PARASEISMIC PROJECT

Yves Duchêne

yduchene@greisch.com

Arnaud Deraemaeker

Arnaud.Deraemaeker@ulb.be

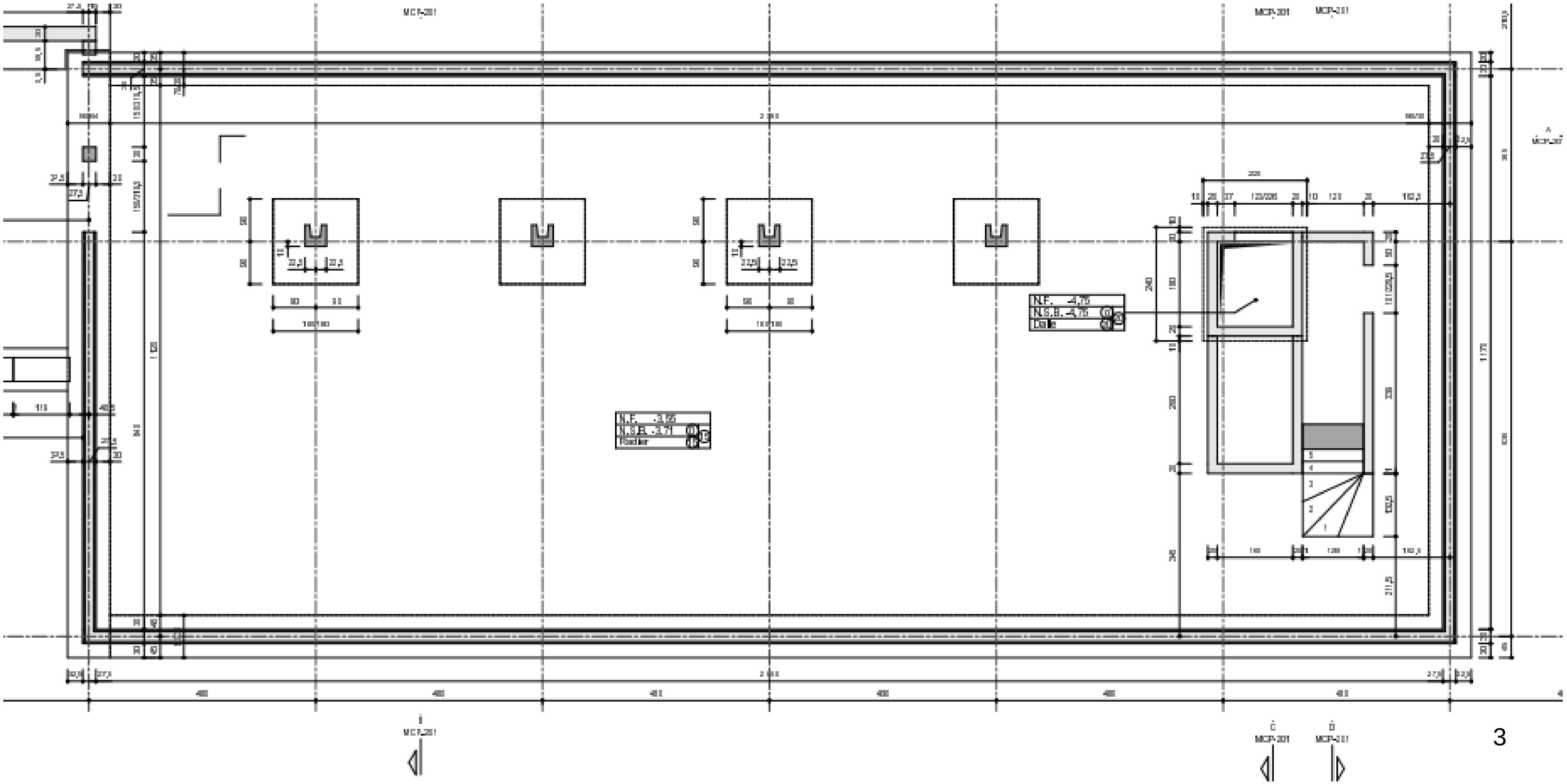
Parasismic verification of a building according to Eurocode 8

Make the seismic verification of the new building of the sports center located in Liege according to the Eurocode EN 1998-1

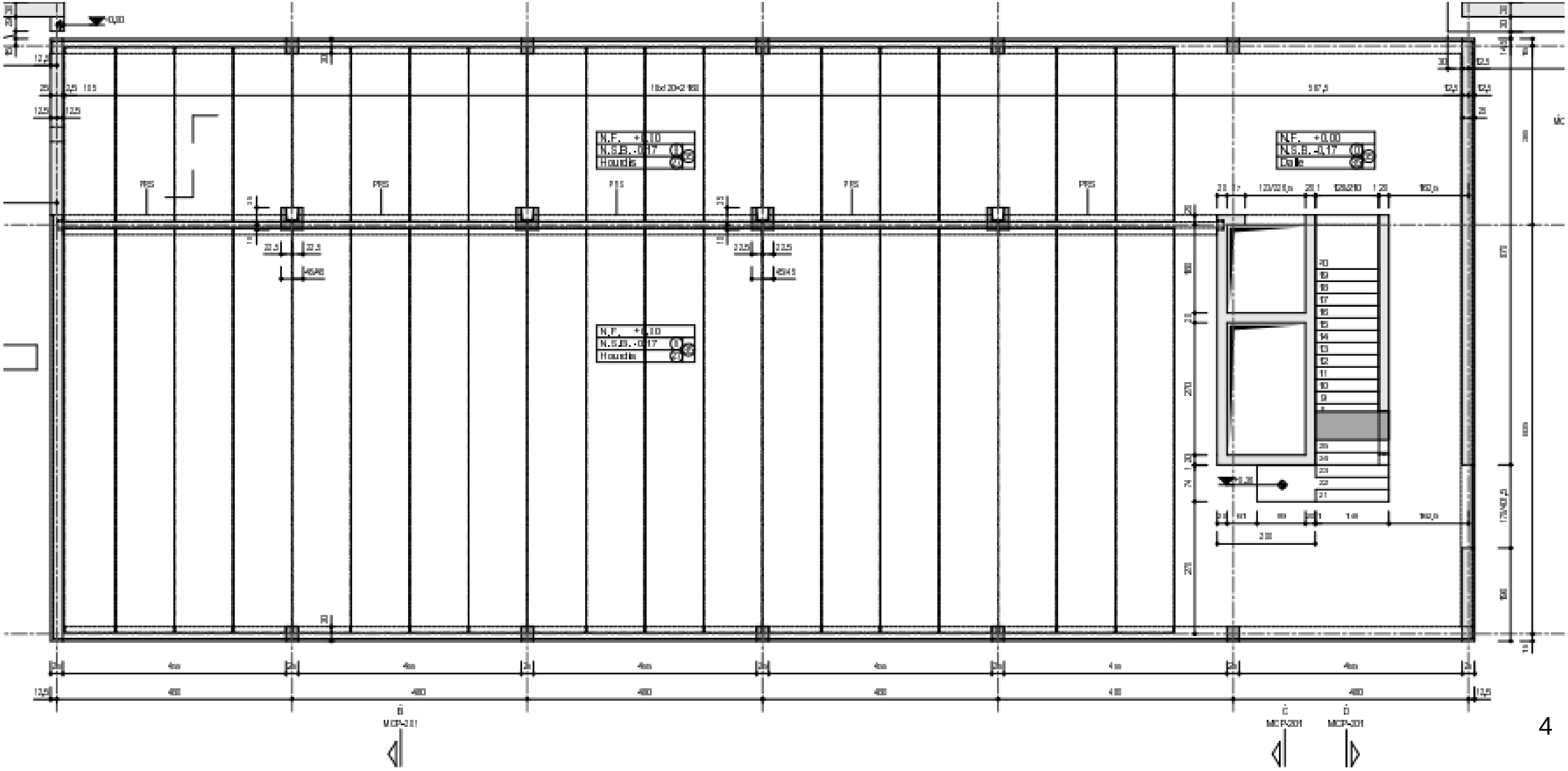
The building characteristics are:

- Rectangular building of dimensions 45 X 15 m
- 1 ground level + 1 level and an underground level ➔ 3 levels
- Columns and central nucleus in concrete. All the other walls are in masonry except the underground walls which are in concrete
- The slabs are in concrete
- The building is located in Liege with a soil class C according to EN 1998-1
- The building is an office building with meeting rooms
- Concrete is C 30/37 with an instantaneous non cracked Young's modulus of 35 000 N/mm²
- The dead masses of the floor are 600 kg/m² and 500 kg/m² for the roof
- The live loads are 500 kg/m²
- The vertical component of the earthquake can be neglected

