{\phi,b} = 19\,000 \text{ N/mm}^2$

Bending modulus cylinder axial $E_{x,b} = 12\,000 \text{ N/mm}^2$

Modulus of elasticity for short time impact $E_e = 1,5 \cdot \sqrt{E_{\phi,b} \cdot E_{x,b}} = 1,5 \cdot \sqrt{19\,000 \cdot 12\,000} = 22\,650 \text{ N/mm}^2$

Cylinder thickness lower $t_{1/2}$ approximately $t_{sk} = 17 \text{ mm}$

third

Vibration period

$$T = \sqrt{\frac{\rho_{liquid} \cdot h_{liquid}}{E_e \cdot t_{1/2}}} \cdot D \cdot \left[0,628 \cdot \left(\frac{h_{liquid}}{D} \right)^2 + \frac{2 \cdot h_{liquid}}{D} + 1,49 \right]$$

$$T = \sqrt{\frac{1,33 \cdot 7200}{22650 \cdot 17,0 \cdot 10^3}} \cdot 3,0 \cdot \left[0,628 \cdot \left(\frac{7200}{3000} \right)^2 + \frac{2 \cdot 7200}{3000} + 1,49 \right] = 0,15 \text{ s}$$

Design spectrum
(plateau area):

$$T \leq T_c \quad S_D(T) = a_g \cdot S \cdot \frac{2,5}{q} = 1,40 \cdot 1,35 \cdot \frac{2,5}{1,5} = 3,15 \text{ m/s}^2$$

Total mass of the vessel
(approximately)

$$W_G = \frac{W_{tot}}{g} + V \cdot \rho_{liquid} = \frac{30}{9,81} + 52 \cdot 1,30 = 70,66 \text{ Tonnen}$$

Horizontal load (Base shear)

$$H_{AE} \cong S_D(T) \cdot W_G = 3,15 \cdot 70,66 = 222,6 \text{ kN}$$

Overturning moment

$$M_{AE,tot} \cong \left[V \cdot \rho_{liquid} \cdot \left(\frac{h_{liquid}}{2} + H_{Sk} - H_B \right) + \frac{W_{tot}}{g} \cdot \frac{H_{tot}}{2} \right] \cdot S_D(T)$$

$$M_{AE,tot} \cong \left[52 \cdot 1,30 \cdot \left(\frac{7\,000}{2} + 800 - 590 \right) \cdot 10^{-3} + \frac{30}{9,81} \cdot \frac{8\,000}{2} \cdot 10^{-3} \right] \cdot 3,15 = 828,5 \text{ kNm}$$

6 Limit strain for laminate (8.2.2)

For the used UP resin is:

The roof is made of a mixed laminate

$$\varepsilon_{lim,R} = \varepsilon_{d,R} = 0,25 \%$$

The bottom is made of a mixed laminate

$$\varepsilon_{lim,B} = \varepsilon_{d,B} = 0,25 \%$$

The cylinder is made of a wound laminate 0°/90°

$$\varepsilon_{lim,x,Cyl} = \varepsilon_{d,x,Cyl} = 0,20 \%$$

$$\varepsilon_{lim,\phi,Cyl} = \varepsilon_{d,\phi,Cyl} = 0,27 \%$$

The skirt is made of a wound laminate 0°/90°

$$\varepsilon_{lim,x,Sk} = \varepsilon_{d,x,Sk} = 0,20 \%$$

$$\varepsilon_{lim,\phi,Sk} = \varepsilon_{d,\phi,Sk} = 0,27 \%$$

7 Influence factors (7.9.5.2)

Influence factor A₁

$$A_1 = 1,0$$

Influence factor A₂

$$A_2 = 1,4 \text{ (Table A.4 of EN 13121-2)}$$

Medium category 2, T_d = 50°C

HDT of the used resin

$$\text{HDT} = 90 \text{ °C}$$

Influence factor A₃

$$A_3 = 1,00 + 0,4 \cdot \left(\frac{TS - 20^\circ\text{C}}{\text{HDT} - 30^\circ\text{C}} \right) = 1,00 + 0,4 \cdot \left(\frac{50 - 20}{90 - 30} \right) = 1,20$$

Influence factor A₄

$$A_4 = 1,0$$

Influence factor A₅

The influence factor A₅ depends on laminate type and is selected separately for each kind of laminate.

