Preliminary design of BRBF system

Use of equivalent force method

This preliminary design guide presents an example for design of a steel structure with Buckling Restrained Braced Frame system in accordance with Eurocode. The internal axial loads are defined from linear static analysis of the earthquake load case.

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Example: Preliminary design of BRBF system

Note: Although in general concept the following BRBF calculation is in accordance with Eurocode 8 (EC8) Part 1, it cannot be used as actual design check, since the corresponding behavior factor q and other seismic relevant parameters are currently not included in EC8.

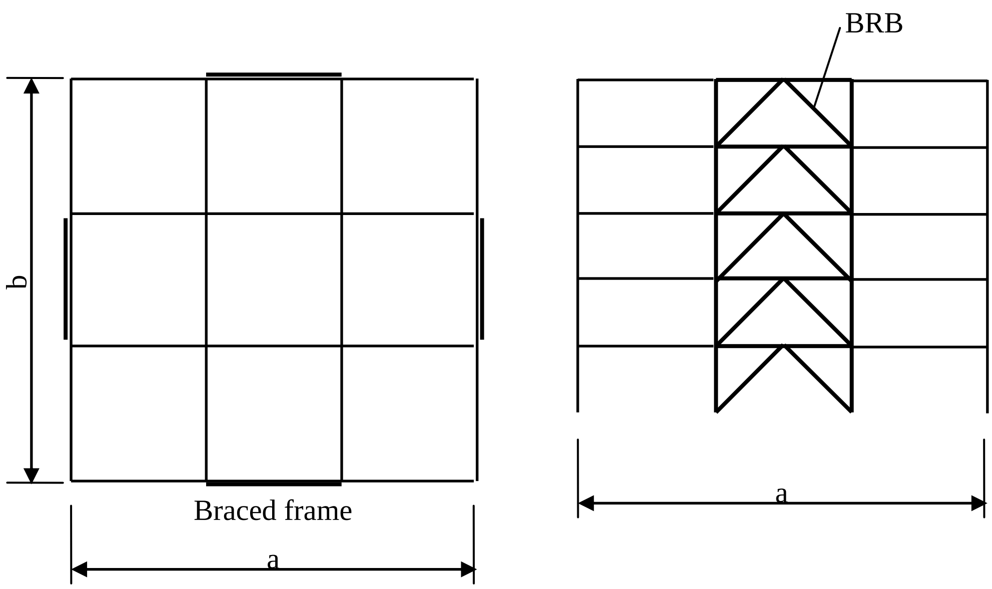
For actual check, use pushover analysis and capacity design.

Note: For information, the new Romanian Seismic Design Code P100-1/2011 (this version is currently under public review) already includes behavior factors and design rules for BRBF system.

1 Building

1.1 Global geometry

- building width: $a = 3x6 = 18m$
- building length: $b = 3x6 = 18m$
- story height: $h = 3m$
- number of stories: $n_s = 5$
- building height: $H = 15m$
- floor area: $A_{floor,tot} = axb = 18x18 = 324m^2$



1.2 Design loads and seismic actions

1.2.1 Dead loads:

- roof: $g_{roof} = 3kN/m^2$
- floor: $g_{floor} = 8kN/m^2$

1.2.2 Live loads (imposed loads):

- on roof: $q_{roof} = 1kN/m^2$
- on floor: $q_{floor} = 2.5kN/m^2$
- combination factor: $\psi_{2,i} = 0.3$