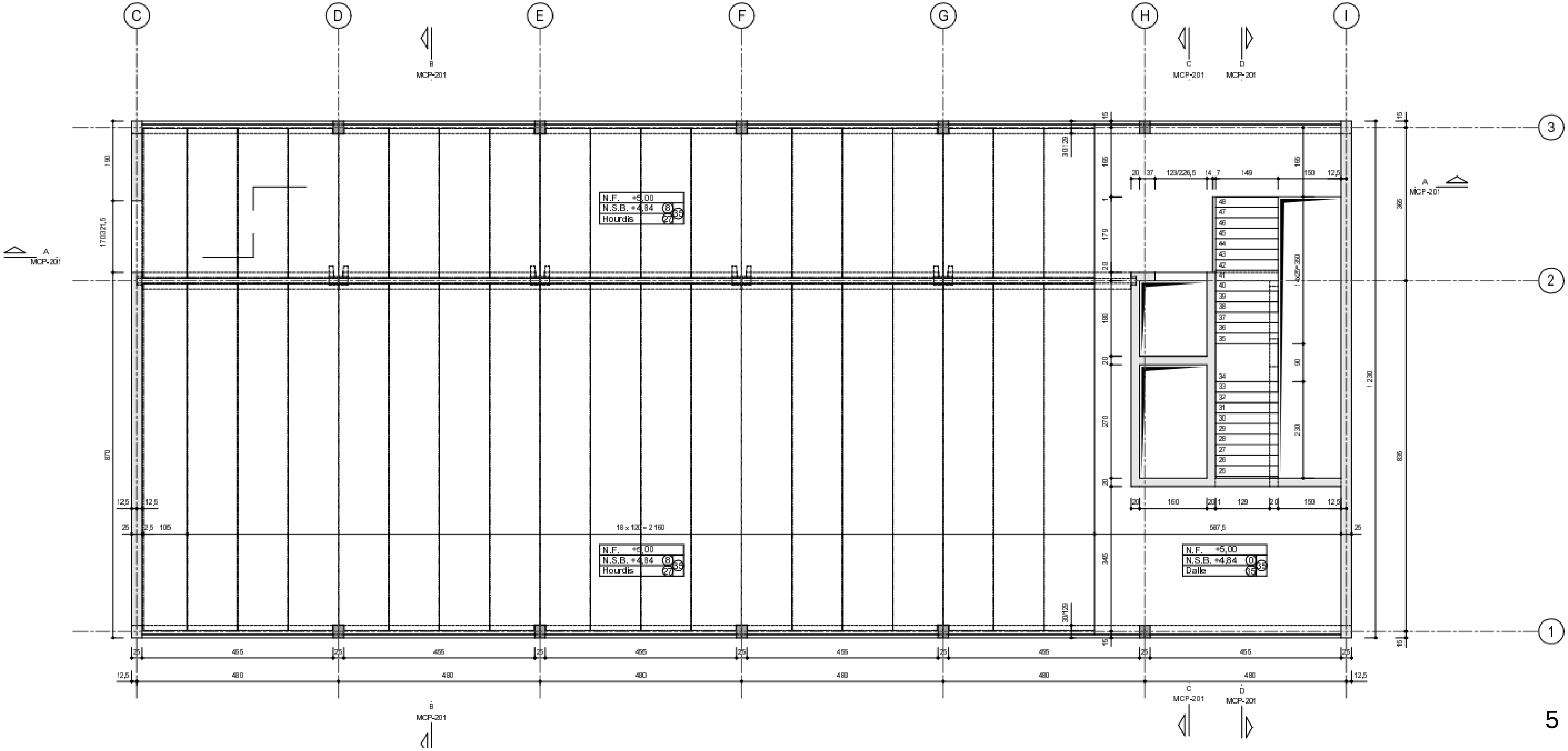
Plane view - underground



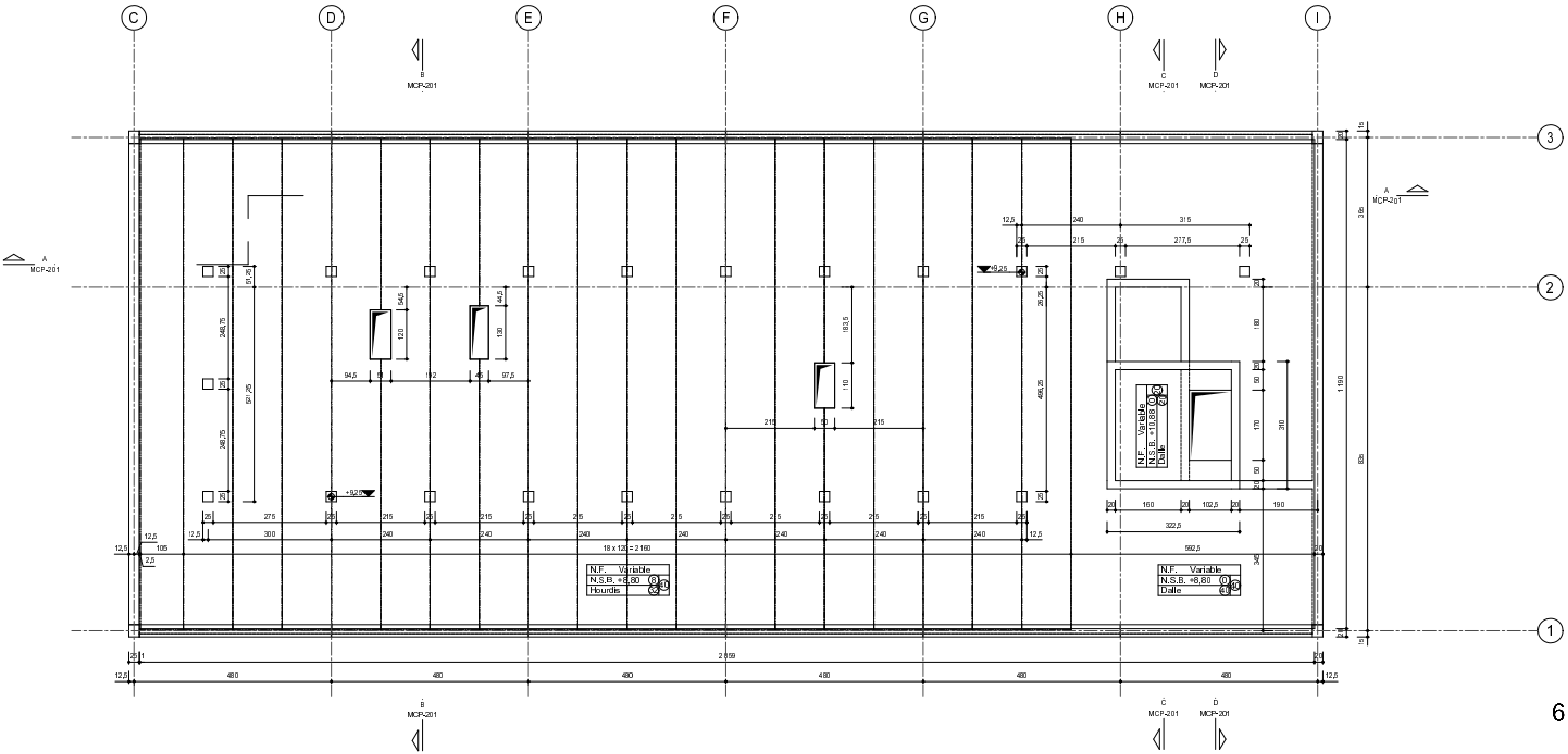
Plane view – level 0



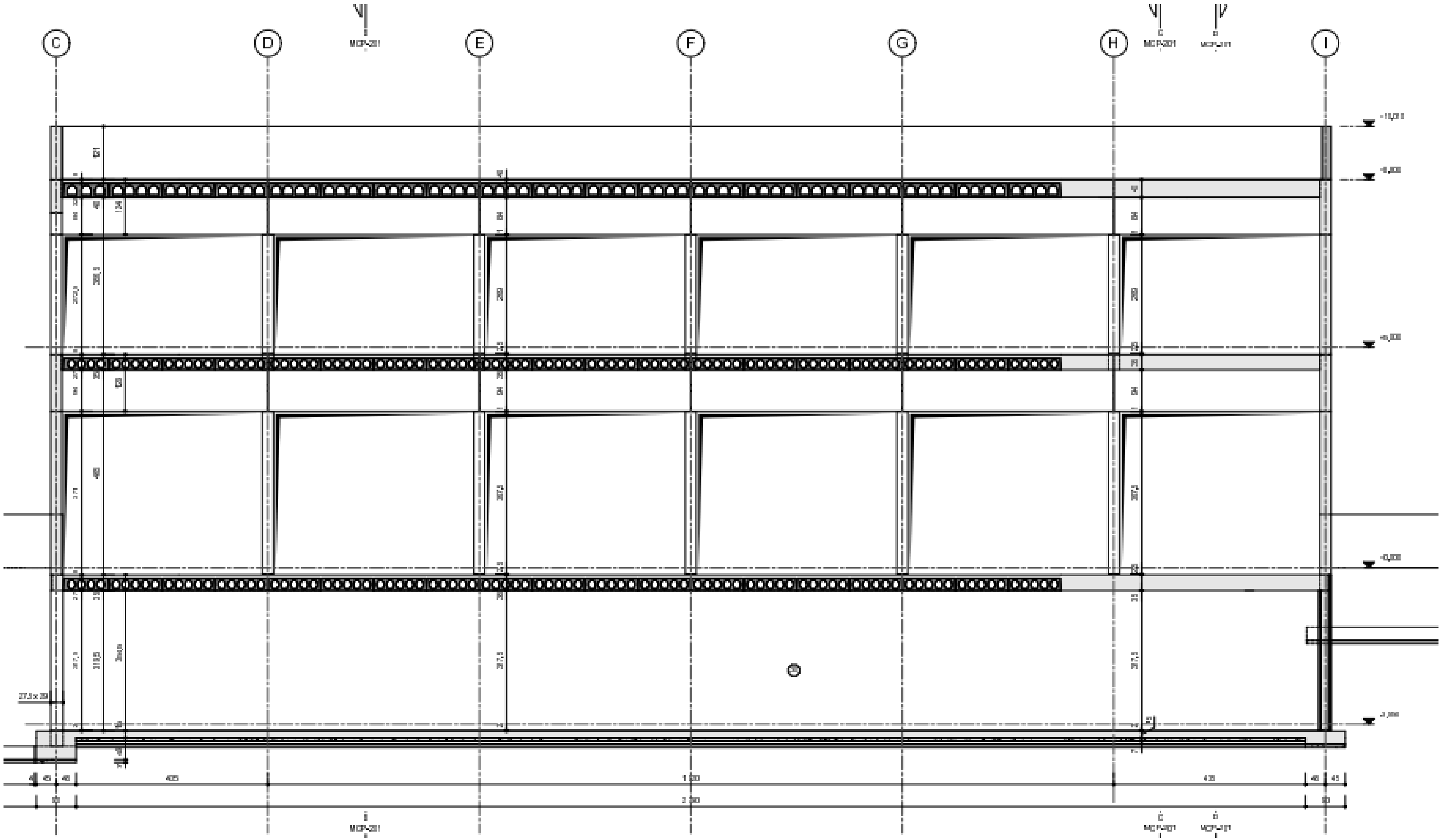
Plane view – level 1



