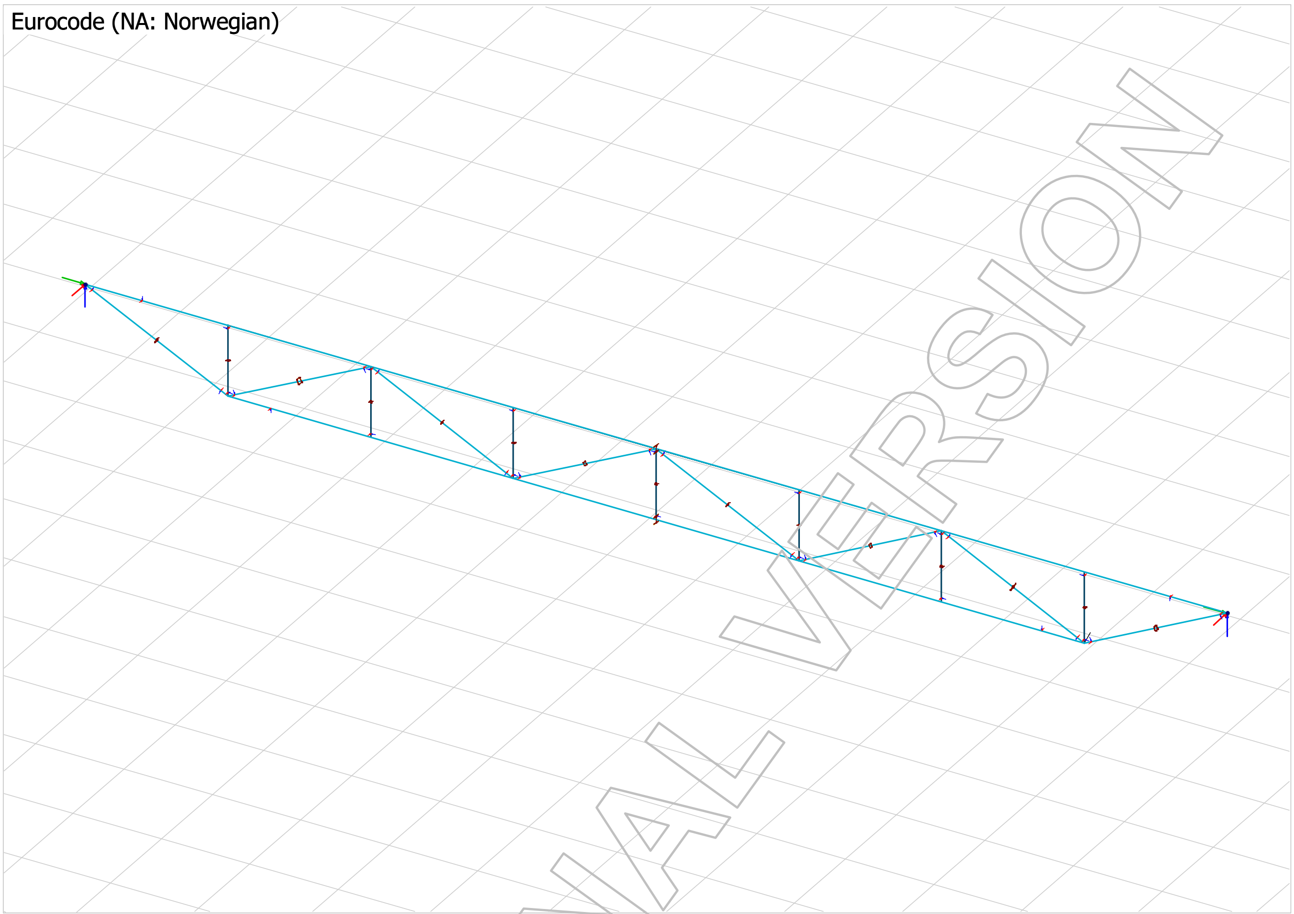
Vedlegg 4.2
FEM-Design dimensjonering av fagverk

1 Fagverk



Project: Kolvikbakken Ungdomsskole	Customer: Norconsult / NTNU
Description: Dimensjonering av fagverk	FEM-Design © StruSoft
Designed: Martin Eikrem, Sondre Aarseth og Fredrik Honningsvåg	Date: 30.03.2020 — Page: 1 / 21

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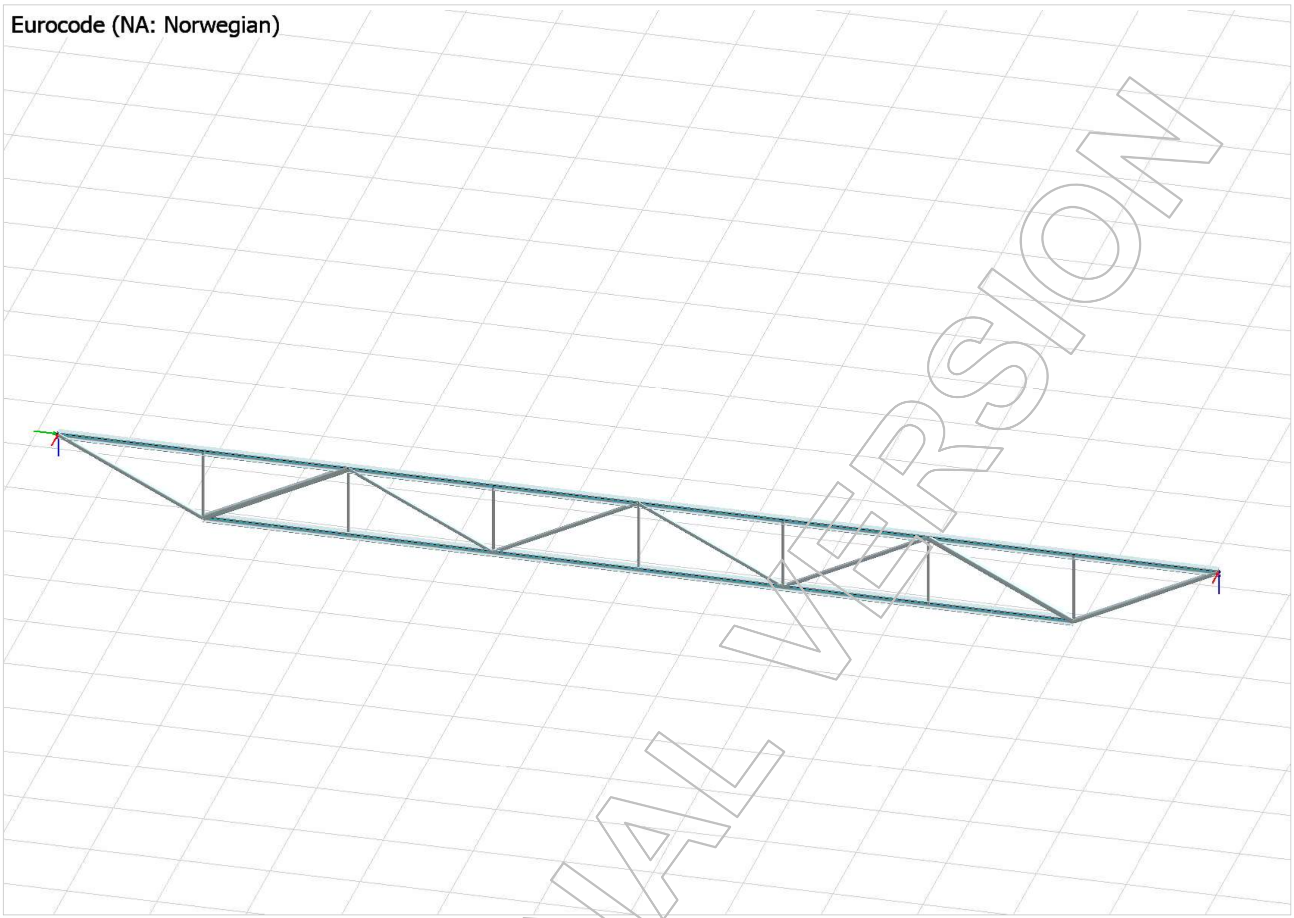
1.1 Utforming



