Encurvadura de elementos uniformes em Flexão (M)

	Verificação	
y-y	0,994586	OK
z-z	0,876301	OK

Dados do perfil

Perfil	IPE 600

Coeficientes parciais de segurança

γ_{M1} = 1

$$\frac{M_{Ed}}{M_{b,Rd}} \le 1{,}0$$

			Eixo y-y		Eixo z-z	
			Módulo de flexão plástico (W_{pl}) =	3512 [cm³]	ico (W_{pl}) =	485,6 [cm³]
	$M_{y,Ed}$ =	500 [kN.m]	ínimo ($W_{el,min}$) =	3069 [cm³]	($W_{el,min}$) =	307,9 [cm³]
	$M_{z,Ed}$ =	100 [kN.m]	nimo ($W_{eff,min}$) =	3000 [cm³]	$W_{eff,min}$) =	300 [cm³]
Classe 1	$M_{b,y,Rd}$ =	502,7218 [kN.m]		f_y = 235 [N/mm²]		
	$M_{b,z,Rd}$ =	114,116 [kN.m]				

Efeito Encurvadura Desprezad

Classe 1 e 2

$M_{pl,y,Rd}$ = 825,32 [kN.m]

$M_{pl,z,Rd}$ = 114,116 [kN.m]

$$M_{pl,Rd} = \frac{W_{pl} f_y}{\gamma_{M0}}$$

Classe 3

$M_{el,y,Rd}$ = 721,215 [kN.m]

$M_{el,z,Rd}$ = 72,3565 [kN.m]

$$M_{el,Rd} = \frac{W_{el,min} f_y}{\gamma_{M0}}$$

Classe 4

$M_{c,y,Rd}$ = 705 [kN.m]

$M_{c,z,Rd}$ = 70,5 [kN.m]

$$\frac{W_{eff,min} f_y}{\gamma_{M0}}$$

Não Desprezar Efeito Encurvadura

Classe 1 e 2

$M_{b,y,Rd}$ = 502,7218 [kN.m]

$M_{b,z,Rd}$ = 114,116 [kN.m]

$$M_{b,Rd} = \frac{x_{LT} W_y f_y}{\gamma_{M1}}$$

Classe 1 e 2 : $W_y = W_{pl,y}$

Classe 3

$M_{b,y,Rd}$ = 442,032 [kN.m]

$M_{b,z,Rd}$ = 72,3565 [kN.m]

$$M_{b,Rd} = \frac{x_{LT} W_y f_y}{\gamma_{M1}}$$

Classe 3 : $W_y = W_{el,y}$

Classe 4

$M_{b,y,Rd}$ = 437,6402 [kN.m]

$M_{b,z,Rd}$ = 72,3565 [kN.m]

$$M_{b,Rd} = \frac{x_{LT} W_y f_y}{\gamma_{M1}}$$

Classe 4 : $W_y = W_{eff,y}$

(4) Para as esbeltezas $\bar{\lambda}_{LT} \le \bar{\lambda}_{LT,0}$ (ver 6.3.2.3) ou para $\frac{M_{Ed}}{M_{cr}} \le \bar{\lambda}_{LT,0}^{\ 2}$ (ver 6.3.2.3), os efeitos da encurvadura lateral poderão ser ignorados, sendo apenas efectuadas as verificações de resistência das secções transversais.

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_y f_y}{M_{cr}}}$$

Classe 1 e 2				
$\bar{\lambda}_{LT}$ =	1,21	$M_{y,Ed}/M_{cr,y}$	0,887614	CONSIDERAR EFEITOS DE ENCURVADURA
$\bar{\lambda}_{LT}$ =	0,06	$M_{z,Ed}/M_{cr,z}$	0,003189	IGNORAR EFEITOS DE ENCURVADURA
Classe 3				
$\bar{\lambda}_{LT}$ =	1,20	$M_{y,Ed}/M_{cr,y}$	1,004779	CONSIDERAR EFEITOS DE ENCURVADURA
$\bar{\lambda}_{LT}$ =	0,05	$M_{z,Ed}/M_{cr,z}$	0,00361	IGNORAR EFEITOS DE ENCURVADURA
Classe 4				
$\bar{\lambda}_{LT}$ =	1,19	$M_{y,Ed}/M_{cr,y}$	1,004779	CONSIDERAR EFEITOS DE ENCURVADURA
$\bar{\lambda}_{LT}$ =	0,05	$M_{z,Ed}/M_{cr,z}$	0,00361	IGNORAR EFEITOS DE ENCURVADURA