1.2.3 Further live loads (imposed loads):

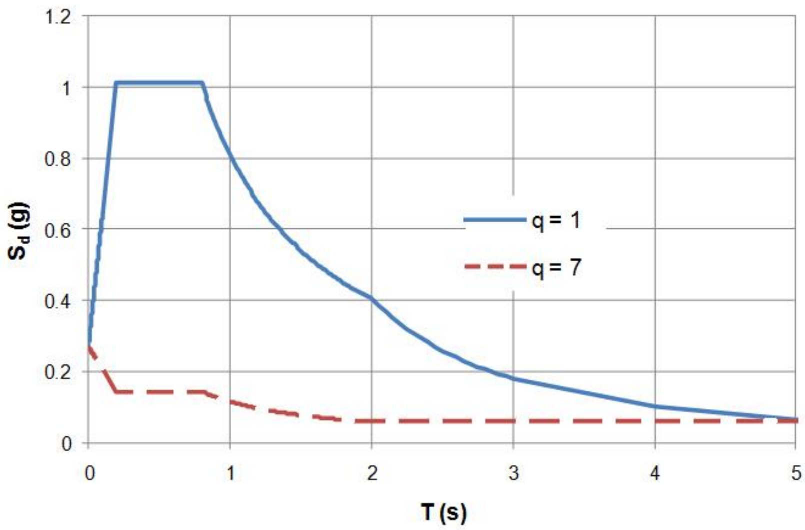
In the seismic load combination, combination factor of meteorological loads is ψ_2 = 0, i.e. they are excluded.

Note that in this example it is assumed that the seismic design situation is dominant, and thus additional (e.g. meteorological) loads and the ULS load combinations are excluded. Designer has to check if e.g. ULS controls the design of bracing system.

1.2.4 Seismic parameters:

Design spectrum parameters:

- peak ground acceleration (PGA): $a_{gR} = 0.3g$
- spectrum: Type 1
- ground type: D
  ($v_{S,30}$ < 180m/s; N_{SPT} < 15; C_u < 70kPa
  Deposits of loose-to-medium cohesionless soil or of predominantly soft-to-firm cohesive soil)
  $S = 1.35$; $T_B = 0.2$s; $T_C = 0.8$s; $T_D = 2$s; $\beta = 0.2$



- period: $T = 0.572s$
- behavior factor: $q = 7$ BRBF, non-moment-resisting
  (response modification factor) beam-to-column connections
- importance class: normal → $\gamma_I = 1.0$
- design PGA: $a_g = \gamma_I \cdot a_{gR} = 0.3g$
- displacement modification factor: $q_d = q$ in general case
  $q_d > q$ for short-period buildings (EC8-1; 4.3.4)
- design spectral acceleration: $S_D(T) = 0.3g \cdot S \dfrac{2.5}{q} = 1.419 \dfrac{m}{s^2}$

1.2.5 Seismic actions:

Total weight in seismic action: $G_k + \psi_{E,i} Q_{k,i}$ (EC8-1; 3.2.4)

- on roof: $q_{d,roof} = g_{roof} + \psi_{2,i}\, q_{roof} = 3.3$ kN/m^2
- on floor: $q_{d,floor} = g_{floor} + \psi_{2,i}\, q_{floor} = 8.75$ kN/m^2
- total seismic action: $Total = A_{floor,tot}\left(q_{d,roof} + (n_s - 1)\cdot q_{d,floor}\right) = 12409.2kN$
- for one bracing: $m_1 = \dfrac{Total}{2} = 6204.6kN$

Base shear force: $F_b = \lambda_1 \cdot S_D(T)\cdot m_1 / g = 0.85 \cdot 1.419 \dfrac{m}{s^2} \cdot 6204.6kN / 9.81 \dfrac{m}{s^2} = 762.8kN$

where: $\lambda_1 = 0.85$ if $T < 2 \cdot T_C$ and building has more than two stories; otherwise 1.00.