1.2 Materialer

1.2.1 Stål

Steel materials

No.	Name	fyk(t<16)	fyk(16<=t<=40)	fyk(40<t<=63)	fyk(63<t<=80)	fyk(80<t<=100)
[-]	[-]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]
1	S 355	355	355	335	335	335

fyk(100<t<=150)	fyk(150<t<=200)	fyk(200<t<=250)	fyk(250<t<=400)	fuk(t<3)	fuk(3<=t<=40)
[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]
335	335	335	335	510	510

fuk(40<t<=100)	fuk(100<t<=150)	fuk(150<t<=250)	fuk(250<t<=400)	Gamma M0	Gamma M0, Acc
[N/mm2]	[N/mm2]	[N/mm2]	[N/mm2]	[-]	[-]
470	470	470	470	1.050	1.000

Gamma M1	Gamma M1, Acc	Gamma M2	Gamma M2, Acc	Gamma M5	Gamma M5, Acc	Gamma Mfi
[-]	[-]	[-]	[-]	[-]	[-]	[-]
1.050	1.000	1.250	1.000	1.000	1.000	1.000

Ek	Poisson's ratio	G	Therm. coeff.	Density
[N/mm2]	[-]	[N/mm2]	[1/°C]	[t/m3]
210000.000	0.300	80769.000	1.2000e-05	7.850000

1.3 Dimensjoner

1.3.1 Bjelker

Beams

ID	Material	Section, start	Section, end	Ecc. mode.
[-]	[-]	[-]	[-]	[-]
B.1.1	S 355	HE-B 160	HE-B 160	Release at END
B.2.1	S 355	HE-B 160	HE-B 160	Release at END
B.3.1	S 355	KKR 100x100x10	KKR 100x100x10	Release at END
B.4.1	S 355	KKR 120x120x6	KKR 120x120x6	Release at END
B.5.1	S 355	KKR 80x80x5	KKR 80x80x5	Release at END
B.6.1	S 355	KKR 80x80x5	KKR 80x80x5	Release at END
B.7.1	S 355	KKR 80x80x5	KKR 80x80x5	Release at END
B.8.1	S 355	KKR 80x80x5	KKR 80x80x5	Release at END
B.9.1	S 355	KKR 120x120x6	KKR 120x120x6	Release at END
B.10.1	S 355	KKR 100x100x10	KKR 100x100x10	Release at END

1.3.2 Søyler

Columns

ID	Material	Section, start	Section, end	Ecc. mode.
[-]	[-]	[-]	[-]	[-]
C.1.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.2.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.3.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.4.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.5.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.6.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END
C.7.1	S 355	KKR 60x60x5	KKR 60x60x5	Release at END

1.4 Laster

1.4.1 Lasttilfeller

Load cases

No.	Name	Type	Duration class
1	Snølast	Ordinary	Short-term
2	Påført egenlast	Ordinary	Permanent
3	Egenlast	+Struc. dead load	Permanent

1.4.2 Lastkombinasjoner

Load combinations

No.	Name	Type	Factor	Load cases
1	Bruddgrensetilstand B1	Ultimate	1.350	Påført egenlast
			1.050	Snølast
			1.350	Egenlast (+Struc. dead load)
2	Bruddgrensetilstand B2	Ultimate	1.200	Påført egenlast
			1.500	Snølast
			1.200	Egenlast (+Struc. dead load)
3	Bruksgrensetilstand	Quasi-permanent	1.000	Påført egenlast
			0.600	Snølast
			1.000	Egenlast (+Struc. dead load)

1.4.3 Linjelaster

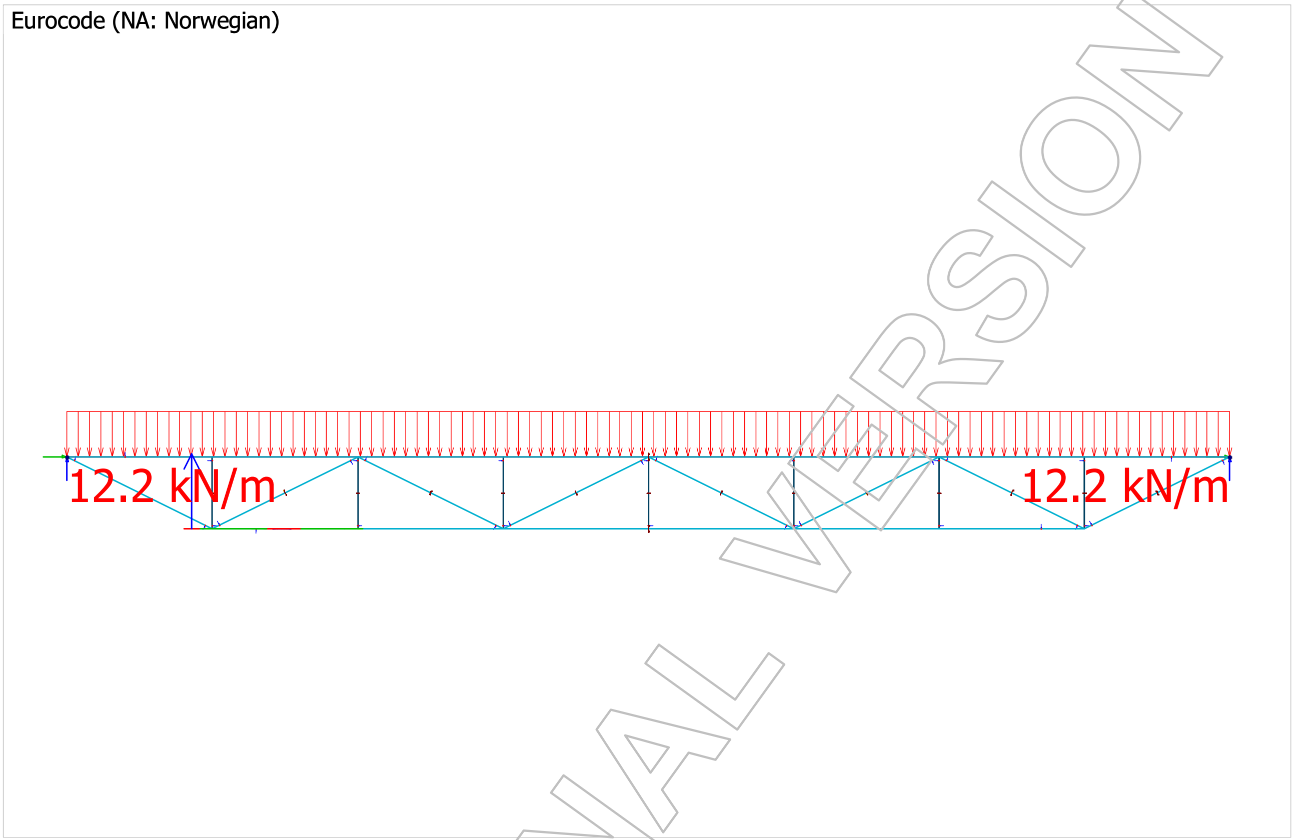
Line loads

No.	q1	q2	m1	m2	Load case	Comment	Applied on Ecc.	Intensity	Direction
[-]	[kN/m]	[kN/m]	[kNm/m]	[kNm/m]	[-]	[-]	[-]	[-]	[-]
1	2.652	2.652	0.000	0.000	Påført egenlast		No	Action	Constant
2	12.240	12.240	0.000	0.000	Snølast		No	Action	Constant