8 Partial safety factors (Table 12)

Action	Symbol	Situation	
		P/T	A/AE
<u>Independent permanent actions (s.a):</u>	$\gamma_{G,sup}$	1,35	1,00
unfavourable	$\gamma_{G,inf}$	1,00	1,00
favourable	$\gamma_{G,sup}$	1,35	1,00
For liquid filling	$\gamma_{G,inf}$	0	0
unfavourable	$\gamma_{Q,sup}$	1,50	1,00
favourable	$\gamma_{Q,inf}$	0	0
<u>Independent variable actions:</u>	γ_A		1,00
unfavourable	γ_{AE}		1,00
favourable			
<u>Accidental actions:</u>			
<u>Seismic actions:</u>			

9 Combination factors (Table 11)

In the following table are shown the relevant Ψ -factors for this example.

Action	ψ_0	ψ_1	ψ_2
Pressures:	1,0	1,0	1,0
- Long term pressures	0	0	0
- Short-term pressures			
Imposed loads in buildings, category (see EN 1991-1-1)	0	0	0
- Category H: roofs			
Snow loads on buildings (see EN 1991-1-3) ^{a)} :	0,5	0,2	0
Remainder of CEN Member States,			
- for sites located at altitude $H \leq 1000$ m a.s.l.			
Wind loads on buildings (see EN 1991-1-4)	0,6	0,2	0
Temperature (non-fire) in buildings (see EN 1991-1-5)	0,6	0,5	0

10 Analysis of the cylinder

The cylinder is made of a wound laminate $0^\circ / 90^\circ$. For mechanical properties are used historic test data. They are verified with tests in accordance to 7.9.3.

10.1 Influence factor A_5

— For stress analysis

25 years:	a)	Axial	$A_{5B.Cyl.25y.x} = 1,60$	b) Tangential	$A_{5B.Cyl.25y.\phi} = 1,20$
3 months:			$A_{5B.Cyl.3m.x} = 1,40$		$A_{5B.Cyl.3m.\phi} = 1,15$
Shorttime:			$A_{5B.Cyl.sh.x} = 1,00$		$A_{5B.Cyl.sh.\phi} = 1,00$

— For stability analysis

25 years:	a)	Axial	$A_{5I.Cyl.25y.x} = 1,60$	b) Tangential	$A_{5I.Cyl.25y.\phi} = 1,20$
3 months:			$A_{5I.Cyl.3m.x} = 1,40$		$A_{5I.Cyl.3m.\phi} = 1,15$
Short time:			$A_{5I.Cyl.sh.x} = 1,00$		$A_{5I.Cyl.sh.\phi} = 1,00$

Check for minimum design factors K and F:

If the value of K does not reach a minimum of 4 (advanced design) only for longtime loads, the A_{5B} values should be increased.

$$\text{Minimum } A_{5B} = \frac{K}{(A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot \gamma_M \cdot \gamma_{F,i})} = \frac{4}{(1,0 \cdot 1,4 \cdot 1,20 \cdot 1,0 \cdot 1,4 \cdot 1,5)} = 1,13$$

If the value of F does not reach a minimum of 2,7 (advanced design) only for longtime loads, the A_{5I} values should be increased.

$$\text{Minimum } A_{5I} = \left(\frac{F}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot \gamma_M \cdot \gamma_{F,i}} \right)^2 \geq 1,0 = \left(\frac{2,7}{1,0 \cdot 1,4 \cdot 1,20 \cdot 1,0 \cdot 1,4 \cdot 1,5} \right)^2 \geq 1,0 = 1,0$$

All A_5 values are greater than the minimum A_5 values.

10.2 Characteristic strength values

— For tension

$$\text{a) Axial } f_{Cyl.x.t.k} = 130 \text{ N/mm}^2 \quad \text{b) Tangential } f_{Cyl.\phi.t.k} = 400 \text{ N/mm}^2$$

— For bending

$$\text{a) Axial } f_{Cyl.x.b.k} = 150 \text{ N/mm}^2 \quad \text{b) Tangential } f_{Cyl.\phi.b.k} = 480 \text{ N/mm}^2$$

10.3 Moduli of elasticity

— For tension

$$\text{a) Axial } E_{Cyl.x.t} = 12500 \text{ N/mm}^2 \quad \text{b) Tangential } E_{Cyl.\phi.t} = 21000 \text{ N/mm}^2$$

— For bending

$$\text{a) Axial } E_{Cyl.x.b} = 12000 \text{ N/mm}^2 \quad \text{b) Tangential } E_{Cyl.\phi.b} = 19000 \text{ N/mm}^2$$