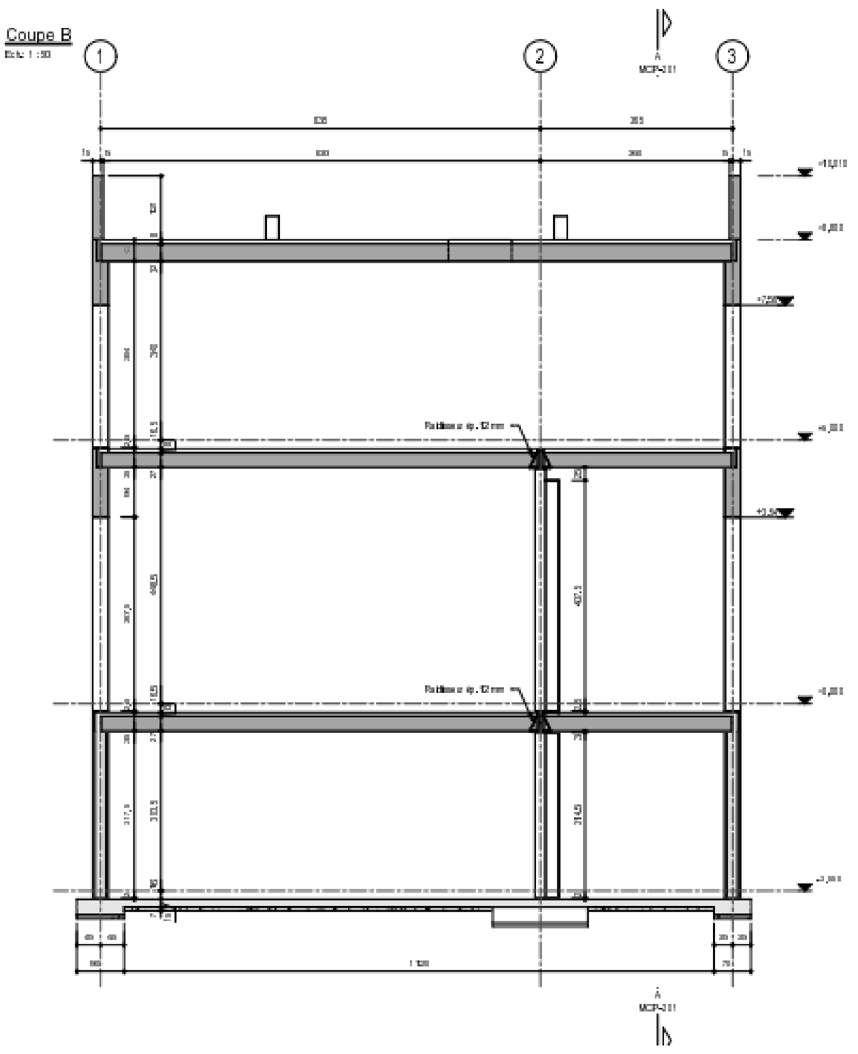
Plane view – roof

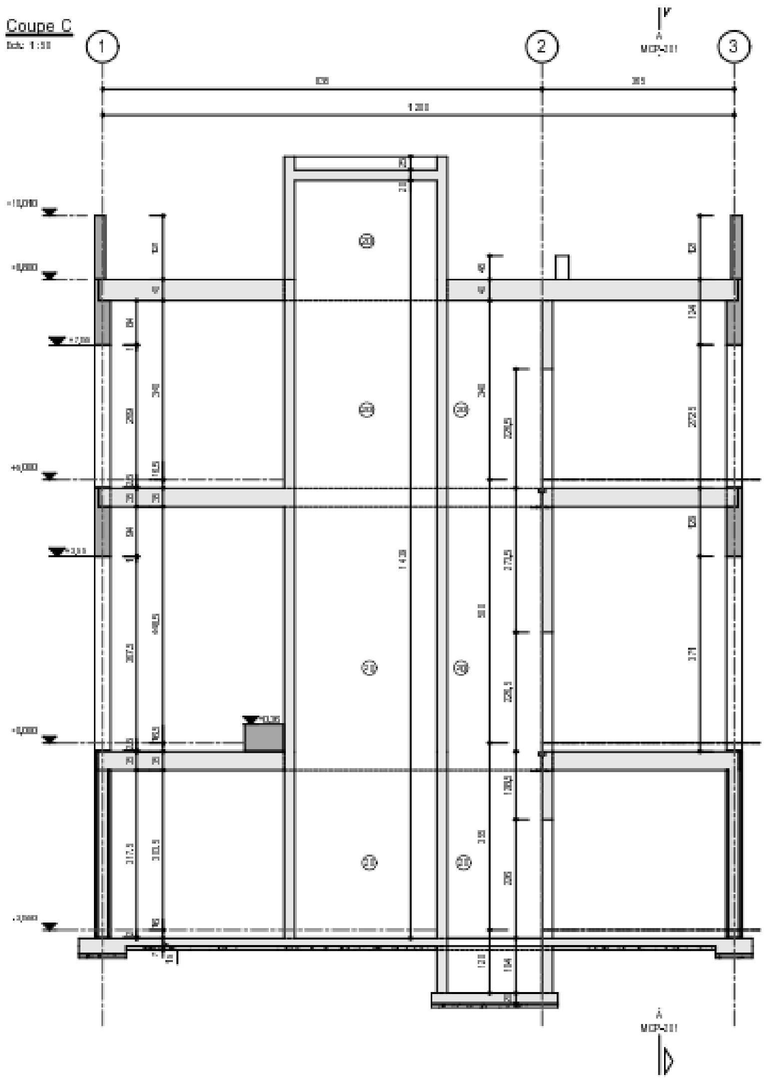


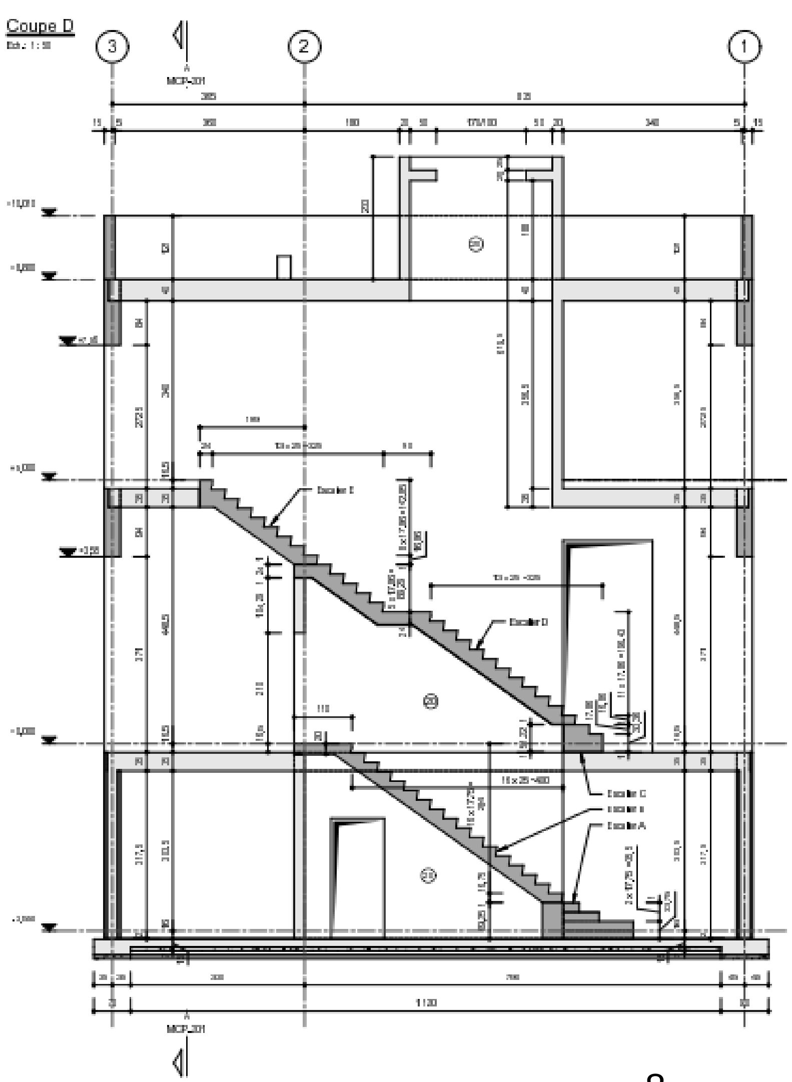
Elevation



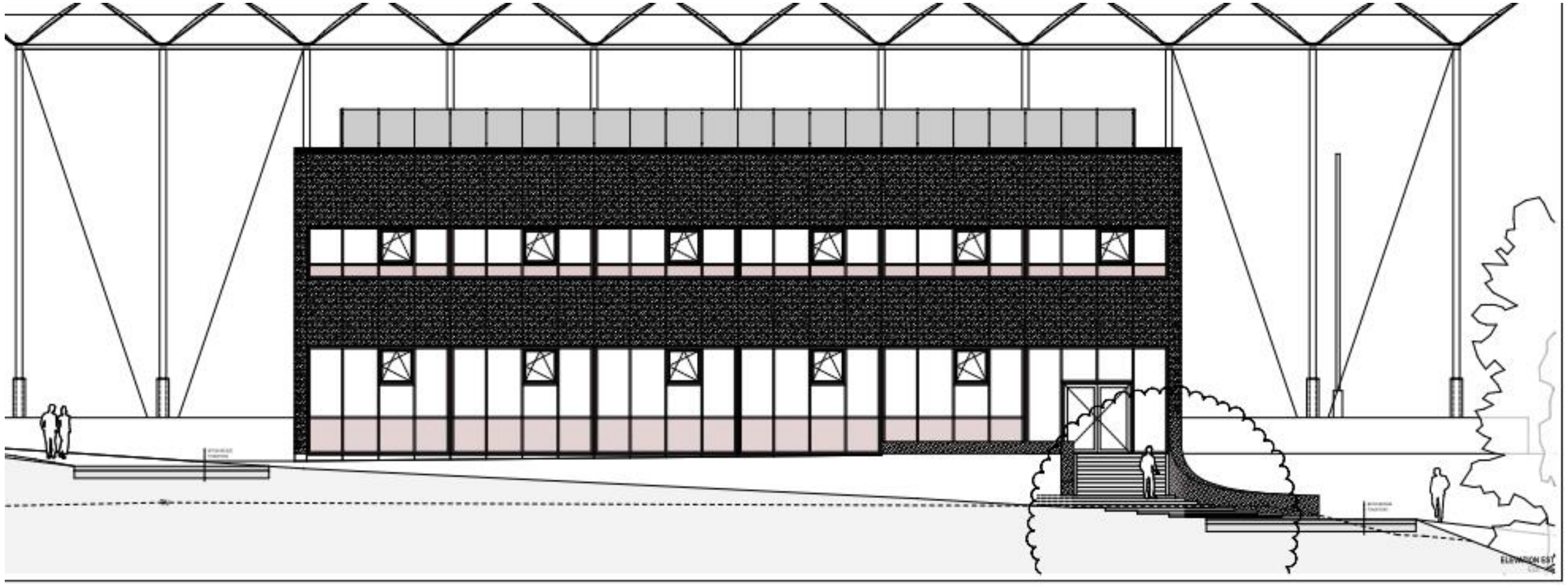
Elevation