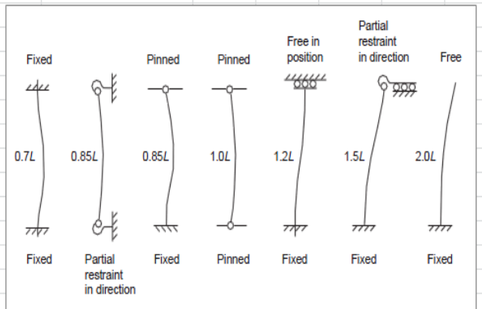
$\bar{\lambda}_{LT,0} = 0.4$ (maximum value)

$\beta = 0.75$ (minimum value)

$$M_{cr} = C_1 \frac{\pi^2 E I_z}{L_{cr}^2} \left(\frac{I_w}{I_z} + \frac{L_{cr}^2 G I_T}{\pi^2 E I_z} \right)^{0.5}$$

E (N/mm²)=	210000
G (N/mm²)=	80769,23

Classe 1 e 2					Classe 3					Classe 4				
Eixo y-y					**Eixo y-y**					**Eixo y-y**				
Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}	Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}	Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}
8,00	563,31	1,21	1,16	0,61	8,00	497,62	1,20	1,15	0,61	8,00	497,62	1,19	1,14	0,62
Eixo z-z					**Eixo z-z**					**Eixo z-z**				
Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}	Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}	Lcr (m)	M_{cr}	$\bar{\lambda}_{LT}$	φ_{LT}	χ_{LT}
2,00	31357,15	0,06	0,49	1,00	2,00	27700,67	0,05	0,49	1,00	2,00	27700,67	0,05	0,49	1,00
Curvas de encurvadura		**Curvas de encurvadura**			**Curvas de encurvadura**		**Curvas de encurvadura**			**Curvas de encurvadura**		**Curvas de encurvadura**		
Eixo (y-y) Parâmetros		Eixo (z-z) Parâmetros			Eixo (y-y) Parâmetros		Eixo (z-z) Parâmetros			Eixo (y-y) Parâmetros		Eixo (z-z) Parâmetros		
λ_1 =	93,9	λ_1 =	93,9		λ_1 =	93,9	λ_1 =	93,9		λ_1 =	93,9	λ_1 =	93,9	
Aço S235	f_y = 235	Aço S235	f_y = 235		Aço S235	f_y = 235	Aço S235	f_y = 235		Aço S235	f_y = 235	Aço S235	f_y = 235	
α_{LT} =	0,21	α_{LT} =	0,21		α_{LT} =	0,21	α_{LT} =	0,21		α_{LT} =	0,21	α_{LT} =	0,21	
C_1 =	1,132	C_1 =	1,132		C_1 =	1	C_1 =	1		C_1 =	1	C_1 =	1	



Nominal buckling lengths L_{cr} for compression members

Table 6.7. Imperfection factors for lateral torsional buckling curves (*Table 6.3* of EN 1993-1-1)

Buckling curve	*a*	*b*	*c*	*d*
Imperfection factor α_{LT}	*0.21*	*0.34*	*0.49*	*0.76*

Table 6.8. Lateral torsional buckling curve for cross-sections using *equation* (*6.56*) (*Table 6.4* of EN 1993-1-1)

Cross-section	*Limits*	*Buckling curve*
Rolled I sections	*h/b* ≤ 2 *h/b* > 2	*a* *b*
Welded I sections	*h/b* ≤ 2 *h/b* > 2	*c* *d*
Other cross-sections	–	*d*

Table 6.9. Lateral torsional buckling curve for cross-sections using *equation* (*6.57*) (*Table 6.5* of EN 1993-1-1)