Distribution of horizontal seismic forces:

- story height: $z_i = i \cdot h \qquad (i = 1..n_s)$
- story loads: $mc_i = A_{floor,tot} \cdot q_{d,floor}$

  $mc_{n_s} = A_{floor,tot} \cdot q_{d,roof}$
- force distribution: $F_i = F_b \cdot \dfrac{z_i \cdot mc_i}{\sum_j \left(z_j \cdot mc_j\right)}$

  (Assume linear fundamental modal shape)

Torsional effects (EC8-1-1; 4.3.3.2.4 for lateral force method):

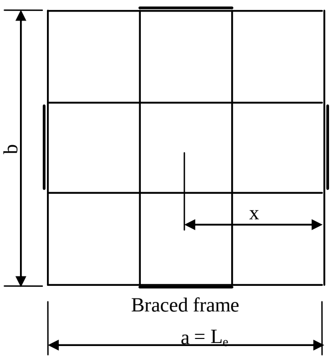
distance of frame under consideration from center of gravity:

$$x = \frac{\max(a,b)}{2} = 9m$$

distance of outermost lateral force-resisting system:

$$L_e = \max(a,b) = 18m$$

$$\delta = 1 + 0.6 \cdot \frac{x}{L_e} = 1.3$$



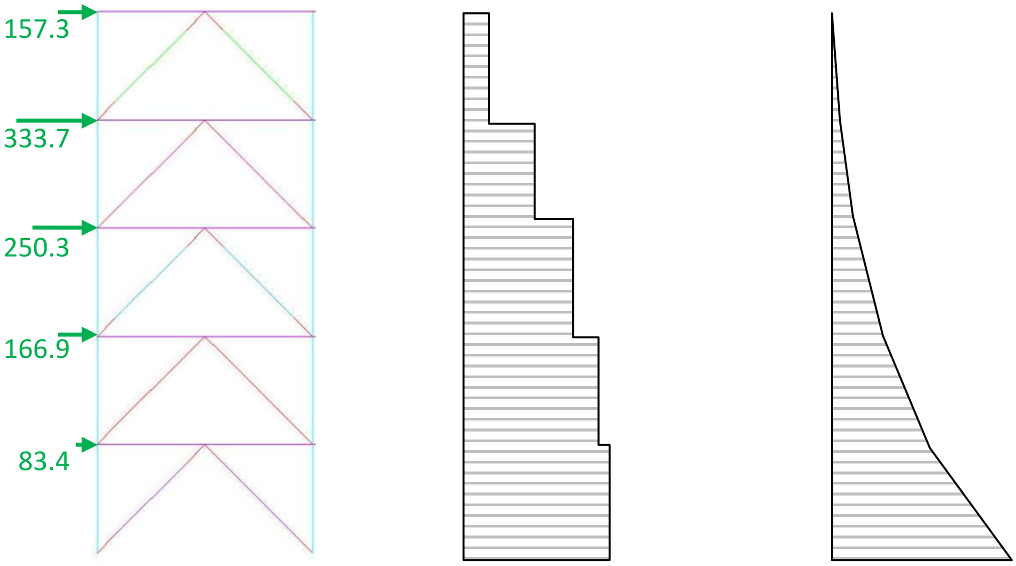
Equivalent lateral loads (one brace) and global internal loads:

$$F_{\delta,i} = F_i \cdot \delta \qquad V_i = \sum_{k=n_s}^{i} F_{\delta,k} \qquad M_{ii} = M_{ii+1} + V_{ii} \cdot h$$

Story#	$F_{\delta,i}$ (kN)
Roof	157.3
4	333.7
3	250.3
2	166.9
1	83.4

Story#	V_i (kN)
Roof	157.3
4	491.1
3	741.4
2	908.2
1	991.7

Story#	M_i (kNm)
Roof	472.0
4	1945.2
3	4169.4
2	6894.1
1	9869.2



Equivalent lateral loads Story shear Overturning moment

1.2.6 Load combinations:

- Combination of different direction EQ:

$$E_{Ed} = E_{Edx} + 0.3 \cdot E_{Edy}$$
$$E_{Edy} + 0.3 \cdot E_{Edx}$$

Since seismic systems are separated in the two directions, no addition is necessary.