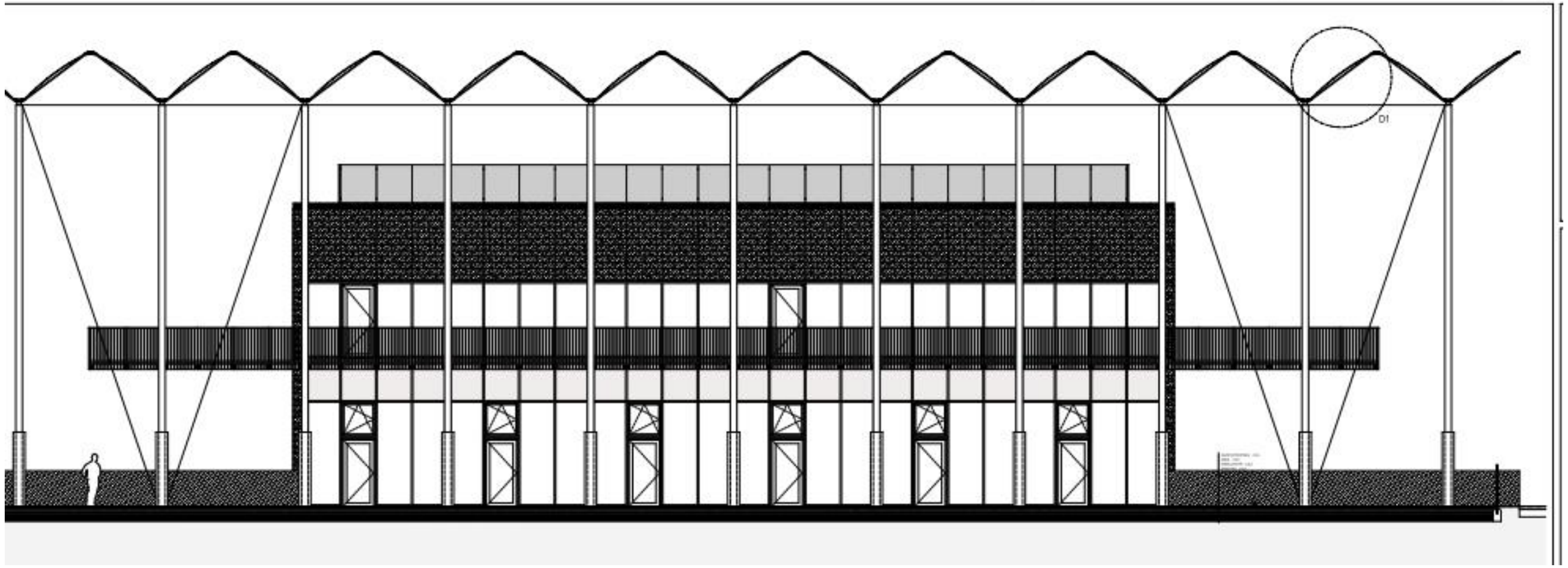




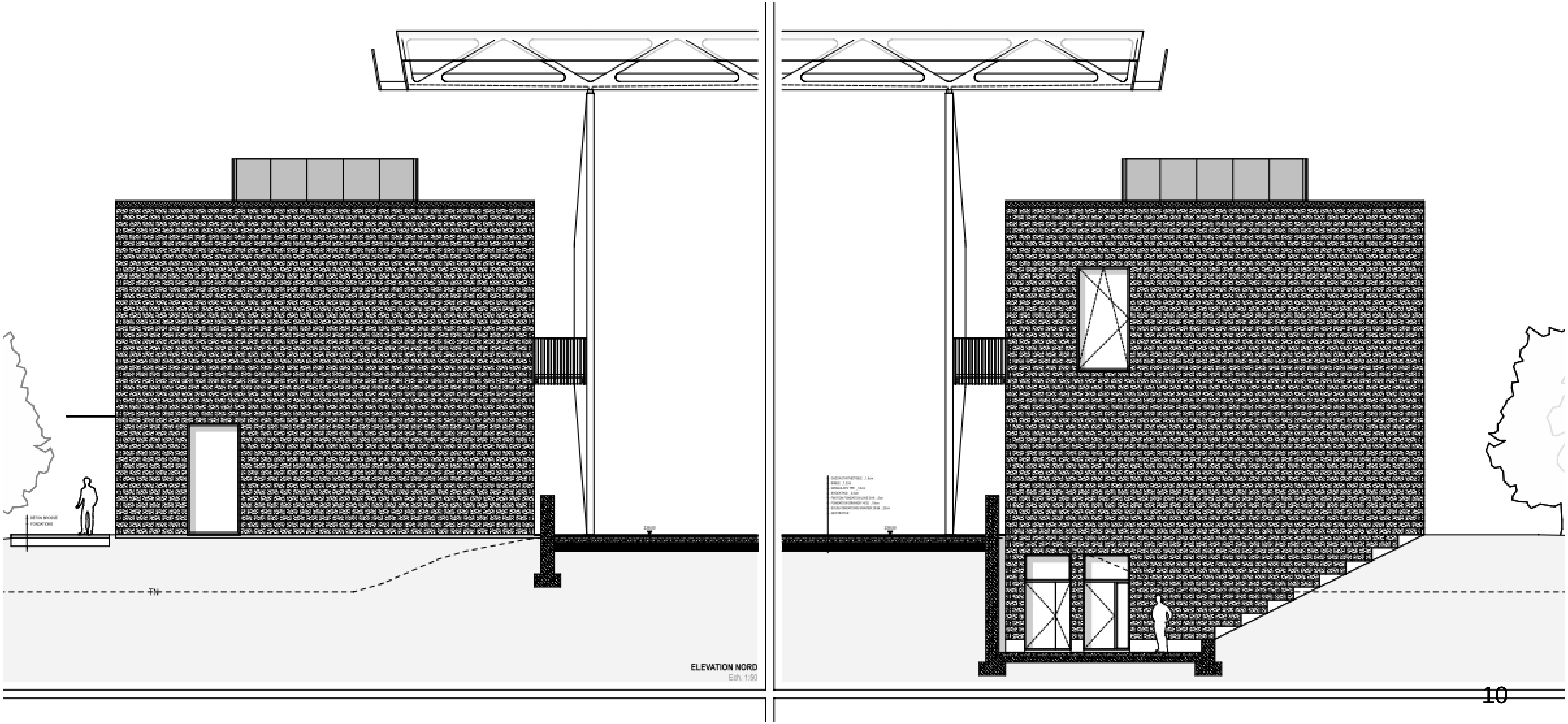


Facades





Facades



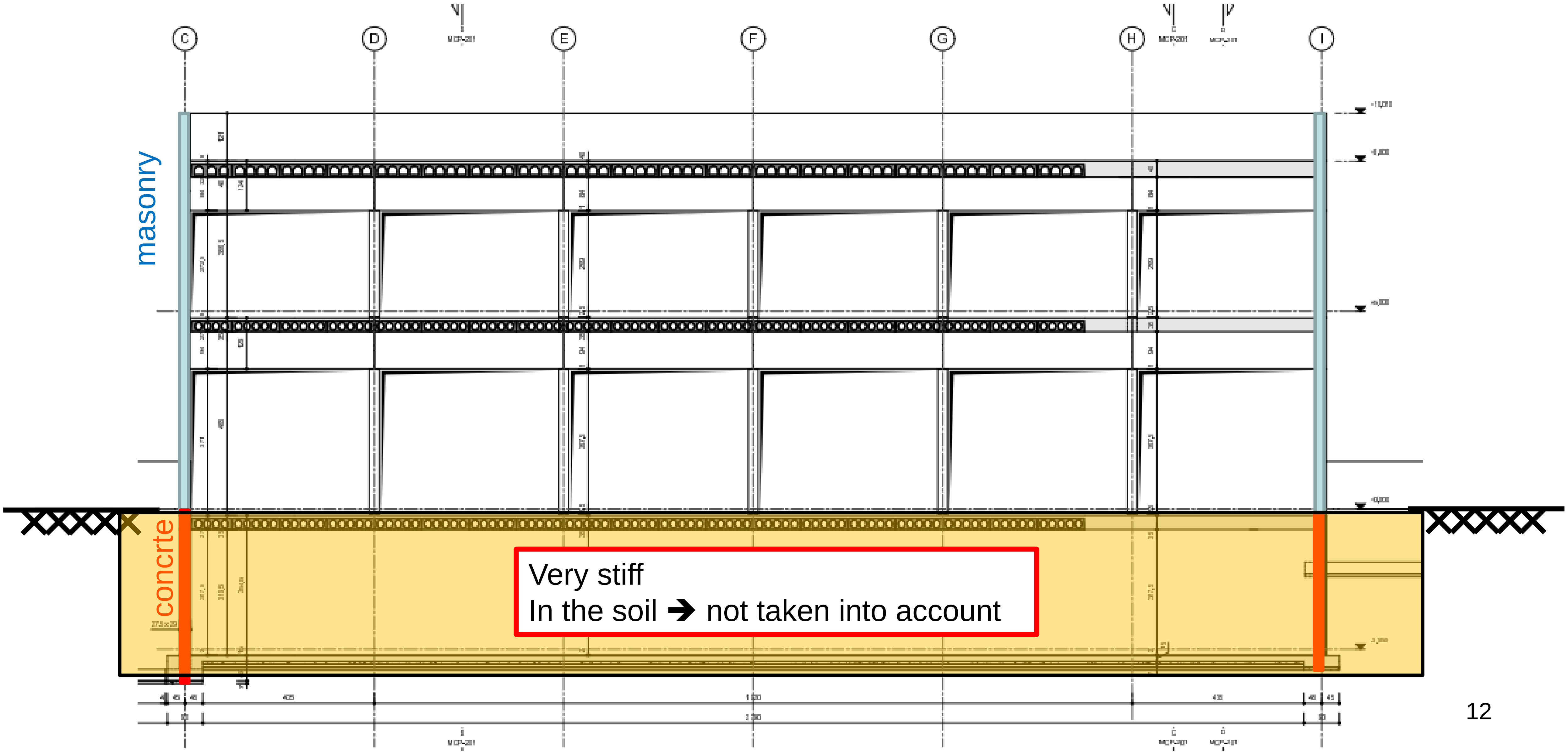
1. Simplify the static scheme

Ask yourself the following questions:

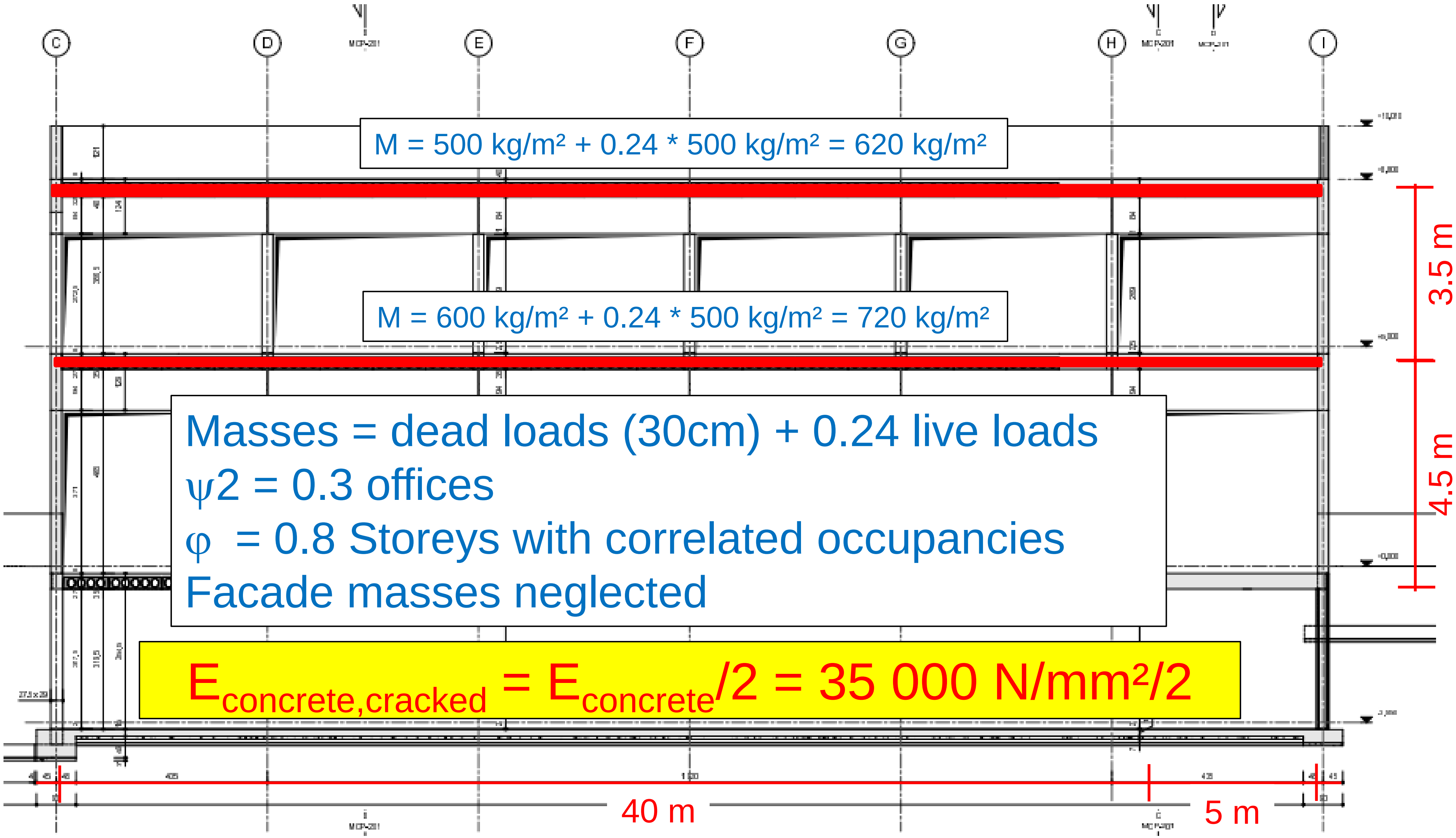
- In which direction do the earthquake loads act?
- What are the resisting elements under earthquake ?
- Do the columns sustain earthquakes loads ?
- What are the flexible parts of the building ?
- Which elements must be modelled ?
- The masonry has a very small resistance to horizontal loads ➔ no resistance
- Make the simplest model to represent the structure behaviour under earthquake, minimise the dofs

Model the building with beam elements with only a few nodes.
Analyse the effect of the number of nodes on the frequency, eigen modes with MyFin
For the Octave/Matlab calculation, keep the simpler model

Static scheme – underground level not taken into account



Static scheme – Masses



M = 500 kg/m² + 0.24 * 500 kg/m² = 620 kg/m²

M = 600 kg/m² + 0.24 * 500 kg/m² = 720 kg/m²

Masses = dead loads (30cm) + 0.24 live loads

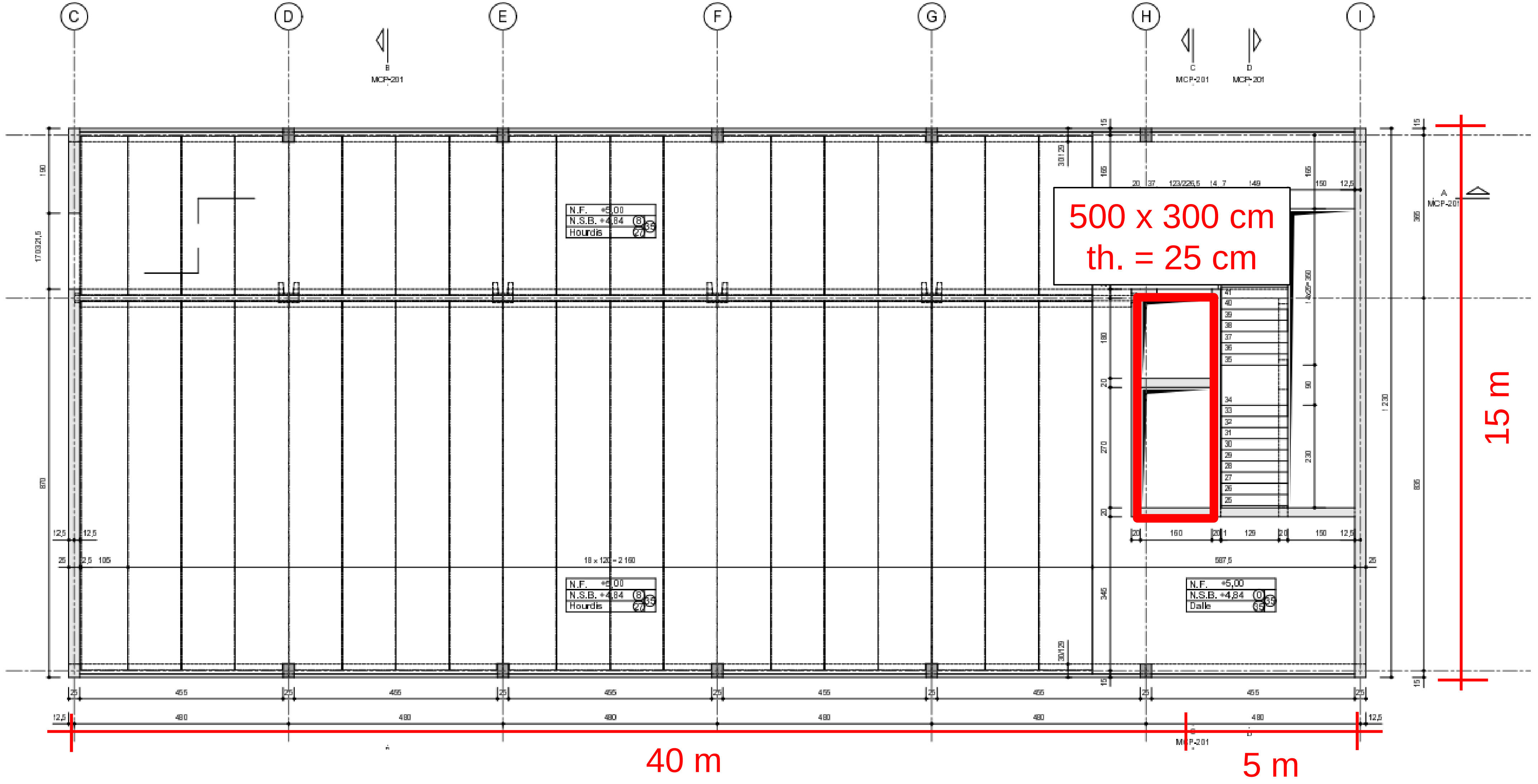
$\psi 2$ = 0.3 offices

φ = 0.8 Storeys with correlated occupancies

Facade masses neglected

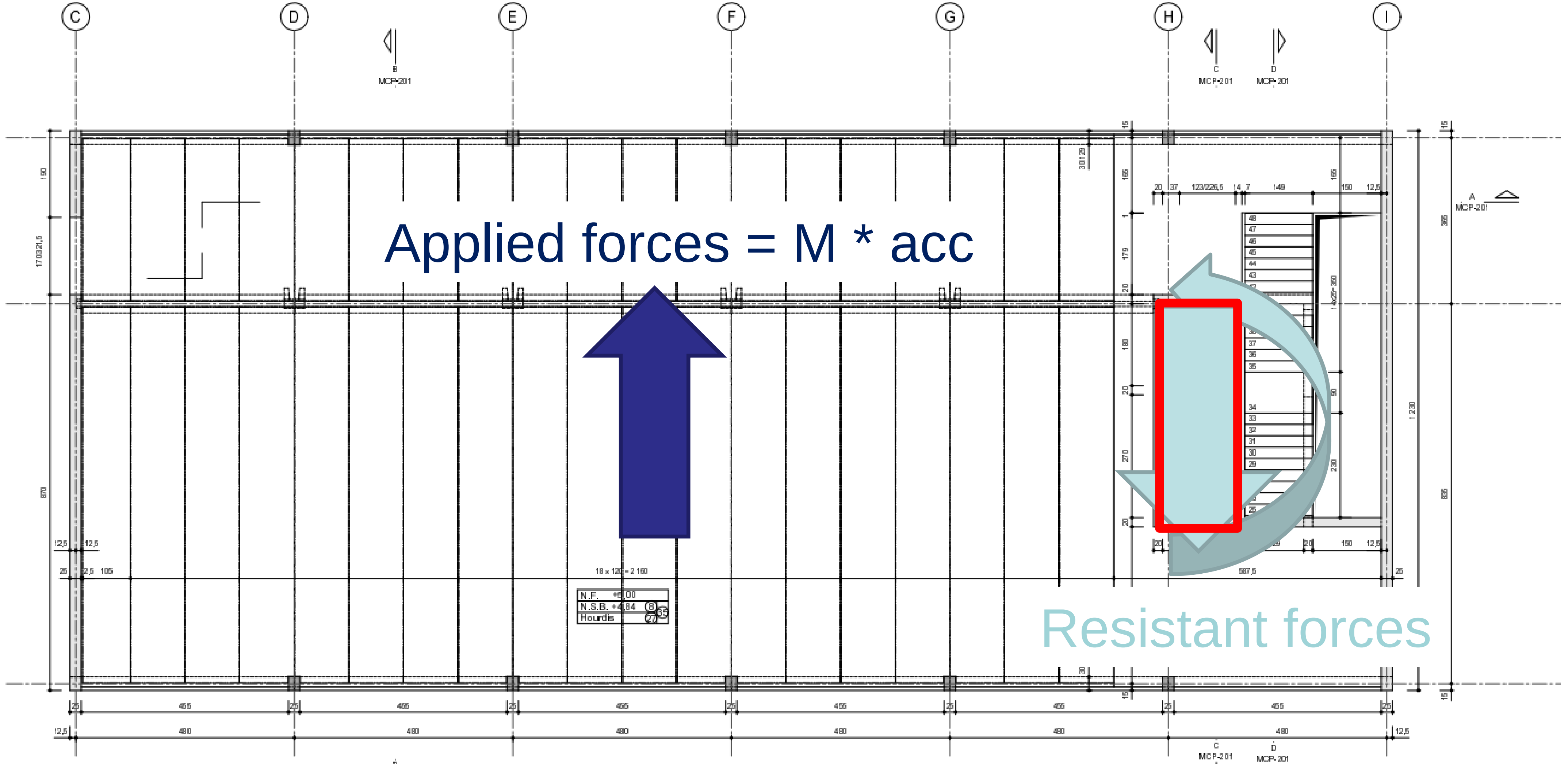
$E_{concrete,cracked} = E_{concrete}/2 = 35\,000\ N/mm^2/2$

Static scheme – which element sustains the horizontal loads ?



Only the concrete central core !