10.4 Analysis of the cylinder in axial direction

1. Step) Calculate all characteristic internal forces from the actions, which may cause internal forces in axial direction

$$\text{LC 1 Dead load: } n_{x.W} = \frac{W_{R,k} + W_{Cyl,k}}{D \cdot \pi} = \frac{4 + 19}{3\,000 \cdot \pi} \cdot 10^3 = 2,44 \text{ N/mm}$$

$$\text{LC 2 Liquid filling: } n_{x,hp} = 0$$

$$\text{LC 3 Long time design over pressure: } n_{x.PS.op.l} = PS_{op.l} \cdot \frac{D}{4} = 0,20 \cdot \frac{3\,000}{4} = 150,00 \text{ N/mm}$$

LC 4 Short time design over pressure: $n_{x,PS.op.s} = PS_{op.s} \cdot \frac{D}{4} = 0,25 \cdot \frac{3\,000}{4} = 187,50 \text{ N / mm}$

LC 5 Long time design negative pressure: $n_{x,PS.ep.l} = PS_{ep.l} \cdot \frac{D}{4} = 0,000 \cdot \frac{3\,000}{4} = 0,00 \text{ N / mm}$

LC 6 Short time design negative pressure: $n_{x,PS.ep.s} = PS_{ep.s} \cdot \frac{D}{4} = 0,005 \cdot \frac{3\,000}{4} = 3,75 \text{ N / mm}$

LC 7 Wind: Wind causes internal forces due to pressure and moment.

LC 7 A Wind moment:

$$M_{Cyl.wind} = \frac{c_f \cdot q_p \cdot (l_{cyl.tot} + H_R)^2 \cdot D}{2} = \frac{0,8 \cdot 0,8 \cdot (6\,610 + 590)^2 \cdot 3\,000}{2} \cdot 10^{-9} = 49,77 \text{ kNm}$$

$$n_{x,M.wind} = \frac{4 \cdot M_{Cyl.wind}}{\pi \cdot D^2} = \frac{4 \cdot 49,77}{\pi \cdot 3\,000^2} \cdot 10^6 = 7,04 \text{ N / mm}$$

LC 7 B Wind pressure $n_{x,pwind} = p_{wind} \cdot \frac{D}{4} = 0,48 \cdot \frac{3\,000}{4} \cdot 10^{-3} = 0,36 \text{ N / mm}$

LC 8 Snow: $n_{x,psnow} = p_{snow} \cdot \frac{D}{4} = 0,68 \cdot \frac{3\,000}{4} \cdot 10^{-3} = 0,51 \text{ N / mm}$

LC 9 Personnel loading: $n_{x,paccess} = p_{access} \cdot \frac{D}{4} = 1,5 \cdot \frac{3\,000}{4} \cdot 10^{-3} = 1,13 \text{ N / mm}$

LC 10 Temperature: The cylinder can expand freely. No axial forces occur.

10.4.1 Proof of strength (Ultimate limit state)

10.4.1.1 Design value of actions

2. Step) Find the decisive combination of actions

Fundamental combination for persistent or transient design situations

$$E_d = \sum \gamma_{G,j} \cdot G_{k,j} \cdot A_5^{long\ term} \oplus \gamma_{Q,1} \cdot Q_{k,1} \cdot A_5^{load\ time} \oplus \sum \gamma_{Q,i} \cdot \psi_{o,i} \cdot Q_{k,i} \cdot A_5^{load\ time}$$

To find the decisive combination of the separate actions, all actions are written down in the E matrix.

As we need $A_{5B} \cdot \gamma_F$ -fold loads for the strength analysis, the actions are multiplied with $A_{5B} \cdot \gamma_F$.

For γ_F factors refer to Table 12 of EN 13121-3.

The $A_{5B} \cdot \gamma_F$ fold internal forces are determined as follows $n_{x,d,R} = n_{x,k} \cdot \gamma_F \cdot A_{5B}$

Then the Ψ -Matrix with the for the separate load cases corresponding Ψ -factors has to be created.

For Ψ factors refer to Table 11 of EN 13121-3.

In this example 4 combinations for compression loads and 2 combinations for tension loads are created.

With this number of combinations, all possibilities to get the maximum $n_{x,d,R}$ load are checked.

Each variable action is one time the predominant action with $\Psi = 1,0$.

In the columns of the Ψ -matrix is determined, which load cases are combined with which Ψ -factor in each load combination.

Because the liquid column doesn't create any cylinder axial forces for this kind of vessel, all Ψ -factors for the load case LC 2 are 0. This would be different for example, if the vessel would be suspended with a support ring.

The way of calculation is shown as an example with a spreadsheet analysis.