1.5 Krefter

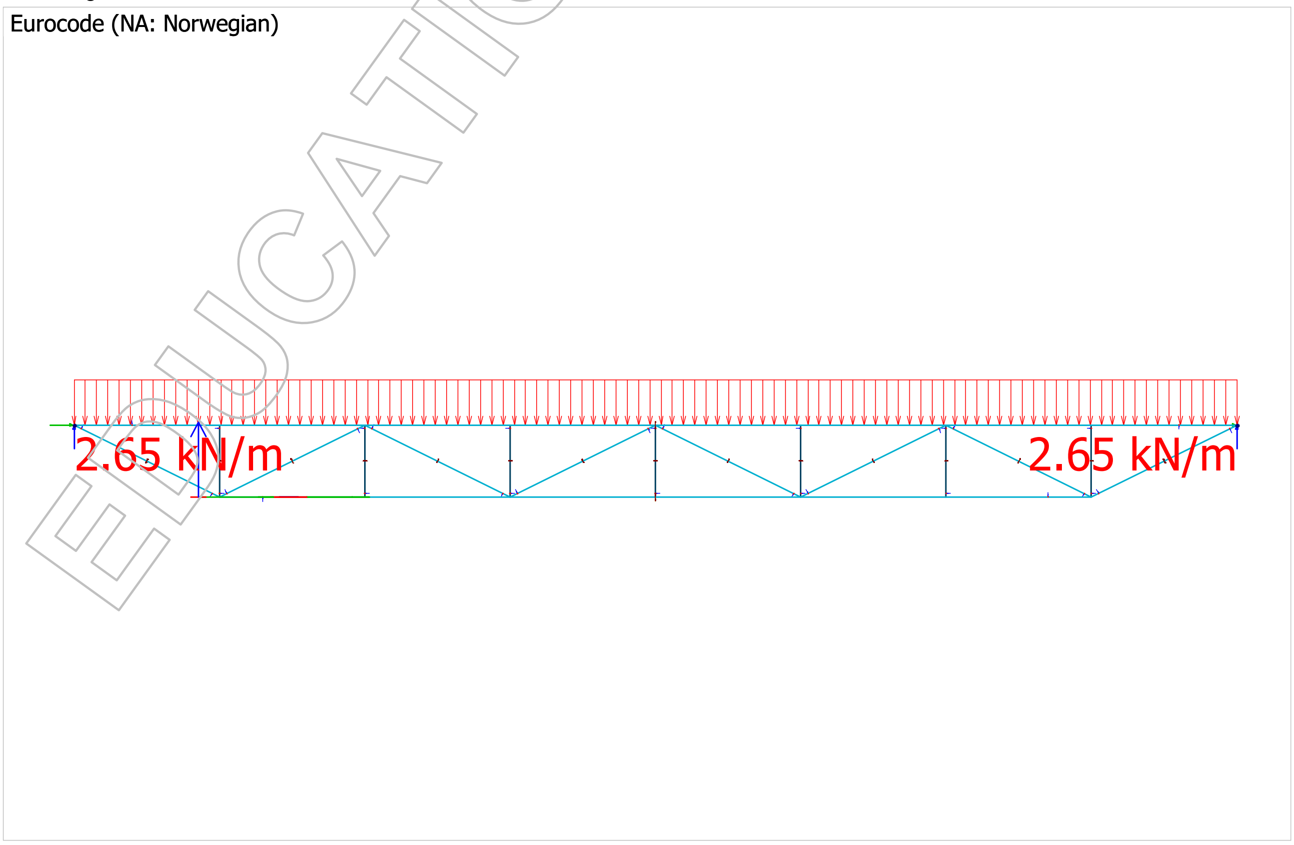
1.5.1 Snølast

Snølast



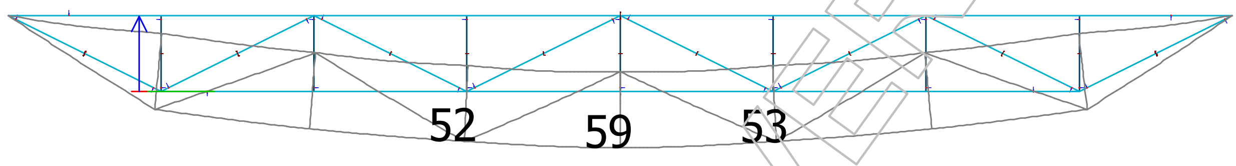
1.5.2 Påført egenlast

Påført egenlast



1.6 Nedbøying

Eurocode (NA: Norwegian) code: Max. of combinations, Ultimate - Translational displacements - All components+ - Graph - [mm]

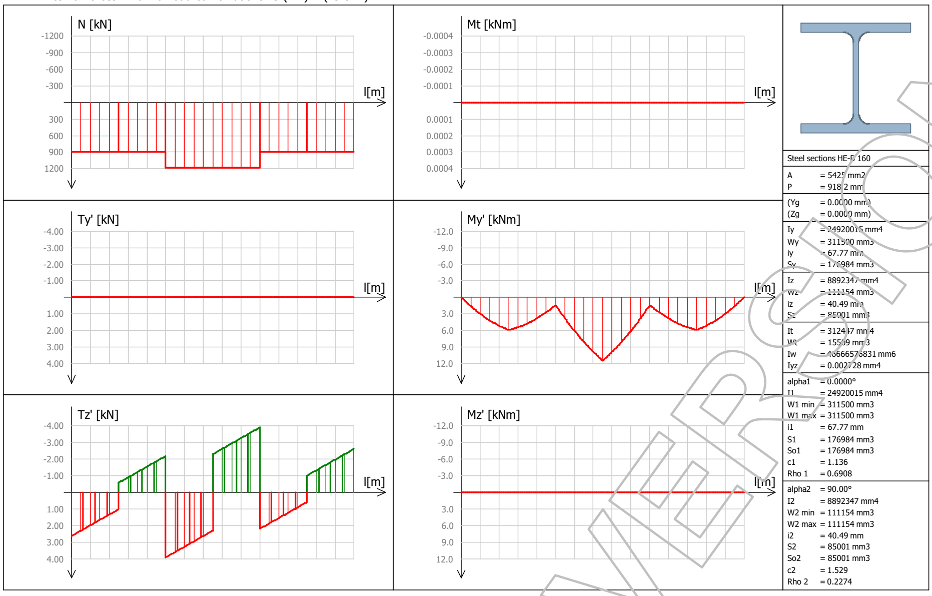


1.7 Utnyttelse

Bar, Utilization, Load comb.: Bruddgrensetilstand B2

Member	Section	Status	Maximum	RCS	FB	TFB	LTB,t	LTB,b	IA
[-]	[-]	[-]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
B.1.1	HE-B 160	Real	74	74	-	-	11	0	11
B.2.1	HE-B 160	Real	42	38	31	20	17	25	42
B.3.1	KKR 100x100x10	Real	55	55	-	-	1	0	1
B.4.1	KKR 120x120x6	Real	88	46	86	45	1	0	88
B.5.1	KKR 80x80x5	Real	54	54	-	-	1	0	1
B.6.1	KKR 80x80x5	Real	51	16	49	14	1	0	51
B.7.1	KKR 80x80x5	Real	51	16	49	14	1	0	51
B.8.1	KKR 80x80x5	Real	54	54	-	-	1	0	1
B.9.1	KKR 120x120x6	Real	88	46	86	45	1	0	88
B.10.1	KKR 100x100x10	Real	55	55	-	-	1	0	1
C.1.1	KKR 60x60x5	Real	2	1	2	1	0	0	-
C.2.1	KKR 60x60x5	Real	1	0	1	0	0	0	-
C.3.1	KKR 60x60x5	Real	38	21	38	21	0	0	-
C.4.1	KKR 60x60x5	Real	42	24	42	24	0	0	-
C.5.1	KKR 60x60x5	Real	1	0	1	0	0	0	-
C.6.1	KKR 60x60x5	Real	42	24	42	24	0	0	-
C.7.1	KKR 60x60x5	Real	38	21	38	21	0	0	-