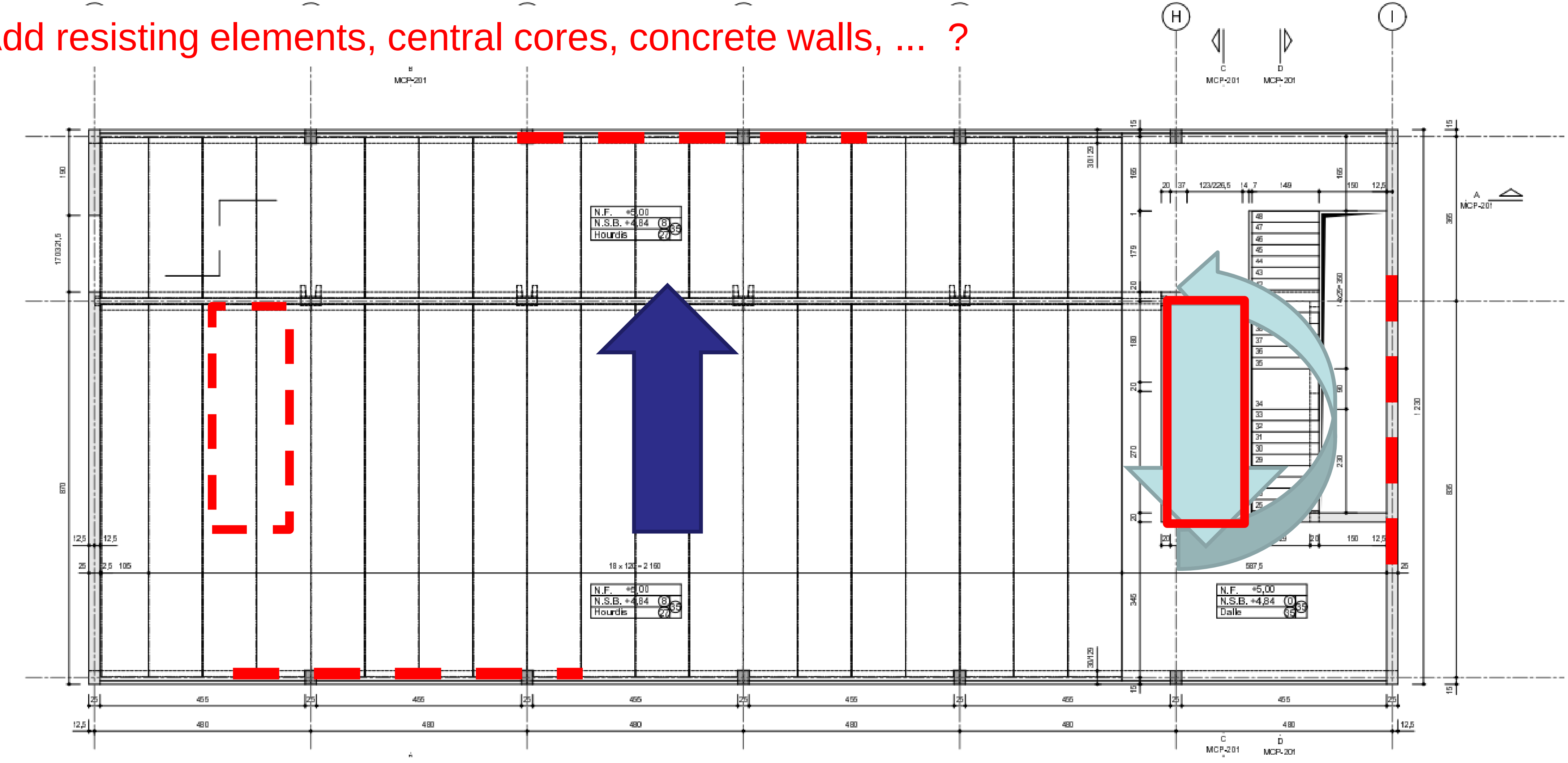
Static scheme – improve the behaviour under horizontal loads



Big torsion in the central core. What can be done to reduce the torsion ?

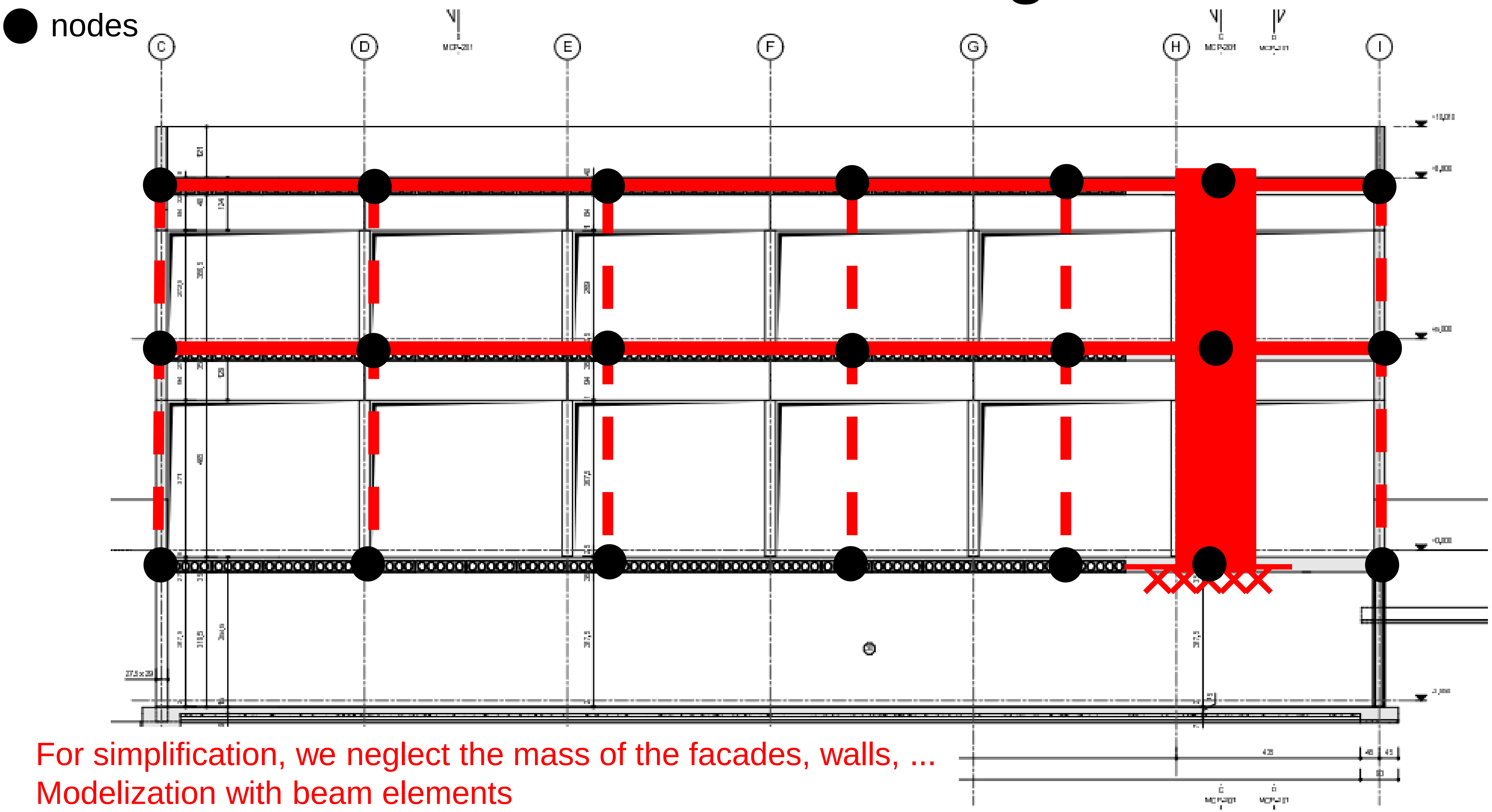
Static scheme – What can we do to improve the torsion

Add resisting elements, central cores, concrete walls, ... ?