- Load combinations:

$$\sum G_{k,j} + E_{Ed} + \sum \phi \cdot \psi_{2,i} \cdot Q_{k,i} =$$
$$\sum G_{k,j} + E_{Ed} + 0.3 \cdot LL$$

where:

$G_{k,j}$ - characteristic value of permanent action *j*

E_{Ed} - design value of seismic action

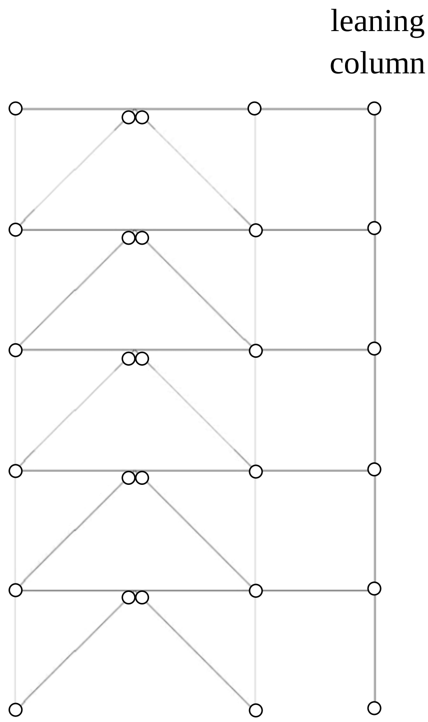
$Q_{k,i}$ - characteristic value of the accompanying variable action *i*

LL - live load

$\phi = 1$

Other, normal (ULS, SLS) combinations are neglected here.

2 Static analysis



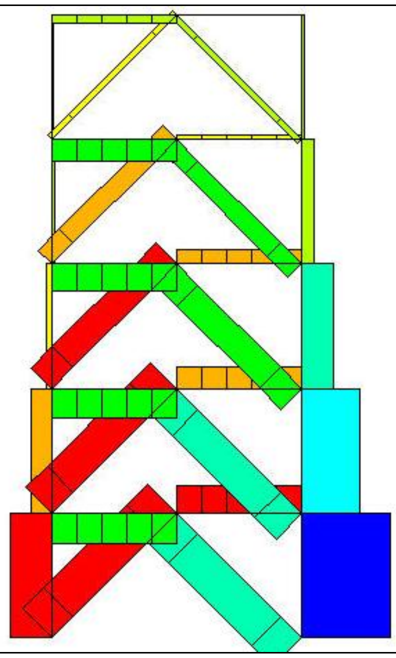
2.1 Static model

Static analysis is being performed, with the equivalent lateral loads considered. In the current case, the following assumptions and simplifications can be made:

- No contribution of columns to the lateral load resistance is considered.
- Behavior of the braced frames can be separately analyzed due to the structural regularity and separation of the braced systems in the two directions.
- Beam-to-column connections are pinned.
- This allows the use of simple 2D truss structure analysis of the braced part only. Each column and BRB element at a story is represented by single, pin-ended spar elements. Beams are continuous over the bracing connection.
- To model realistic rigidity, one has to consider the relative large stiffness of the BRB endings. Because a single element is used between the nodes (workpoints), an effective rigidity (1.4 x actual rigidity in this example) of BRB is applied. Contact Star Seismic Europe to obtain the relevant value.
- Leaning column (additional pinned columns, connected to the frame with pin-ended rigid links at each floor) is used to consider the whole mass tributary to the bracing system, primarily for inclusion of second-order (P-Δ) effects

2.2 Internal forces – Brace demands

From linear static analysis of the EQ load case, internal axial loads ($N_{Ed,i}$) in the BRB elements:



110kN
334
491
586
622

2.3 Second-order (P-Δ) effects

As per EC8-1; 4.4.2.2, second-order effects shall be considered as follows:

If	$\Theta < 0.1$	neglect P-Δ effect,
	$0.1 < \Theta < 0.2$	simplified procedure: increasing factor = 1/(1-Θ),
	$0.2 < \Theta < 0.3$	second-order analysis,
	$\Theta > 0.3$	not allowed.