Cross-section	*Limits*	*Buckling curve*
Rolled I sections	*h/b* ≤ 2 *h/b* > 2	*b* *c*
Welded I sections	*h/b* ≤ 2 *h/b* > 2	*c* *d*

Encurvadura de Elementos Uniformes em Flexão Composta com Compressão – Método 1 (Franco-Belga)

Classe	1	2	3	4	
A_i	156	156	156	100	[cm²]
W_y	3512	3512	3069	3000	[cm³]
W_z	485,6	485,6	307,9	300	[cm³]
$\Delta M_{y,Ed}$	0	0	0	30	
$\Delta M_{z,Ed}$	0	0	0	30	
N_{Rk} =	3666	3666	3666	2350	[kN]
$M_{y,Rk}$ =	825,32	825,32	721,215	705	[kN.m]
$M_{z,Rk}$ =	114,116	114,116	72,3565	70,5	[kN.m]

Quadro 6.7 – Valores de $N_{Rk} = f_y A_i$, $M_{i,Rk} = f_y W_i$ e $\Delta M_{i,Ed}$

Classe	1	2	3	4
A_i	A	A	A	A_{eff}
W_y	$W_{pl,y}$	$W_{pl,y}$	$W_{el,y}$	$W_{eff,y}$
W_z	$W_{pl,z}$	$W_{pl,z}$	$W_{el,z}$	$W_{eff,z}$
$\Delta M_{y,Ed}$	0	0	0	$e_{N,y} N_{Ed}$
$\Delta M_{z,Ed}$	0	0	0	$e_{N,z} N_{Ed}$

NOTA: No caso de elementos não susceptíveis à deformação por torção, ter-se-á $\chi_T = 1,0$.

Dados do perfil

Perfil	IPE 600		
Eixo y-y		Eixo z-z	
	3512 [cm³]		485,6 [cm³]
	3069 [cm³]		307,9 [cm³]
	3000 [cm³]		300 [cm³]

f_y = 235 [N/mm²]

Área = 156 [cm²]

Área útil (A_{eff}) = 100 [cm²]

Coeficientes parciais de segurança

γ_{M0} = 1

γ_{M1} = 1

$$\frac{N_{Ed}}{\chi_y \frac{N_{Rk}}{\gamma_{M1}}} + k_{yy} \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT} \frac{M_{y,Rk}}{\gamma_{M1}}} + k_{yz} \frac{M_{z,Ed} + \Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}} \le 1 \qquad (6.61)$$

$$\frac{N_{Ed}}{\chi_z \frac{N_{Rk}}{\gamma_{M1}}} + k_{zy} \frac{M_{y,Ed} + \Delta M_{y,Ed}}{\chi_{LT} \frac{M_{y,Rk}}{\gamma_{M1}}} + k_{zz} \frac{M_{z,Ed} + \Delta M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}} \le 1 \qquad (6.62)$$

	Rácio N	Rácio M_y	Rácio M_z	Rácio Total	
Equação 6.61	0,173949	0,025534	0,03878	0,23826264	OK
Equação 6.62	0,18884	0,013631	0,05795	0,26042031	OK

$e_{N,y}$ =	0,05	e_N afastamento entre os centros de gravidade da área efectiva (A_{eff}) e da área bruta da secção transversal, quando esta se encontra submetida apenas à compressão, ver 6.2.2.5(4).
$e_{N,z}$ =	0,05	

$$\varepsilon_y = \frac{M_{y,Ed}}{N_{Ed}} \frac{A}{W_{el,y}} \text{ para as secções transversais das Classes 1, 2 e 3}$$

$$\varepsilon_y = \frac{M_{y,Ed}}{N_{Ed}} \frac{A_{eff}}{W_{eff,y}} \text{ para as secções transversais da Classe 4}$$

ε_y = 0,1694363

$$a_{LT} = 1 - \frac{I_T}{I_y} \ge 0$$

I_y = 165,4 [cm⁴]

a_{LT} = 0,99820374

Classe 1, 2 e 3		
$N_{cr,y}$ =	27975,38665	[kN]
$N_{cr,z}$ =	17548,31765	[kN]
Classe 4		
$N_{cr,y}$ =	29823,33579	[kN]
$N_{cr,z}$ =	17548,31765	[kN]
$N_{y,Ed}$ =	600	[kN]
$N_{z,Ed}$ =	600	[kN]