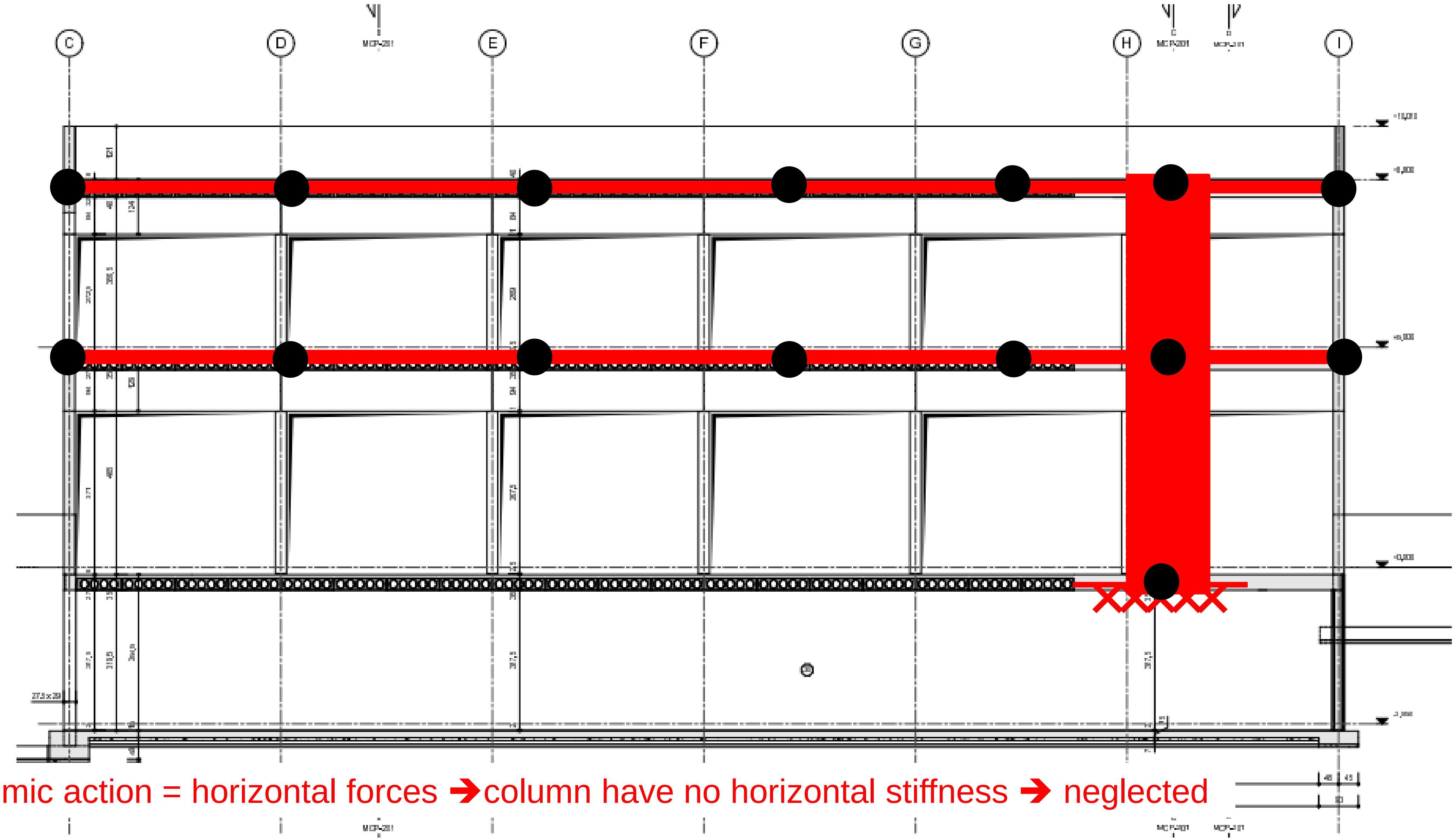
Propose minimum 2 alternatives

Modelization – resisting elements



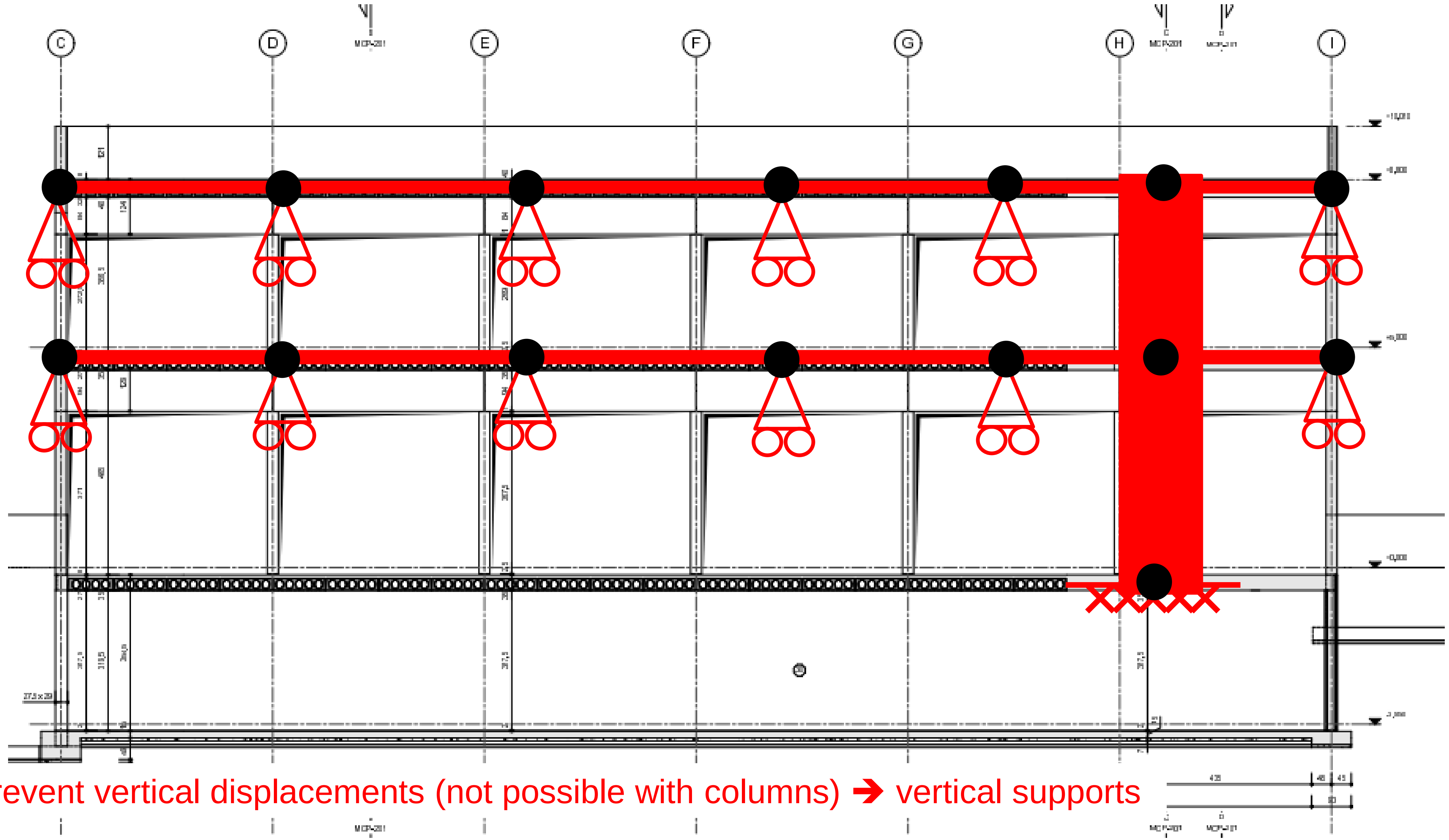
For simplification, we neglect the mass of the facades, walls, ...
Modelization with beam elements

Modelization – resisting elements



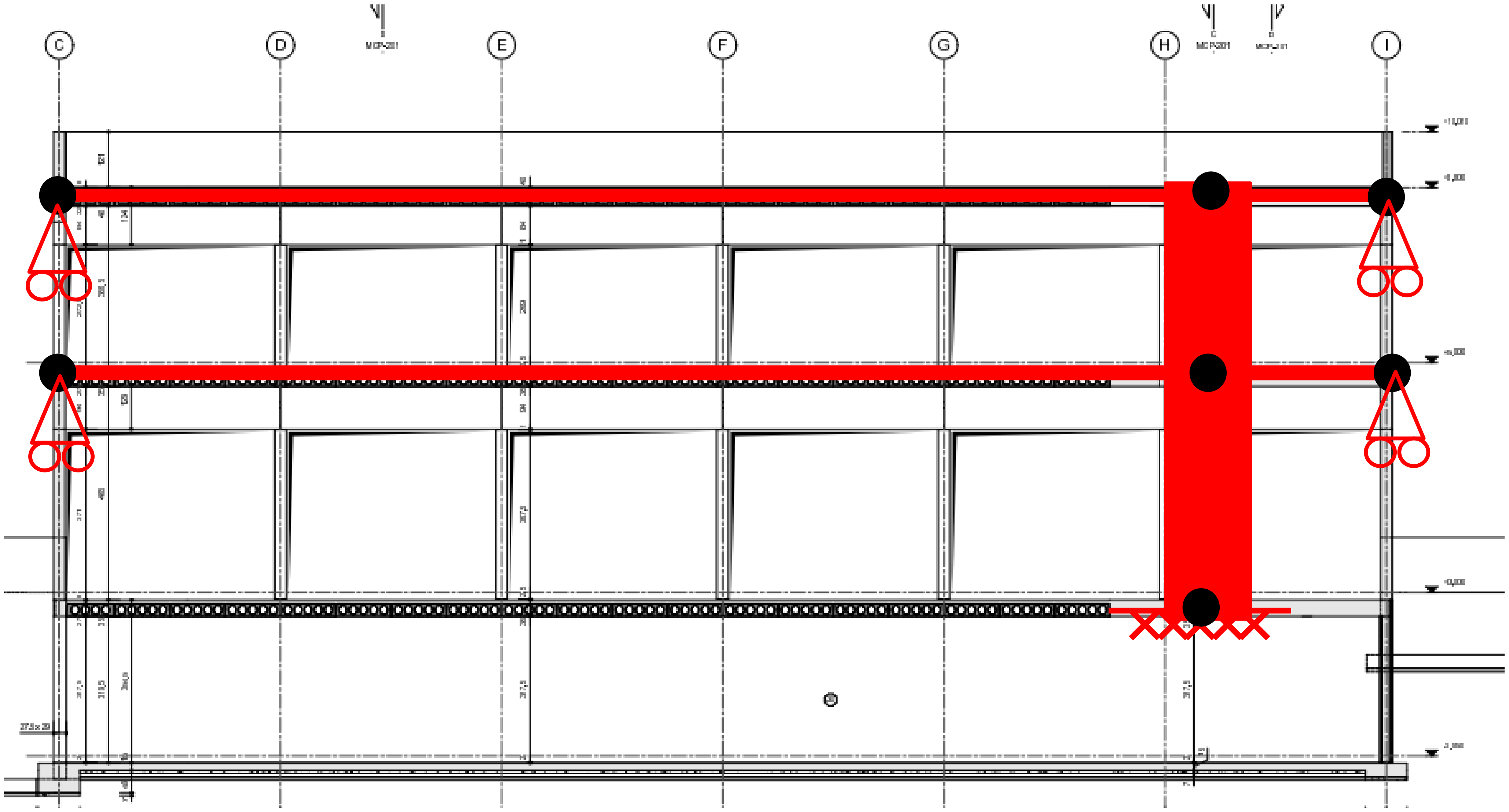
Seismic action = horizontal forces ➔column have no horizontal stiffness ➔ neglected

Modelization – resisting elements



To prevent vertical displacements (not possible with columns) ➔ vertical supports

Modelization – resisting elements

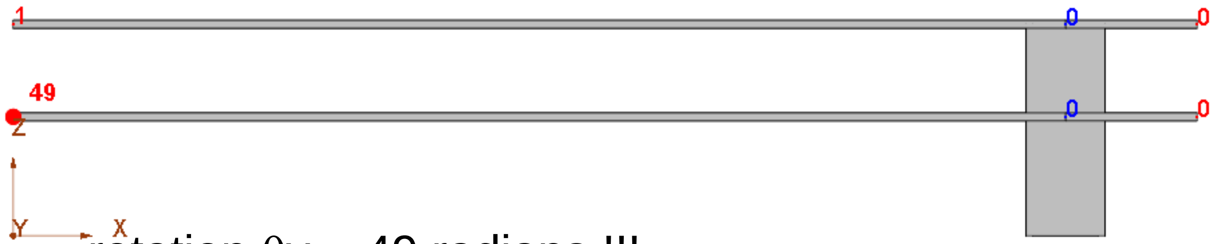


Suppress non necessary nodes to decrease the number of dofs – slab modelled by **1** element

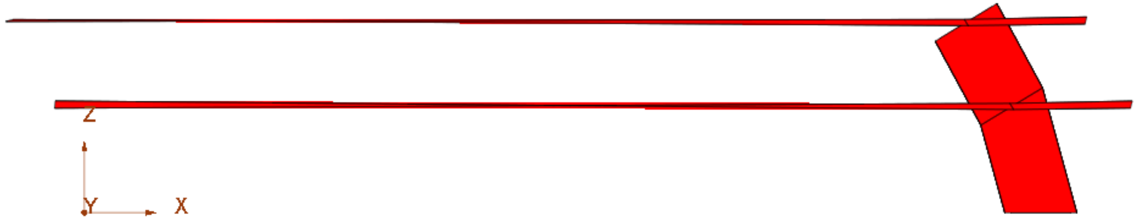
Modelization – local bending mode

if modelization of the slab with 1 element ➔ we obtain a local bending mode not possible with the columns