Horizontal displ.		Total vertical load and shear load above the story:				Check P-Δ effect:			
$\Delta e_{i2} = d_{S_{i2}} - d_{S_{i2-1}}$		$P_{tot_i} = \sum_{k=n_s}^{i} mc_k$		$V_{tot_i} = \sum_{k=n_s}^{i} F_{\delta,k}$		$\Theta_i = \frac{P_{tot_i} \cdot \Delta e_i}{V_{tot_i} \cdot h}$		$f_{PD_i} = \frac{1}{1-\Theta_i}$	
#	$d_{s,i}$ (mm)	#	P_{tot} (kN)	#	V_{tot} (kN)	#	Θ (-)	#	f_{PD} (-)
R	189	R	535	R	157	R	0.046	R	1.049
4	148	4	1952	4	491	4	0.056	4	1.059
3	106.1	3	3370	3	741	3	0.061	3	1.065
2	66.1	2	4787	2	908	2	0.064	2	1.068
1	29.8	1	6205	1	992	1	0.062	1	1.066

$$f_{PD} = \max(f_{PD,i}) = 1.068$$

Where: *Δe* - is the design interstory drift as defined in EC8-1; 4.4.2.2 (2)

Accordingly, it is confirmed that second-order effects can be neglected.

3 Design of BRB elements

At this step, determine the strand area (BRB steel core). Use characteristic or low-bound values for material properties.

Material: S235 steel: f_y = 235 MPa; E = 210 GPa
Partial safety factors: γ_{M0} = 1.0; γ_{M1} = 1.0

Design can be strength- or stiffness controlled.

Required steel core area:				t_{pl} = 14 mm				Member force check	
$A_{req_i} = \frac{N_{Ed_i} \cdot \gamma_{M0}}{f_y}$		Stiffness control:*		$b_{pl_i} = \frac{A_{req_i}}{t_{pl}}$		$A_{sc_i} = t_{pl} \cdot b_{pl_i}$		$N_{pl,Rd_i} = \frac{A_{sc_i} \cdot f_y}{\gamma_{M0}}$	
#	A_{req} (cm^2)	#	A_{req} (cm^2)	#	b_{pl} (mm)	#	A_{sc} (cm^2)	#	$N_{Ed}/N_{pl,Rd}$ (%)
R	4.7	R	5.3	R	40	R	5.6	R	84
4	14.2	4	16.5	4	120	4	16.8	4	85
3	20.9	3	25.0	3	180	3	25.2	3	83
2	24.9	2	30.6	2	220	2	30.8	2	81
1	26.5	1	33.4	1	240	1	33.6	1	79

* In the given case not strength but lateral displacement (BRB stiffness) governs the design.

Based on the required core area and overall geometry conditions (workpoint-to-workpoint length, beam and column sizes, connection, etc.), Star Seismic Europe will provide detailed design of the BRB member.

4 Damage limitation check

Limitation of interstory drift, considering 95-year return period EQ, as per EC8-1; 4.4.3.2:

brittle non-structural elements:	$\nu \cdot \Delta e / h \leq 0.005$
ductile non-structural elements:	$\nu \cdot \Delta e / h \leq 0.0075$
non-interfering non-structural elements:	$\nu \cdot \Delta e / h \leq 0.010$

where ν=0.5 for importance class II.

Damage limitation criteria:

Story#	$\frac{\nu \cdot \Delta e_i}{h}$
Roof	0.683%
4	0.698%
3	0.667%
2	0.605%
1	0.497%

where: Δe - is the design interstory drift as defined in EC8-1; 4.4.2.2 (2)

Assuming ductile non-structural elements, the damage limitation criteria are met.

5 Determination of overstrength factor

Estimated yield length:

To calculate this, consult with Star Seismic Europe.