B.1.1 - Internal forces - Max. of load combinations: U (N+) - (19.3 m)



B.1.1
Maximum of load combinations

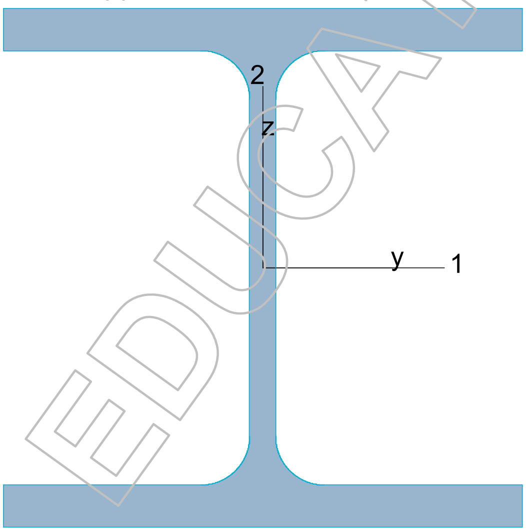
S 355

$E = 210000\ \text{N/mm}^2$

$G = 80769\ \text{N/mm}^2$

$\gamma_{M0,ult}$	=	1.05	$\gamma_{M0,acc/seis}$	=	1.00
$\gamma_{M1,ult}$	=	1.05	$\gamma_{M1,acc/seis}$	=	1.00
$\gamma_{M2,ult}$	=	1.25	$\gamma_{M2,acc/seis}$	=	1.00

HE-B 160



P	=	918 mm	f_y	=	355 N/mm^2
A	=	5425 mm^2	ε	=	0.81
I_y	=	2.492e+07 mm^4	λ_1	=	76.40
I_z	=	8.892e+06 mm^4			
I_1	=	2.492e+07 mm^4			
I_2	=	8.892e+06 mm^4			
$W_{pl,1}$	=	3.540e+05 mm^3			
$W_{pl,2}$	=	1.700e+05 mm^3			
$W_{el,min,1}$	=	3.115e+05 mm^3			
$W_{el,min,2}$	=	1.112e+05 mm^3			
i_1	=	68 mm			
i_2	=	40 mm			
I_t	=	3.124e+05 mm^4			
I_w	=	4.667e+10 mm^6			

Shear resistance, 1-1 - Part 1-1: 6.2.6, 6.2.8
LC: 'Bruddgrensetilstand B2', x = 12900 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$$V_{1,pl,Rd} = \frac{A_{1,v} \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = \frac{4353 \cdot 355}{\sqrt{3} \cdot 1.05} = 849.73 \text{ kN} \quad (6.18)$$

$$V_{1,pl,T,Rd} = \sqrt{1 - \frac{\tau_{t,Ed}}{1.25 \left(f_y / \sqrt{3}\right) / \gamma_{M0}}} \cdot V_{1,pl,Rd} =$$

$$= \sqrt{1 - \frac{0.00}{1.25 \left(355 / \sqrt{3}\right) / 1.05}} \cdot 849.73 = 849.73 \text{ kN} \quad (6.26)$$

$$\frac{V_{1,Ed}}{V_{1,pl,T,Rd}} = \frac{0.00}{849.73} = 0.00 \leq 1.00 \quad (6.25) \text{ - OK}$$

Shear resistance, 2-2 - Part 1-1: 6.2.6, 6.2.8
LC: 'Bruddgrensetilstand B2', x = 12900 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$$V_{2,pl,Rd} = \frac{A_{2,v} \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = \frac{1759 \cdot 355}{\sqrt{3} \cdot 1.05} = 343.38 \text{ kN} \quad (6.18)$$

$$V_{2,pl,T,Rd} = \sqrt{1 - \frac{\tau_{t,Ed}}{1.25 \left(f_y / \sqrt{3}\right) / \gamma_{M0}}} \cdot V_{2,pl,Rd} =$$

$$= \sqrt{1 - \frac{0.00}{1.25 \left(355 / \sqrt{3}\right) / 1.05}} \cdot 343.38 = 343.38 \text{ kN} \quad (6.26)$$

$$\frac{V_{2,Ed}}{V_{2,pl,T,Rd}} = \frac{3.93}{343.38} = 0.01 \leq 1.00 \quad (6.25) \text{ - OK}$$

Torsional resistance - Part 1-1: 6.2.7
LC: 'Bruddgrensetilstand B1', x = 0 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$\tau_{max,unit} = 64.48 \frac{N/mm^2}{kNm}$ is calculated by FEM analysis.

$$T_{Rd} = \frac{f_y}{\sqrt{3} \cdot \tau_{max,unit} \cdot \gamma_{M0}} = \frac{355}{\sqrt{3} \cdot 64.48 \cdot 1.05} = 3.03 \text{ kNm}$$

$$\frac{T_{Ed}}{T_{Rd}} = \frac{0.00}{3.03} = 0.00 \leq 1.00 \quad (6.23) \text{ - OK}$$

Shear stress - Part 1-1: 6.2.6
Not relevant

Normal stress - Part 1-1: 6.2.1
Not relevant

Normal capacity - Part 1-1: 6.2
LC: 'Bruddgrensetilstand B2', x = 9675 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$V_{1,Ed} = 0.00 \text{ kN} \leq 0.5 \cdot V_{1,pl,T,Rd} = 0.5 \cdot 849.73 = 424.87 \text{ kN} \rightarrow \rho_1 = 0.00$

$V_{2,Ed} = 2.31 \text{ kN} \leq 0.5 \cdot V_{2,pl,T,Rd} = 0.5 \cdot 343.38 = 171.69 \text{ kN} \rightarrow \rho_1 = 0.00$

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{1,Ed}}{M_{1,Rd}} + \frac{M_{2,Ed}}{M_{2,Rd}} = \frac{1180.84}{1834.21} + \frac{11.45}{119.67} + \frac{0.00}{57.48} = 0.74 \leq 1.00 \quad (6.2) \text{ - OK}$$

Flexural buckling, 1-1 - Part 1-1: 6.3.1
Not relevant

Flexural buckling, 2-2 - Part 1-1: 6.3.1
Not relevant

Torsional-flexural buckling - Part 1-1: 6.3.1
Not relevant

Lateral torsional buckling, top flange - Part 1-1: 6.3.2.2
LC: 'Bruddgrensetilstand B2', x = 9675 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$$N_{cr,LT} = \frac{\pi^2 \cdot E \cdot I_z}{(k_z \cdot L_{cr})^2} = \frac{\pi^2 \cdot 2.100e{+}05 \cdot 8.892e{+}06}{(1.00 \cdot 3225)^2} = 1772.08 \text{ kN}$$

Loaded on top edge.

$$Z = (C_2 \cdot z_g - C_3 \cdot z_j) = (0.00 \cdot -80 - 0.96 \cdot 0) = 0.00 \text{ mm}$$

$$M_{cr} = C_1 \cdot N_{cr,LT} \cdot \left\{ \left[\left(\frac{k_z}{k_w} \right)^2 \cdot \frac{I_w}{I_z} + \frac{G \cdot I_t}{N_{cr,LT}} + Z^2 \right]^{0.5} - Z \right\} =$$

$$= 1.65 \cdot 1.772e{+}06 \cdot \left\{ \left[\left(\frac{1.00}{1.00} \right)^2 \cdot \frac{4.667e{+}10}{8.892e{+}06} + \frac{8.077e{+}04 \cdot 3.124e{+}05}{1.772e{+}06} + 0.00^2 \right]^{0.5} - 0.00 \right\} =$$

$$= 407.60 \text{ kNm}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y \cdot f_y}{M_{cr}}} = \sqrt{\frac{353967 \cdot 355}{4.076e{+}08}} = 0.56$$