Table 8.2. Equivalent uniform moment factors $C_{m,0}$ (*Table A.2 of EN 1993-1-1*)

Moment diagram	$C_{m,0}$
M_1, ψM_1, $-1 \le \psi \le 1$	$C_{m,0} = 0.79 + 0.21\psi_1 + 0.36(\psi_1 - 0.33)\frac{N_{Ed}}{N_{cr,i}}$
M(x)	$C_{m,0} = 1 + \left(\frac{\pi^2 EI \lvert\delta_s\rvert}{L^2 \lvert M_{y,Ed}(x)\rvert} - 1\right)\frac{N_{Ed}}{N_{cr,i}}$ $M_{y,Ed(x)}$ *is the maximum moment* $M_{y,Ed}$ *or* $M_{z,Ed}$ $\lvert\delta_s\rvert$ *is the maximum member displacement along the member*
M(x)	
	$C_{m,0} = 1 - 0.18\frac{N_{Ed}}{N_{cr,i}}$
	$C_{m,0} = 1 + 0.03\frac{N_{Ed}}{N_{cr,i}}$

$\bar{\lambda}_{máx}$ = 0,45706555

Classe 1

$\bar{\lambda}_0$ = esbelteza normalizada relativa à encurvadura lateral para o caso de momento flector uniforme, ou seja, ψ_y =1,0 no Quadro A.2

(y-y)	$\bar{\lambda}_0$ =	0,39312728	C_1 =	1,005173	
(z-z)	$\bar{\lambda}_0$ =	0,06401883	$M_{cr,y}$ =	5340,18	[kN.m]
			$M_{cr,z}$ =	27843,96	[kN.m]

Classe 1 e 2		
$\bar{\lambda}_0$ =	0,393127275	
$\bar{\lambda}_0$ =	0,06401883	
Classe 3		
$\bar{\lambda}_0$ =	0,367497481	
$\bar{\lambda}_0$ =	0,050976878	
Classe 4		
$\bar{\lambda}_0$ =	0,363342793	
$\bar{\lambda}_0$ =	0,050318655	
$M_{y,Ed}$ =	20	[kN.m]
$M_{z,Ed}$ =	10	[kN.m]

$\bar{\lambda}_{LT}$ = esbelteza normalizada relativa à encurvadura lateral

(y-y)	$\bar{\lambda}_{LT}$ =	0,41957352
(z-z)	$\bar{\lambda}_{LT}$ =	0,07982328

$$n_{pl} = \frac{N_{Ed}}{N_{Rk} / \gamma_{M0}}$$

(y-y)	n_{pl} =	0,16366612
(z-z)	n_{pl} =	0,16366612

$$\mu_y = \frac{1 - \frac{N_{Ed}}{N_{cr,y}}}{1 - \chi_y \frac{N_{Ed}}{N_{cr,y}}} \qquad \mu_z = \frac{1 - \frac{N_{Ed}}{N_{cr,z}}}{1 - \chi_z \frac{N_{Ed}}{N_{cr,z}}}$$

μ_y = 0,99870608

μ_z = 0,99530287

$$w_y = \frac{W_{pl,y}}{W_{el,y}} \le 1,5 \qquad w_z = \frac{W_{pl,z}}{W_{el,z}} \le 1,5$$

w_y = 1,14346693

w_z = 1,5

Se $\bar{\lambda}_0 \le 0,2\sqrt{C_1}\sqrt{\left(1 - \frac{N_{Ed}}{N_{cr,z}}\right)\left(1 - \frac{N_{Ed}}{N_{cr,TF}}\right)}$: $C_{my} = C_{my,0}$, $C_{mz} = C_{mz,0}$, $C_{mLT} = 1,0$

(y-y)	$\bar{\lambda}_0$ =	0,3931273	C_1 =	1,132
(z-z)	$\bar{\lambda}_0$ =	0,0640188	C_1 =	1,132