$L_t = 4243mm$	workpoint-to-workpoint length
$L_y = 0.70L_t = 2970mm$	assume now 70% of workpoint-to-workpoint length, exact value is provided by Star Seismic Europe
$\Delta_{be,i}$	value of deformation quantity
$\Delta_{bs,i}$	value of deformation quantity according to behavior factor
ε_{bs_i}	deformation corresponding to 2.0 times the design story drift

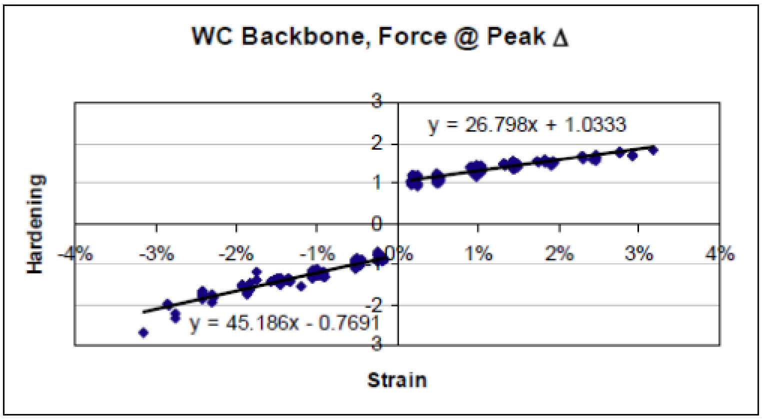
BRB axial deformation and strains:

N_{Ed_i}		$\Delta_{be,i} = \frac{N_{Ed_i} \cdot L_y}{E \cdot A_{sc_i}}$		$\Delta_{bs,i} = q_d \cdot \Delta_{be,i}$		$\varepsilon_{bs_i} = \frac{2 \cdot \Delta_{bs,i}}{L_y}$	
Story#	N_{Ed} (kN)	Story#	Δ_{be} (mm)	Story#	Δ_{bs} (mm)	Story#	ε_{bs} (%)
Roof	110	Roof	2.78	Roof	19.45	Roof	1.310
4	334	4	2.81	4	19.68	4	1.325
3	491	3	2.76	3	19.29	3	1.299
2	586	2	2.69	2	18.84	2	1.268
1	622	1	2.62	1	18.33	1	1.234

Note: multiplier of 2.0 is a safety factor, based on AISC 341-05.

Strain hardening effects:

To derive strain hardening parameters, consult with Star Seismic Europe.



Wildcat test report, USA

Full Scale Testing of Wildcat Series Buckling-Restrained Braces Final Report

By: Pedro Romero, Ph.D., P.E.
Lawrence D. Reaveley, Ph.D., P.E.
Philip J. Miller
Terry Okahashi
May 15, 2007

Page 11, Figure 5 - WC backbone curve

For tension, the regression equation is: $\omega = 26.798\varepsilon + 1.0333$

For compression, the regression equation is: $\omega\beta = 45.186\varepsilon - 0.7691$

where: ω - the strain hardening adjustment factor

β - the compression strength factor

Note: Eurocode does not include strain hardening adjustment factors, but BRBF design is similar to the design of other dissipative structures. The new Romanian Seismic Design Code P100-1/2011 already includes BRBF system and section 6.11.4 includes the aforementioned factors. AISC 341-05 Section 16.2d also includes these factors.

As per AISC 341-05 Section 16.2d "In no case shall β be taken as less than 1.0".

For tension:

Story#	ω_i
Roof	1.384
4	1.388
3	1.381
2	1.373
1	1.364

For compression:

Story#	$\omega\beta_i$
Roof	-1.361
4	-1.368
3	-1.356
2	-1.342
1	-1.327

Adjusted brace strength – material overstrength factor:

$\gamma_{ov} = 1.25$ In most cases, actual material overstrength factor will be lower than 1.25. For calculation of a given structure, contact Star Seismic Europe. In this preliminary calculation, overstrength factor of 1.25 was applied.