$\alpha_{LT} = 0.21$ (Buckling curve: a)

$$\varphi_{LT} = 0.5 \left[1 + \alpha_{LT} \cdot (\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2 \right] =$$

$$= 0.5 \left[1 + 0.21 \cdot (0.56 - 0.2) + 0.56^2 \right] = 0.69$$

$$\chi_{LT} = \min\left(\frac{1}{\varphi_{LT} + \sqrt{\varphi_{LT}^2 - \bar{\lambda}_{LT}^2}}, 1.0 \right) = \min\left(\frac{1}{0.69 + \sqrt{0.69^2 - 0.56^2}}, 1.0 \right) = 0.91 \qquad (6.56)$$

$$M_{y,b,Rd} = \frac{\chi_{LT} \cdot W_y \cdot f_y}{\gamma_{M1}} = \frac{0.91 \cdot 353967 \cdot 355}{1.05} = 108.45 \text{ kNm} \qquad (6.55)$$

$$\frac{M_{1,Ed}}{M_{y,b,Rd}} = \frac{11.45}{108.45} = 0.11 \leq 1.00 \qquad (6.54) \text{ - OK}$$

Lateral torsional buckling, bottom flange - Part 1-1: 6.3.2.2
LC: 'Bruddgrensetilstand B1', x = 0 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

$$N_{cr,LT} = \frac{\pi^2 \cdot E \cdot I_z}{(k_z \cdot L_{cr})^2} = \frac{\pi^2 \cdot 2.100e{+}05 \cdot 8.892e{+}06}{(1.00 \cdot 3225)^2} = 1772.08 \text{ kN}$$

Loaded on top edge.

$$Z = (C_2 \cdot z_g - C_3 \cdot z_j) = (0.09 \cdot 80 - 0.75 \cdot 0) = 6.95 \text{ mm}$$

$$M_{cr} = C_1 \cdot N_{cr,LT} \cdot \left\{ \left[\left(\frac{k_z}{k_w}\right)^2 \cdot \frac{I_w}{I_z} + \frac{G \cdot I_t}{N_{cr,LT}} + Z^2 \right]^{0.5} - Z \right\} =$$

$$= 1.45 \cdot 1.772e{+}06 \cdot \left\{ \left[\left(\frac{1.00}{1.00}\right)^2 \cdot \frac{4.667e{+}10}{8.892e{+}06} + \frac{8.077e{+}04 \cdot 3.124e{+}05}{1.772e{+}06} + 6.95^2 \right]^{0.5} - 6.95 \right\} =$$

$$= 340.78 \text{ kNm}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y \cdot f_y}{M_{cr}}} = \sqrt{\frac{353967 \cdot 355}{3.408e{+}08}} = 0.61$$

$\alpha_{LT} = 0.21$ (Buckling curve: a)

$$\varphi_{LT} = 0.5\left[1 + \alpha_{LT} \cdot (\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2\right] =$$

$$= 0.5\left[1 + 0.21 \cdot (0.61 - 0.2) + 0.61^2\right] = 0.73$$

$$\chi_{LT} = \min\left(\frac{1}{\varphi_{LT} + \sqrt{\varphi_{LT}^2 - \bar{\lambda}_{LT}^2}}, 1.0\right) = \min\left(\frac{1}{0.73 + \sqrt{0.73^2 - 0.61^2}}, 1.0\right) = 0.89 \qquad (6.56)$$

$$M_{y,b,Rd} = \frac{\chi_{LT} \cdot W_y \cdot f_y}{\gamma_{M1}} = \frac{0.89 \cdot 353967 \cdot 355}{1.05} = 106.18 \text{ kNm} \qquad (6.55)$$

$$\frac{M_{1,Ed}}{M_{y,b,Rd}} = \frac{0.00}{106.18} = 0.00 \leq 1.00 \qquad (6.54) \text{ - OK}$$

Interaction between normal force and bending 1. - Part 1-1: 6.3.3
LC: 'Bruddgrensetilstand B2', x = 9675 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

k_{ij} factors are calculated according to Method 1

C_{my}	=	1.00	C_{yy}	=	1.00
C_{mz}	=	1.00	C_{yz}	=	0.96
C_{mLT}	=	1.00	C_{zy}	=	1.00
			C_{zz}	=	0.95

$$M_{2,Rk} = f_y \cdot W_{pl,2} = 355 \cdot 170002 = 60.35 \text{ kNm}$$

$$\frac{N_{Ed}^{comp}}{N_{b,Rd,1}} + k_{11} \cdot \frac{M_{1,Ed}}{M_{y,b,Rd}} + k_{12} \cdot \frac{M_{2,Ed}}{\frac{M_{2,Rk}}{\gamma_{M1}}} =$$

$$= \frac{0.00}{1514.03} + 1.00 \cdot \frac{11.45}{108.45} + 0.72 \cdot \frac{0.00}{\frac{60.35}{1.05}} = 0.11 \leq 1.00 \qquad (6.61) \text{ - OK}$$

Interaction between normal force and bending 2. - Part 1-1: 6.3.3
LC: 'Bruddgrensetilstand B2', x = 9675 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

k_{ij} factors are calculated according to Method 1

C_{my}	= 1.00	C_{yy}	= 1.00
C_{mz}	= 1.00	C_{yz}	= 0.96
C_{mLT}	= 1.00	C_{zy}	= 1.00
		C_{zz}	= 0.95

$M_{2,Rk} = f_y \cdot W_{pl,2} = 355 \cdot 170002 = 60.35$ kNm

$$\frac{N_{Ed}^{comp}}{N_{b,Rd,2}} + k_{21} \cdot \frac{M_{1,Ed}}{M_{y,b,Rd}} + k_{22} \cdot \frac{M_{2,Ed}}{\frac{M_{2,Rk}}{\gamma_{M1}}} =$$

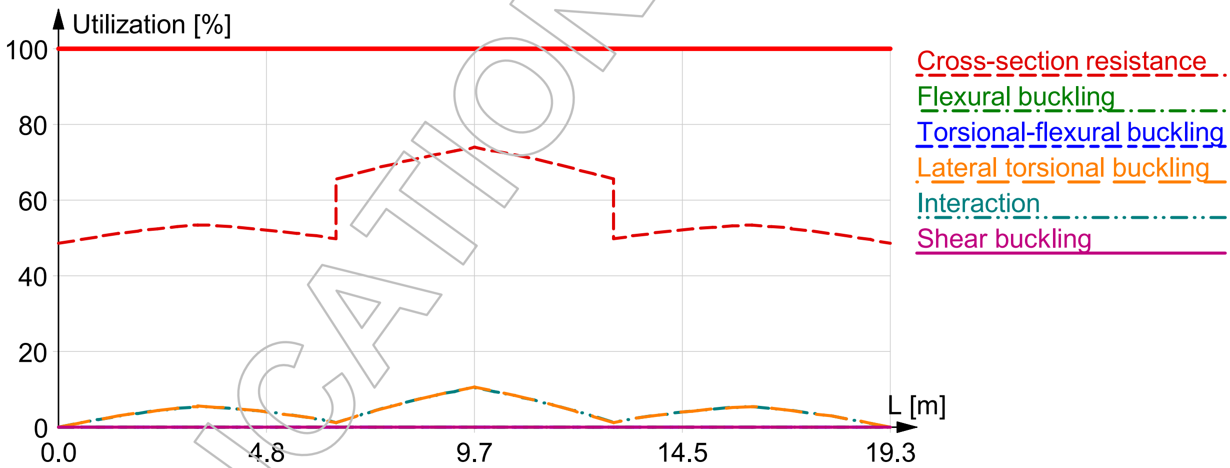
$$= \frac{0.00}{945.71} + 0.52 \cdot \frac{11.45}{108.45} + 1.05 \cdot \frac{0.00}{\frac{60.35}{1.05}} = 0.06 \leq 1.00 \qquad (6.62) \text{ - OK}$$