E-Matrix					
LC	Action	$n_{x,k}$	γ_F	A_{5B}	$n_{x,d,R}$
		[N/mm]			[N/mm]
LC 1	$n_{x,w} =$	2,44	1,35	1,60	5,27
LC 2	$n_{x,hp} =$	61,31	1,35	1,60	132,4
LC 3	$n_{x,op,l} =$	150,0	1,50	1,60	360,0
LC 4	$n_{x,op,s} =$	187,5	1,50	1,00	281,3
LC 5	$n_{x,ep,l} =$	0,00	1,50	1,60	0,00
LC 6	$n_{x,ep,s} =$	3,75	1,50	1,00	5,63
LC 7A	$n_{x,M,wind} =$	7,04	1,50	1,00	10,56
LC 7B	$n_{x,p,wind} =$	0,36	1,50	1,00	0,54
LC 8	$n_{x,psnow} =$	0,51	1,50	1,40	1,07
LC 9	$n_{x,paccess} =$	1,13	1,50	1,00	1,69
LC 10	$n_{x,\Delta T} =$	0,00	1,00	1,60	0,00

Ψ_0 -Matrix					
CO.1	CO.2	CO.3	CO.4	CO.5	CO.6
1,0	1,0	1,0	1,0	0,0	0,0
1,0	1,0	1,0	1,0	0,0	0,0
0,0	0,0	0,0	0,0	1,0	0,0
0,0	0,0	0,0	0,0	0,0	1,0
1,0	1,0	1,0	0,0	0,0	0,0
0,0	0,0	0,0	1,0	0,0	0,0
1,0	0,6	0,6	0,0	1,0	0,0
1,0	0,6	0,6	0,0	0,0	0,0
0,5	1,0	0,5	0,5	0,0	0,0
0,0	0,0	1,0	0,0	0,0	0,0
1,0	1,0	1,0	1,0	1,0	1,0

$n_{x,d,R} * \Psi$ -Matrix						
Compression				Tension		
CO.1	CO.2	CO.3	CO.4	CO.5	CO.6	
[N/mm]	[N/mm]	[N/mm]	[N/mm]	[N/mm]	[N/mm]	
$n_{x,d,R} \cdot \Psi$	5,27	5,27	5,27	5,27	0,00	0,00
	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	360,0	0,00
	0,00	0,00	0,00	0,00	0,00	281,3
	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	5,63	0,00	0,00
	10,56	6,34	6,34	0,00	10,56	0,00
	0,54	0,32	0,32	0,00	0,00	0,00
	0,54	1,07	0,54	0,54	0,00	0,00
	0,00	0,00	1,69	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	0,00	0,00
$\Sigma =$	16,9	13,0	14,2	11,4	370,6	281,3

Then the internal load $n_{x,d,R}$ of a load case has to be multiplied with each corresponding Ψ -factor as it's shown in the $n_{x,d,R} * \Psi$ -Matrix below. After that, you have to summarize the columns of the several combinations.

The maximum value of the sums from combination 1 to 4 reflects the decisive compression load $n_{x,d,R}$ and is marked in red. The maximum value of the sums from combination 5-6 shows the decisive tension load $n_{x,d,R}$ and is marked in yellow.

Decisive design axial force: $n_{x,d,R} = 370,6 \text{ N/mm}$ (from CO.5)

10.4.1.2 Design value of corresponding resistance

Characteristic limit unit load: $U_{Lam,Cyl,x,k} = f_{Cyl,x,t,k} \cdot t_{Cyl} = 130 \cdot 11,7 = 1\,521 \text{ N/mm}$

Design value of limit unit load $U_{Lam,Cyl,x,Rd} = \frac{U_{Lam,Cyl,x,k}}{A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot \gamma_M} = \frac{1\,521}{1,0 \cdot 1,4 \cdot 1,20 \cdot 1,0 \cdot 1,4} = 647 \text{ N / mm}$

10.4.1.3 Verification

It shall be verified that: $E_d \leq R_d$

So the utilization is given with $\eta = \frac{E_d}{R_d} \leq 1 = \frac{371}{647} = 0,57 \leq 1$

10.4.2 Proof of strain (Serviceability limit state)

10.4.2.1 Design value of actions

Characteristic combination (used to verify limit strain)

$$E_{d,rare} = \sum G_{k,j} \oplus \sum Q_{k,1} \oplus \sum \psi_{o,1} \cdot Q_{k,i}$$

The characteristic combination is determined without taking into account any A_5 or γ_F factor.

The design internal forces are determined as follows $n_{x,d,\varepsilon} = n_{x,k}$

The way to determine the decisive load combination is similar as for the ultimate limit state.