Element and system overstrength:

$\Omega_i = \dfrac{N_{pl.Rd_i}}{N_{Ed_i}}$	Story#	Ω_i
	Roof	1.196
	4	1.182
	3	1.206
	2	1.235
	1	1.269
$\Omega_d = \min(\Omega)$	$\Omega_d = 1.182$	

Max deviation: $\dfrac{\max(\Omega)}{\min(\Omega)} - 1 = 7.40\%$ < 25% which means global plastic mechanism (acceptable uniform mechanism)

Formulation of non-dissipative elements (integrate system overstrength):

General formula for non-dissipative elements:

$$N_{Ed} = N_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot \Omega \cdot N_{Ed,E}$$
$$V_{Ed} = V_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot \Omega \cdot V_{Ed,E}$$
$$M_{Ed} = M_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot \Omega \cdot M_{Ed,E}$$

Note: These design rules shall be used to design non-dissipative elements, for example columns, beams and foundation (as per EN 1998-1 Section 6.7.4).

General formula for connections:

$$N_{Ed} = N_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot N_{pl,Rd}$$
$$V_{Ed} = V_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot V_{pl,Rd}$$
$$M_{Ed} = M_{Ed,G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot M_{pl,Rd}$$

Safety factor of 2.0 was already used in this section in the calculation of ω and ωβ. Although the multiplier of 1.1 is not used in these BRBF design rules of P100-1/2011 Romanian Seismic Design Code, to be in conjunction with EC8 design rules, as an additional safety factor, 1.1 may be applied as it was done in this example.

System overstrength:

$1.1 \cdot \gamma_{ov} \cdot \max(\omega, \omega\beta) \cdot \Omega_d =$

Story#	
Roof	2.277
4	2.257
3	2.291
2	2.332
1	2.381

6 Design of non-dissipative elements

Design check of the first story column is illustrated. Unbalanced forces due to the difference between tension and compression ultimate resistance of BRB elements at the collapse level are neglected in this example.

Contribution of column bending to the seismic resistance is now neglected for simplification.

Design internal forces from ESP: $N_{Ed.E} = -1150kN$ $N_{Ed.G} = -633kN$

Overstrength factors: $\gamma_{ov} = 1.25$ $\Omega_d = 1.182$

Design load:

$$N_{Ed} = N_{Ed.G} + 1.1 \cdot \gamma_{ov} \cdot \max(\omega_1, \omega\beta_1) \cdot \Omega_d \cdot N_{Ed.E} = -3220.3kN$$

Applied section: HEA450 $A_c = 178.03cm^2$ $i_z = 7.29cm$

Material: S235 $f_y = 235MPa$ $\lambda_1 = \pi \cdot \sqrt{\frac{E}{f_y}} = 93.913$

Cross section class: Class 1 for compression.

Cross section strength: $N_{pl.Rd} = A_c \cdot f_y = 4183.7kN > |N_{Ed}| = 3220.3kN$ ***OK***

Buckling strength: $l_z = h = 3.00m$ $\nu_z = 1.00$

$$\lambda_z = \frac{\nu_z \cdot l_z}{i_z \cdot \lambda_1} = 0.438$$

$$\alpha = 0.34$$

$$\Phi = 0.5 \cdot \left[1 + \alpha \cdot \left(\lambda_z - 0.2\right) + \lambda_z{}^2\right]$$

$$\chi_z = \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda_z{}^2}} = 0.911$$

$$N_{b.Rd} = \chi_z \cdot A_c \cdot \frac{f_y}{\gamma_{M1}} = 3810kN > |N_{Ed}| = 3220.3kN$$

OK

Similarly to the above check, all structural members (e.g. columns and beams) shall be designed with the appropriate design values and combinations (M, N, V, M-V, M-N).

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