Interaction between normal force and bending, 2nd order - Part 1-1: 6.3.3
Not relevant

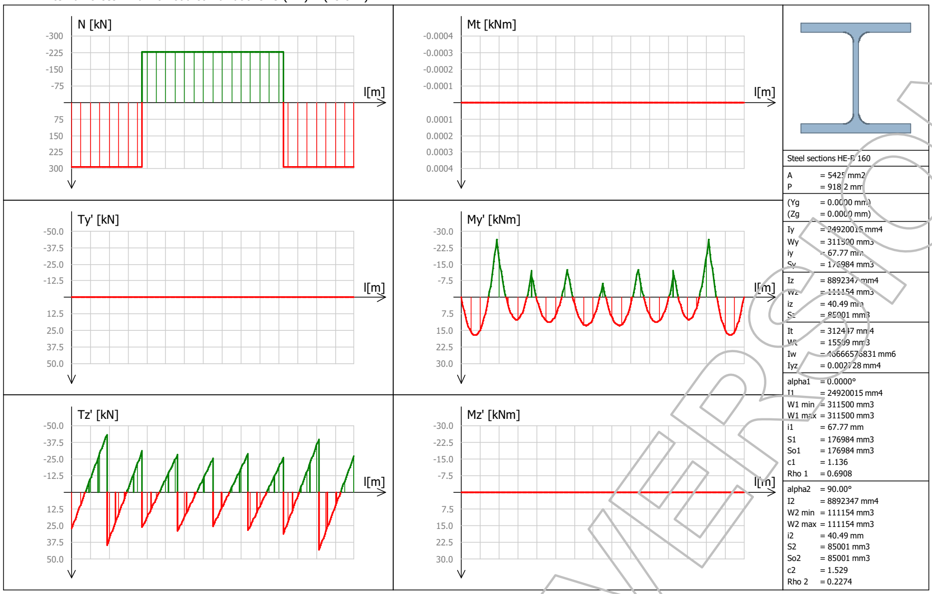
Shear buckling - Part 1-5: 5

$$\frac{h_w}{t} = \frac{134}{8} = 16.8 \leq \frac{72}{\eta} \cdot \varepsilon = \frac{72}{1.20} \cdot 0.81 = 48.8 \rightarrow \quad \text{Not relevant}$$

Summary



B.2.1 - Internal forces - Max. of load combinations: U (N+) - (25.8 m)

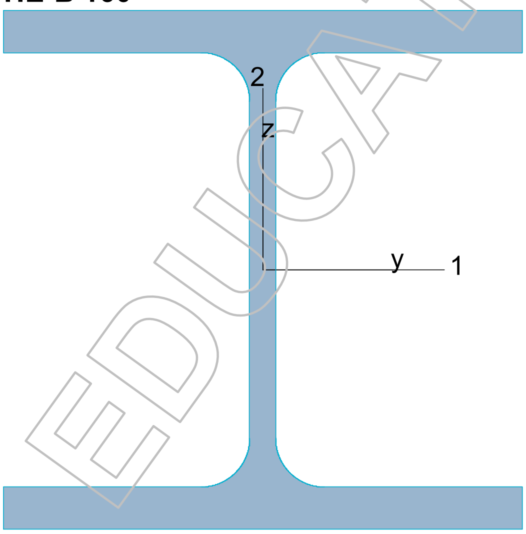


B.2.1
Maximum of load combinations

S 355

E	=	210000 N/mm^2			
G	=	80769 N/mm^2			
$\gamma_{M0,ult}$	=	1.05	$\gamma_{M0,acc/seis}$	=	1.00
$\gamma_{M1,ult}$	=	1.05	$\gamma_{M1,acc/seis}$	=	1.00
$\gamma_{M2,ult}$	=	1.25	$\gamma_{M2,acc/seis}$	=	1.00

HE-B 160



P	=	918 mm	f_y	=	355 N/mm^2
A	=	5425 mm^2	ε	=	0.81
I_y	=	2.492e+07 mm^4	λ_1	=	76.40
I_z	=	8.892e+06 mm^4			
I_1	=	2.492e+07 mm^4			
I_2	=	8.892e+06 mm^4			
$W_{pl,1}$	=	3.540e+05 mm^3			
$W_{pl,2}$	=	1.700e+05 mm^3			
$W_{el,min,1}$	=	3.115e+05 mm^3			
$W_{el,min,2}$	=	1.112e+05 mm^3			
i_1	=	68 mm			
i_2	=	40 mm			
I_t	=	3.124e+05 mm^4			
I_w	=	4.667e+10 mm^6			

Shear resistance, 1-1 - Part 1-1: 6.2.6, 6.2.8
LC: 'Bruddgrensetilstand B2', x = 3225 mm

$Class_N = 1,\quad Class_{M1} = 1,\quad Class_{M2} = 1$

$$V_{1,pl,Rd} = \frac{A_{1,v} \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = \frac{4353 \cdot 355}{\sqrt{3} \cdot 1.05} = 849.73\ \text{kN} \qquad (6.18)$$

$$V_{1,pl,T,Rd} = \sqrt{1 - \frac{\tau_{t,Ed}}{1.25\left(f_y / \sqrt{3}\right) / \gamma_{M0}}} \cdot V_{1,pl,Rd} =$$

$$= \sqrt{1 - \frac{0.00}{1.25\left(355 / \sqrt{3}\right) / 1.05}} \cdot 849.73 = 849.73\ \text{kN} \qquad (6.26)$$

$$\frac{V_{1,Ed}}{V_{1,pl,T,Rd}} = \frac{0.00}{849.73} = 0.00 \leq 1.00 \qquad (6.25)\text{ - OK}$$

Shear resistance, 2-2 - Part 1-1: 6.2.6, 6.2.8
LC: 'Bruddgrensetilstand B2', x = 3225 mm

$Class_N = 1,\quad Class_{M1} = 1,\quad Class_{M2} = 1$

$$V_{2,pl,Rd} = \frac{A_{2,v} \cdot f_y}{\sqrt{3} \cdot \gamma_{M0}} = \frac{1759 \cdot 355}{\sqrt{3} \cdot 1.05} = 343.38\ \text{kN} \qquad (6.18)$$

$$V_{2,pl,T,Rd} = \sqrt{1 - \frac{\tau_{t,Ed}}{1.25\left(f_y / \sqrt{3}\right) / \gamma_{M0}}} \cdot V_{2,pl,Rd} =$$

$$= \sqrt{1 - \frac{0.00}{1.25\left(355 / \sqrt{3}\right) / 1.05}} \cdot 343.38 = 343.38\ \text{kN} \qquad (6.26)$$

$$\frac{V_{2,Ed}}{V_{2,pl,T,Rd}} = \frac{43.62}{343.38} = 0.13 \leq 1.00 \qquad (6.25)\text{ - OK}$$

Torsional resistance - Part 1-1: 6.2.7
LC: 'Bruddgrensetilstand B1', x = 0 mm

$Class_N = 1,\quad Class_{M1} = 1,\quad Class_{M2} = 1$

$\tau_{max,unit} = 64.48\ \frac{\text{N/mm}^2}{\text{kNm}}$ is calculated by FEM analysis.

$$T_{Rd} = \frac{f_y}{\sqrt{3} \cdot \tau_{max,unit} \cdot \gamma_{M0}} = \frac{355}{\sqrt{3} \cdot 64.48 \cdot 1.05} = 3.03\ \text{kNm}$$

$$\frac{T_{Ed}}{T_{Rd}} = \frac{0.00}{3.03} = 0.00 \leq 1.00 \qquad (6.23)\text{ - OK}$$