0,393127275	>	0,210242
0,06401883	<=	0,210242

Se $\bar{\lambda}_0 > 0,2\sqrt{C_1}\sqrt{\left(1 - \frac{N_{Ed}}{N_{cr,z}}\right)\left(1 - \frac{N_{Ed}}{N_{cr,TF}}\right)}$: $C_{mz} = C_{mz,0}$

$$C_{my} = C_{my,0} + \left(1 - C_{my,0}\right)\frac{\sqrt{\varepsilon_y}\, a_{LT}}{1 + \sqrt{\varepsilon_y}\, a_{LT}}$$

$$C_{mLT} = C_{my}^2 \frac{a_{LT}}{\sqrt{\left(1 - \frac{N_{Ed}}{N_{cr,z}}\right)\left(1 - \frac{N_{Ed}}{N_{cr,T}}\right)}} \ge 1$$

C_{my} = 1,005173

C_{mz} = 0,712576

C_{mLT} = 1

Diag. Momentos (y-y)	
Tipo de Diagrama	1
$C_{my,0}$ =	1,005173

Tipo de Diagrama	1	2	3	4
$C_{my,0}$	1,005173	0,9785526	0,996139	0,999357

1	
ψ ("-1 a 1")	1
$C_{my,0}$	1,005173

2		
δ_s	0,00105	[m]
$M_{y,Ed(máx)}$	20	[kN.m]
L	8	[m]
I_y	92080	[cm⁴]
$C_{my,0}$	0,978553	

3	
$C_{my,0}$	0,996139

4	
$C_{my,0}$	0,999357

Diag. Momentos (z-z)	
Tipo de Diagrama	1
$C_{mz,0}$ =	0,712576

Tipo de Diagrama	1	2	3	4
$C_{my,0}$	0,712576	0,9658088	0,993846	0,998974

1	
ψ ("-1 a 1")	-0,33
$C_{my,0}$	0,712576

2		
δ_s	0,00105	[m]
$M_{z,Ed(máx)}$	6	[kN.m]
L	2	[m]
I_z	3387	[cm⁴]
$C_{mz,0}$	0,965809	

3	
$C_{mz,0}$	0,993846

4	
$C_{mz,0}$	0,998974

Factores de interacção	Hipóteses de cálculo: Propriedades elásticas das secções transversais, Classe 3, Classe 4	Hipóteses de cálculo: Propriedades plásticas das secções transversais, Classe 1, Classe 2	
k_{yy}	$C_{my} C_{mLT} \frac{\mu_y}{1 - \frac{N_{Ed}}{N_{cr,y}}}$	$C_{my} C_{mLT} \frac{\mu_y}{1 - \frac{N_{Ed}}{N_{cr,y}}} \frac{1}{C_{yy}}$	k_{yy} = 1,000919
k_{yz}	$C_{mz} \frac{\mu_y}{1 - \frac{N_{Ed}}{N_{cr,z}}}$	$C_{mz} \frac{\mu_y}{1 - \frac{N_{Ed}}{N_{cr,z}}} \frac{1}{C_{yz}} 0,6\sqrt{\frac{w_z}{w_y}}$	k_{yz} = 0,442541
k_{zy}	$C_{my} C_{mLT} \frac{\mu_z}{1 - \frac{N_{Ed}}{N_{cr,y}}}$	$C_{my} C_{mLT} \frac{\mu_z}{1 - \frac{N_{Ed}}{N_{cr,y}}} \frac{1}{C_{zy}} 0,6\sqrt{\frac{w_y}{w_z}}$	k_{zy} = 0,534322
k_{zz}	$C_{mz} \frac{\mu_z}{1 - \frac{N_{Ed}}{N_{cr,z}}}$	$C_{mz} \frac{\mu_z}{1 - \frac{N_{Ed}}{N_{cr,z}}} \frac{1}{C_{zz}}$	k_{zz} = 0,661298

N_{Ed} = 600 [kN]

$$N_{cr,TF} = \frac{N_{cr,y}}{2\beta}\left(1 + \frac{N_{cr,T}}{N_{cr,y}} - \sqrt{\left(1 - \frac{N_{cr,T}}{N_{cr,y}}\right)^2 + 4\left(\frac{y_0}{i_0}\right)^2 \frac{N_{cr,T}}{N_{cr,y}}}\right)$$