Shear stress - Part 1-1: 6.2.6
Not relevant

Normal stress - Part 1-1: 6.2.1
Not relevant

Normal capacity - Part 1-1: 6.2
LC: 'Bruddgrensetilstand B2', x = 22575 mm

$Class_N = 1,\quad Class_{M1} = 1,\quad Class_{M2} = 1$

$V_{1,Ed} = 0.00\ \text{kN} \leq 0.5 \cdot V_{1,pl,T,Rd} = 0.5 \cdot 849.73 = 424.87\ \text{kN} \rightarrow \rho_1 = 0.00$

$V_{2,Ed} = 39.87\ \text{kN} \leq 0.5 \cdot V_{2,pl,T,Rd} = 0.5 \cdot 343.38 = 171.69\ \text{kN} \rightarrow \rho_1 = 0.00$

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{1,Ed}}{M_{1,Rd}} + \frac{M_{2,Ed}}{M_{2,Rd}} = \frac{292.37}{1834.21} + \frac{26.05}{119.67} + \frac{0.00}{57.48} = 0.38 \leq 1.00 \qquad (6.2)\text{ - OK}$$

Flexural buckling, 1-1 - Part 1-1: 6.3.1
LC: 'Bruddgrensetilstand B2', x = 6450 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

$$\bar{\lambda}_1 = \frac{L_{cr,1}}{i_1 \cdot \lambda_1} = \frac{3225}{68 \cdot 76.40} = 0.62 \qquad (6.50)$$

$\alpha_1 = 0.34$ (Buckling curve: b)

$$\varphi_1 = 0.5\left[1 + \alpha_1 \cdot (\bar{\lambda}_1 - 0.2) + \bar{\lambda}_1^2\right] = 0.5\left[1 + 0.34 \cdot (0.62 - 0.2) + 0.62^2\right] = 0.77$$

$$\chi_1 = \min\left(\frac{1}{\varphi_1 + \sqrt{\varphi_1^2 - \bar{\lambda}_1^2}}, 1.0\right) = \min\left(\frac{1}{0.77 + \sqrt{0.77^2 - 0.62^2}}, 1.0\right) = 0.83 \qquad (6.49)$$

$$N_{b,Rd,1} = \frac{\chi_1 \cdot A \cdot f_y}{\gamma_{M1}} = \frac{0.83 \cdot 5425 \cdot 355}{1.05} = 1514.03 \text{ kN} \qquad (6.47)$$

$$\frac{N_{Ed}}{N_{b,Rd,1}} = \frac{292.38}{1514.03} = 0.19 \leq 1.00 \qquad (6.46) \text{ - OK}$$

Flexural buckling, 2-2 - Part 1-1: 6.3.1
LC: 'Bruddgrensetilstand B2', x = 6450 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

$$\bar{\lambda}_2 = \frac{L_{cr,2}}{i_2 \cdot \lambda_1} = \frac{3225}{40 \cdot 76.40} = 1.04 \qquad (6.50)$$

$\alpha_2 = 0.49$ (Buckling curve: c)

$$\varphi_2 = 0.5\left[1 + \alpha_2 \cdot (\bar{\lambda}_2 - 0.2) + \bar{\lambda}_2^2\right] = 0.5\left[1 + 0.49 \cdot (1.04 - 0.2) + 1.04^2\right] = 1.25$$

$$\chi_2 = \min\left(\frac{1}{\varphi_2 + \sqrt{\varphi_2^2 - \bar{\lambda}_2^2}}, 1.0\right) = \min\left(\frac{1}{1.25 + \sqrt{1.25^2 - 1.04^2}}, 1.0\right) = 0.52 \qquad (6.49)$$

$$N_{b,Rd,2} = \frac{\chi_2 \cdot A \cdot f_y}{\gamma_{M1}} = \frac{0.52 \cdot 5425 \cdot 355}{1.05} = 945.71 \text{ kN} \qquad (6.47)$$

$$\frac{N_{Ed}}{N_{b,Rd,2}} = \frac{292.38}{945.71} = 0.31 \leq 1.00 \qquad (6.46) \text{ - OK}$$

Torsional-flexural buckling - Part 1-1: 6.3.1
LC: 'Bruddgrensetilstand B2', x = 6450 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

$$i_0 = \sqrt{i_1^2 + i_2^2 + y_0^2 + z_0^2} = \sqrt{68^2 + 40^2 + 0^2 + 0^2} = 79 \text{ mm}$$

$$N_{cr,1} = \frac{\pi^2 \cdot E \cdot I_1}{L_{cr,1}^2} = \frac{\pi^2 \cdot 210000 \cdot 24920015}{3225^2} = 4966.10 \text{ kN}$$

$$N_{cr,2} = \frac{\pi^2 \cdot E \cdot I_2}{L_{cr,2}^2} = \frac{\pi^2 \cdot 210000 \cdot 8892347}{3225^2} = 1772.08 \text{ kN}$$

$$N_{cr,T} = \frac{1}{i_0^2}\left(G \cdot I_t + \frac{\pi^2 \cdot E \cdot I_w}{L_t^2}\right) =$$

$$= \frac{1}{79^2}\left(80769 \cdot 3.124e{+}05 + \frac{\pi^2 \cdot 210000 \cdot 4.667e{+}10}{3225^2}\right) = 5541.24 \text{ kN}$$

$$i_0^2\,(N - N_{cr,1})\,(N - N_{cr,2})\,(N - N_{cr,T}) - N^2\,y_0^2\,(N - N_{cr,2}) - N^2\,z_0^2\,(N - N_{cr,1}) =$$

$$= 79^2\,(N - 4966.10)\,(N - 1772.08)\,(N - 5541.24) - N^2\,0^2\,(N - 1772.08) - N^2\,0^2\,(N - 4966.10) = 0$$

Smallest root of the above equation related to the torsional-flexural buckling:

$N_{cr,TF} = 5541.24$ kN

$N_{cr} = \min(N_{cr,T}, N_{cr,TF}) = \min(5541.24, 5541.24) = 5541.24$ kN

$$\bar{\lambda}_T = \sqrt{\frac{A \cdot f_y}{N_{cr}}} = \sqrt{\frac{5425 \cdot 355}{5541.24}} = 0.59 \qquad (6.53)$$

$\alpha_T = 0.49$ (Buckling curve: c)

$$\varphi_T = 0.5\left[1 + \alpha_T \cdot (\bar{\lambda}_T - 0.2) + \bar{\lambda}_T^2\right] = 0.5\left[1 + 0.49 \cdot (0.59 - 0.2) + 0.59^2\right] = 0.77$$

$$\chi_T = \min\left(\frac{1}{\varphi_T + \sqrt{\varphi_T^2 - \bar{\lambda}_T^2}}, 1.0\right) = \min\left(\frac{1}{0.77 + \sqrt{0.77^2 - 0.59^2}}, 1.0\right) = 0.79 \qquad (6.49)$$

$$N_{b,Rd,T} = \frac{\chi_T \cdot A \cdot f_y}{\gamma_{M1}} = \frac{0.79 \cdot 5425 \cdot 355}{1.05} = 1451.90 \text{ kN} \qquad (6.47)$$

$$\frac{N_{Ed}}{N_{b,Rd,T}} = \frac{292.38}{1451.90} = 0.20 \leq 1.00 \text{ - OK}$$

Lateral torsional buckling, top flange - Part 1-1: 6.3.2.2
LC: 'Bruddgrensetilstand B2', x = 14282 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

$$N_{cr,LT} = \frac{\pi^2 \cdot E \cdot I_z}{(k_z \cdot L_{cr})^2} = \frac{\pi^2 \cdot 2.100e{+}05 \cdot 8.892e{+}06}{(1.00 \cdot 3225)^2} = 1772.08 \text{ kN}$$

Loaded on top edge.

$$Z = (C_2 \cdot z_g - C_3 \cdot z_j) = (0.87 \cdot 80 - 0.75 \cdot 0) = 69.56 \text{ mm}$$

$$M_{cr} = C_1 \cdot N_{cr,LT} \cdot \left\{ \left[\left(\frac{k_z}{k_w} \right)^2 \cdot \frac{I_w}{I_z} + \frac{G \cdot I_t}{N_{cr,LT}} + Z^2 \right]^{0.5} - Z \right\} =$$

$$= 1.26 \cdot 1.772e{+}06 \cdot \left\{ \left[\left(\frac{1.00}{1.00} \right)^2 \cdot \frac{4.667e{+}10}{8.892e{+}06} + \frac{8.077e{+}04 \cdot 3.124e{+}05}{1.772e{+}06} + 69.56^2 \right]^{0.5} - 69.56 \right\} =$$

$$= 193.09 \text{ kNm}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y \cdot f_y}{M_{cr}}} = \sqrt{\frac{353967 \cdot 355}{1.931e{+}08}} = 0.81$$

$\alpha_{LT} = 0.21$ (Buckling curve: a)

$$\varphi_{LT} = 0.5 \left[1 + \alpha_{LT} \cdot (\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2 \right] =$$

$$= 0.5 \left[1 + 0.21 \cdot (0.81 - 0.2) + 0.81^2 \right] = 0.89$$

$$\chi_{LT} = \min\left(\frac{1}{\varphi_{LT} + \sqrt{\varphi_{LT}^2 - \bar{\lambda}_{LT}^2}}, 1.0 \right) = \min\left(\frac{1}{0.89 + \sqrt{0.89^2 - 0.81^2}}, 1.0 \right) = 0.79 \quad (6.56)$$

$$M_{y,b,Rd} = \frac{\chi_{LT} \cdot W_y \cdot f_y}{\gamma_{M1}} = \frac{0.79 \cdot 353967 \cdot 355}{1.05} = 94.76 \text{ kNm} \quad (6.55)$$

$$\frac{M_{1,Ed}}{M_{y,b,Rd}} = \frac{16.25}{94.76} = 0.17 \leq 1.00 \quad (6.54) \text{ - OK}$$

Lateral torsional buckling, bottom flange - Part 1-1: 6.3.2.2
LC: 'Bruddgrensetilstand B2', x = 3225 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

$$N_{cr,LT} = \frac{\pi^2 \cdot E \cdot I_z}{(k_z \cdot L_{cr})^2} = \frac{\pi^2 \cdot 2.100e+05 \cdot 8.892e+06}{(1.00 \cdot 3225)^2} = 1772.08 \text{ kN}$$

Loaded on top edge.

$$Z = (C_2 \cdot z_g - C_3 \cdot z_j) = (0.83 \cdot 80 - 0.75 \cdot 0) = 66.58 \text{ mm}$$

$$M_{cr} = C_1 \cdot N_{cr,LT} \cdot \left\{ \left[\left(\frac{k_z}{k_w}\right)^2 \cdot \frac{I_w}{I_z} + \frac{G \cdot I_t}{N_{cr,LT}} + Z^2 \right]^{0.5} - Z \right\} =$$

$$= 1.96 \cdot 1.772e+06 \cdot \left\{ \left[\left(\frac{1.00}{1.00}\right)^2 \cdot \frac{4.667e+10}{8.892e+06} + \frac{8.077e+04 \cdot 3.124e+05}{1.772e+06} + 66.58^2 \right]^{0.5} - 66.58 \right\} =$$

$$= 305.56 \text{ kNm}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y \cdot f_y}{M_{cr}}} = \sqrt{\frac{353967 \cdot 355}{3.056e+08}} = 0.64$$

$\alpha_{LT} = 0.21$ (Buckling curve: a)

$$\varphi_{LT} = 0.5 \left[1 + \alpha_{LT} \cdot (\bar{\lambda}_{LT} - 0.2) + \bar{\lambda}_{LT}^2 \right] =$$

$$= 0.5 \left[1 + 0.21 \cdot (0.64 - 0.2) + 0.64^2 \right] = 0.75$$

$$\chi_{LT} = \min\left(\frac{1}{\varphi_{LT} + \sqrt{\varphi_{LT}^2 - \bar{\lambda}_{LT}^2}}, 1.0 \right) = \min\left(\frac{1}{0.75 + \sqrt{0.75^2 - 0.64^2}}, 1.0 \right) = 0.87 \quad (6.56)$$

$$M_{y,b,Rd} = \frac{\chi_{LT} \cdot W_y \cdot f_y}{\gamma_{M1}} = \frac{0.87 \cdot 353967 \cdot 355}{1.05} = 104.55 \text{ kNm} \quad (6.55)$$

$$\frac{M_{1,Ed}}{M_{y,b,Rd}} = \frac{26.05}{104.55} = 0.25 \leq 1.00 \quad (6.54) \text{ - OK}$$

Interaction between normal force and bending 1. - Part 1-1: 6.3.3
LC: 'Bruddgrensetilstand B2', x = 16125 mm

$Class_N = 1$, $Class_{M1} = 1$, $Class_{M2} = 1$

k_{ij} factors are calculated according to Method 1

C_{my}	=	1.01	C_{yy}	=	0.98
C_{mz}	=	0.84	C_{yz}	=	0.98
C_{mLT}	=	1.13	C_{zy}	=	0.87
			C_{zz}	=	0.95

$$M_{2,Rk} = f_y \cdot W_{pl,2} = 355 \cdot 170002 = 60.35 \text{ kNm}$$

$$\frac{N_{Ed}^{comp}}{N_{b,Rd,1}} + k_{11} \cdot \frac{M_{1,Ed}}{M_{y,b,Rd}} + k_{12} \cdot \frac{M_{2,Ed}}{\frac{M_{2,Rk}}{\gamma_{M1}}} =$$

$$= \frac{292.38}{1514.03} + 1.22 \cdot \frac{16.36}{94.76} + 0.70 \cdot \frac{0.00}{\frac{60.35}{1.05}} = 0.40 \leq 1.00 \quad (6.61) \text{ - OK}$$

Interaction between normal force and bending 2. - Part 1-1: 6.3.3
LC: 'Bruddgrensetilstand B2', x = 16125 mm

$Class_N = 1, \quad Class_{M1} = 1, \quad Class_{M2} = 1$

k_{ij} factors are calculated according to Method 1

$C_{my} = 1.01 \qquad C_{yy} = 0.98$
$C_{mz} = 0.84 \qquad C_{yz} = 0.98$
$C_{mLT} = 1.13 \qquad C_{zy} = 0.87$
$\qquad\qquad\qquad C_{zz} = 0.95$

$M_{2,Rk} = f_y \cdot W_{pl,2} = 355 \cdot 170002 = 60.35\ \text{kNm}$

$$\frac{N_{Ed}^{comp}}{N_{b,Rd,2}} + k_{21} \cdot \frac{M_{1,Ed}}{M_{y,b,Rd}} + k_{22} \cdot \frac{M_{2,Ed}}{\frac{M_{2,Rk}}{\gamma_{M1}}} =$$

$$= \frac{292.38}{945.71} + 0.66 \cdot \frac{16.36}{94.76} + 0.96 \cdot \frac{0.00}{\frac{60.35}{1.05}} = 0.42 \le 1.00 \qquad (6.62)\text{ - OK}$$

Interaction between normal force and bending, 2nd order - Part 1-1: 6.3.3
Not relevant

Shear buckling - Part 1-5: 5
$\frac{h_w}{t} = \frac{134}{8} = 16.8 \le \frac{72}{\eta} \cdot \varepsilon = \frac{72}{1.20} \cdot 0.81 = 48.8 \rightarrow$ Not relevant

Summary