$N_{cr,TF}$ = 45004,855 [kN]

$$N_{cr,T} = \frac{1}{i_0^2}\left(GI_t + \frac{\pi^2 EI_w}{L_T^2}\right)$$

$N_{cr,T}$ = 45004,86 [kN]

$$\beta = 1 - \left(\frac{y_0}{i_0}\right)^2$$

β = 1

$$i_0^2 = i_y^2 + i_z^2 + y_0^2 + z_0^2$$

i_0^2 = 612,2056 [cm²]

y_0 =	0	[m]
z_0 =	0	[m]
i_y =	24,3	[cm]
i_z =	4,66	[cm]
I_T =	1,5	[m]

I_t is the torsion constant of the gross cross-section
I_w is the warping constant of the gross cross-section
i_y is the radius of gyration of the gross cross-section about the *y*–*y* axis
i_z is the radius of gyration of the gross cross-section about the *z*–*z* axis
l_T is the buckling length of the member for torsional buckling
y_0 is the distance from the shear centre to the centroid of the gross cross-section along the *y* axis
z_0 is the distance from the shear centre to the centroid of the gross cross-section along the *z* axis.

$$b_{LT} = 0,5\, a_{LT}\, \bar{\lambda}_0^2 \frac{M_{y,Ed}}{\chi_{LT} M_{pl,y,Rd}} \frac{M_{z,Ed}}{M_{pl,z,Rd}}$$

b_{LT} = 0,000625

$$c_{LT} = 10\, a_{LT} \frac{\bar{\lambda}_0^2}{5 + \bar{\lambda}_z^4} \frac{M_{y,Ed}}{C_{my} \chi_{LT} M_{pl,y,Rd}}$$

c_{LT} = 0,007763

$$d_{LT} = 2\, a_{LT} \frac{\bar{\lambda}_0}{0,1 + \bar{\lambda}_z^4} \frac{M_{y,Ed}}{C_{my} \chi_{LT} M_{pl,y,Rd}} \frac{M_{z,Ed}}{C_{mz} M_{pl,z,Rd}}$$

d_{LT} = 0,061821

$$e_{LT} = 1,7\, a_{LT} \frac{\bar{\lambda}_0}{0,1 + \bar{\lambda}_z^4} \frac{M_{y,Ed}}{C_{my} \chi_{LT} M_{pl,y,Rd}}$$

e_{LT} = 0,243216

$$C_{yy} = 1 + \left(w_y - 1\right)\left[\left(2 - \frac{1,6}{w_y} C_{my}^2 \bar{\lambda}_{max} - \frac{1,6}{w_y} C_{my}^2 \bar{\lambda}_{max}^2\right) n_{pl} - b_{LT}\right] \ge \frac{W_{el,y}}{W_{pl,y}}$$

C_{yy} = 1,024933

$$C_{yz} = 1 + \left(w_z - 1\right)\left[\left(2 - 14 \frac{C_{mz}^2 \bar{\lambda}_{max}^2}{w_z^5}\right) n_{pl} - c_{LT}\right] \ge 0,6\sqrt{\frac{w_z}{w_y}} \frac{W_{el,z}}{W_{pl,z}}$$

C_{yz} = 1,143781

$$C_{zy} = 1 + \left(w_y - 1\right)\left[\left(2 - 14 \frac{C_{my}^2 \bar{\lambda}_{max}^2}{w_y^5}\right) n_{pl} - d_{LT}\right] \ge 0,6\sqrt{\frac{w_y}{w_z}} \frac{W_{el,y}}{W_{pl,y}}$$

C_{zy} = 1,002751

$$C_{zz} = 1 + \left(w_z - 1\right)\left[2 - \frac{1,6}{w_z} C_{mz}^2 \bar{\lambda}_{max} - \frac{1,6}{w_z} C_{mz}^2 \bar{\lambda}_{max}^2 - e_{LT}\right] n_{pl} \ge \frac{W_{el,z}}{W_{pl,z}}$$

C_{zz} = 1,114246