1 element



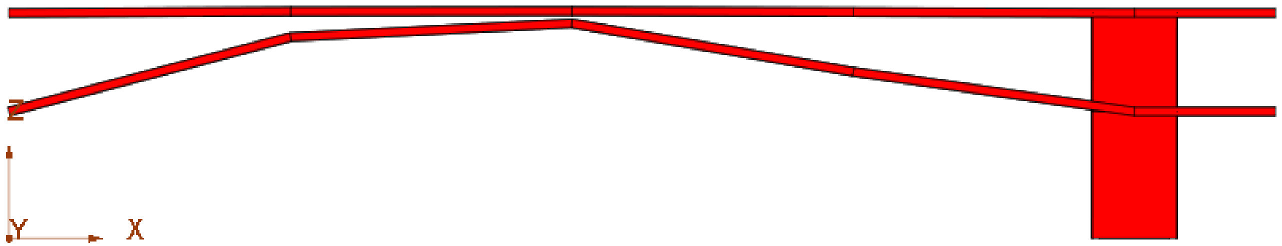
rotation θy = 49 radians !!!



deformed shape – bending not visible because the software draw only the nodal displacement not the rotations

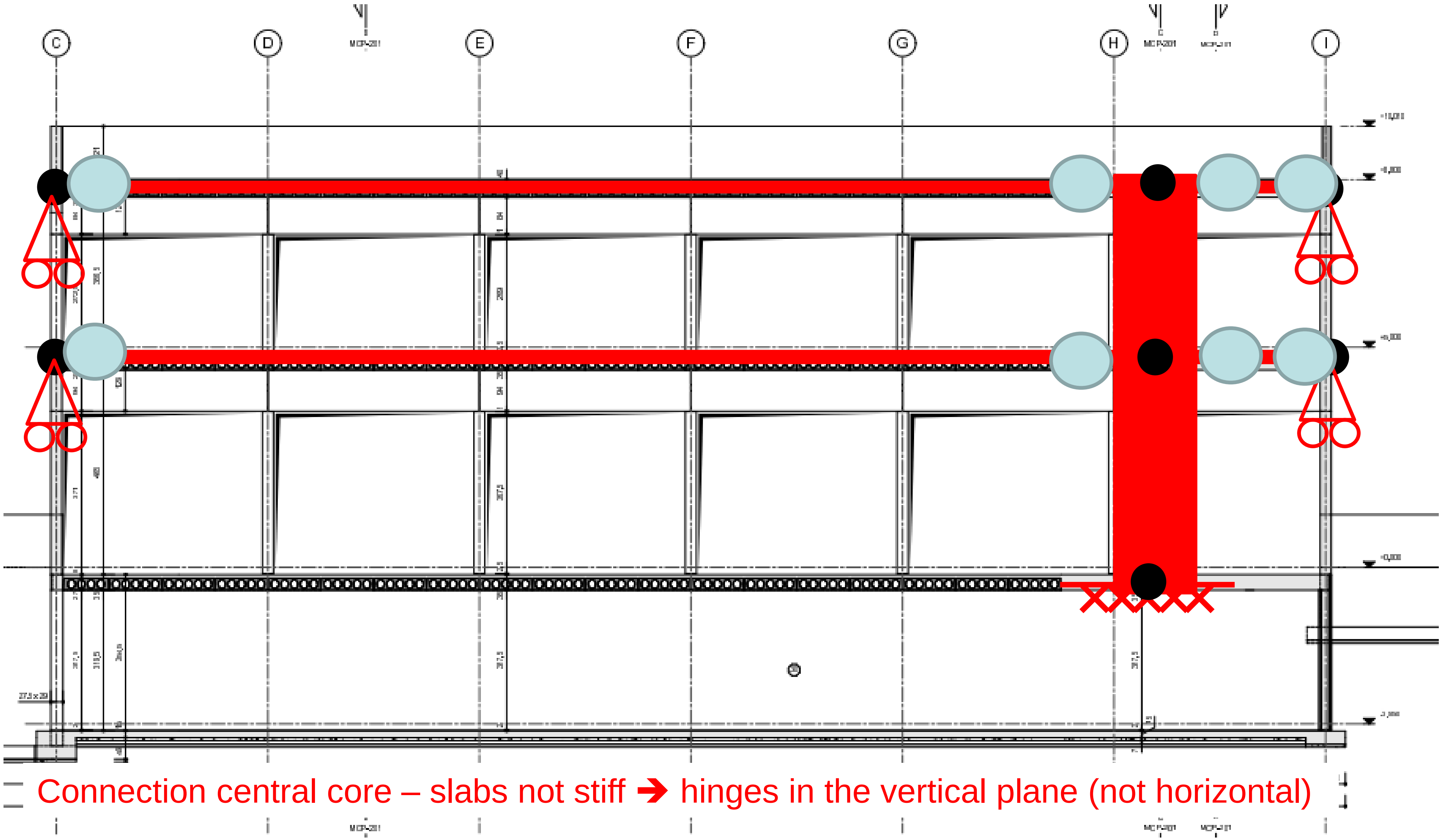
4 elements

if we use 4 elements to model the beam ➔ bending mode visible



we have to suppress this bending mode, we suppress the rotation dofs

Modelization – resisting elements



Connection central core – slabs not stiff ➔ hinges in the vertical plane (not horizontal)

2.Frequencies and eigen modes

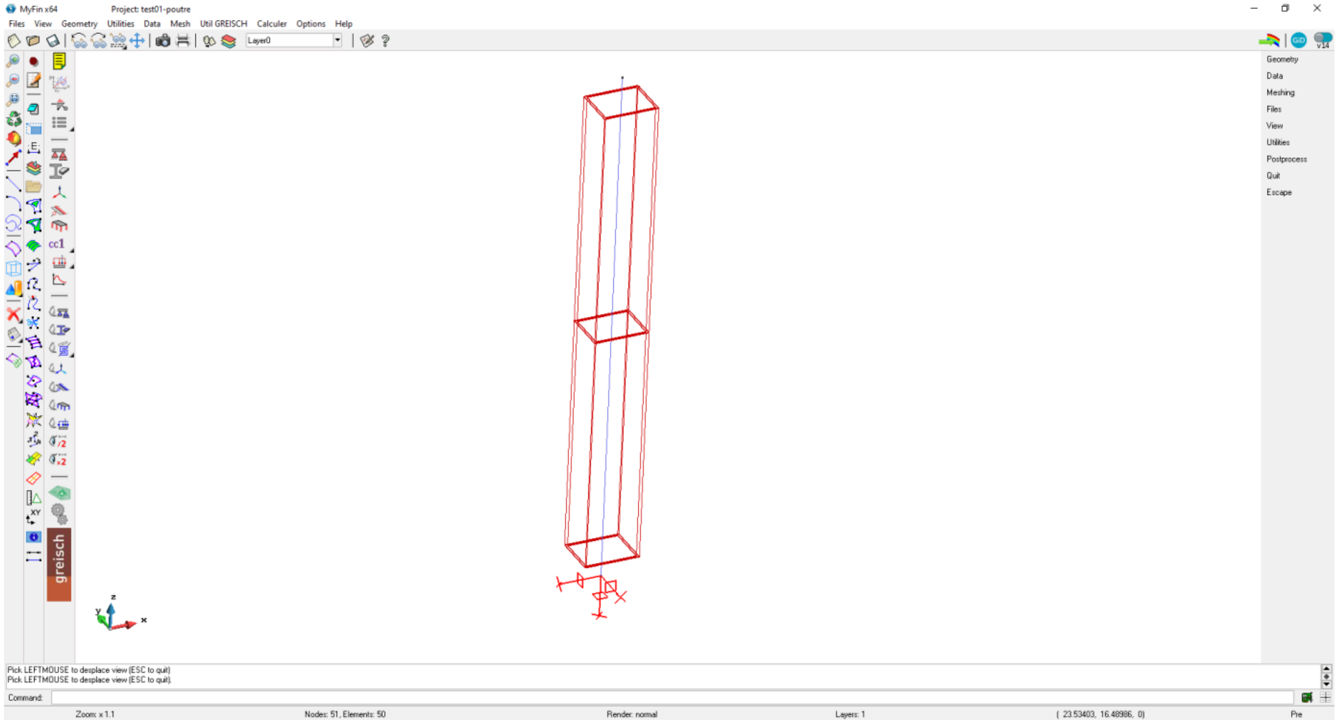
1. Establish the static scheme of the structure
   - Simplify the structure to focus on the horizontal behavior of the structure to represent the dynamic behavior under earthquake. Use beam elements.
   - Make some modification to improve the torsion behavior
2. Frequencies and eigen modes
   - Make the modelization of the structure with MyFin. Use beam elements
   - Compute the first eigen modes and draw the first important eigen modes
   - Analyse the effects of the number of beams for the vertical columns, the horizontal beams
   - Extract the stiffness and mass matrix of the system ***for the minimum of beam elements***
   - Import the matrices in Octave (Matlab)
   - Compute the eigen modes and the frequencies

     Eigen mode normalized with maximal nodal displacement = 1.00
   - Compare with the MyFin solution

2.Frequencies and eigen modes

Use MyFin – Finelg software

- Compute first eigen modes
- Draw the eigen shape



- Extract the stiffness and mass matrices
  - Stiffness : *filename*_MATK.txt
  - Mass : *filename*_MATM.txt
- Import the matrices in Matlab and compute the eigen modes
  - `K = readmatrix('filename_MATK.TXT')`
  - `M = readmatrix('filename_MATM.TXT')`
  - **Warning: K and M are the full matrices with the supported nodes**

Take supports into account (example)

Attention: *Matrices from MyFin include all the nodes*
Suppress the node related to the support

NODES (columns) / NODES (rows)

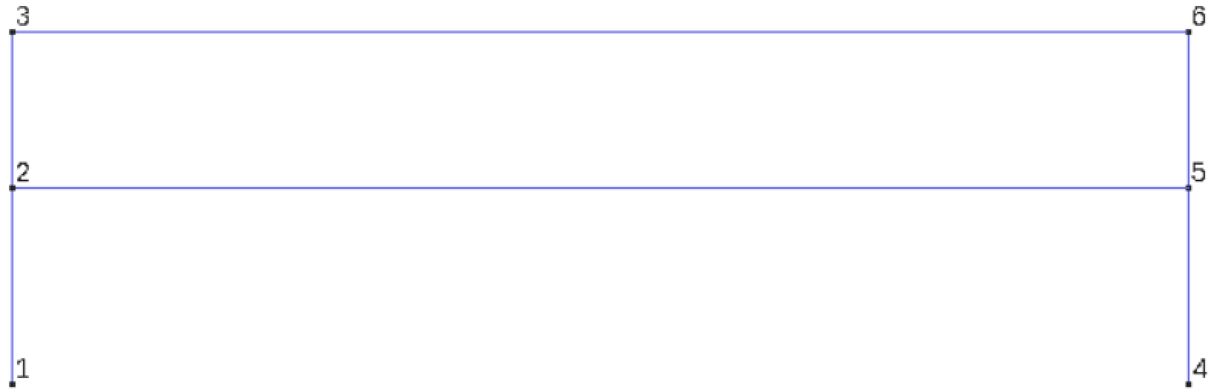
	1	2	3	4
1	6x6	6x6	0	0
2	6x6	6x6	0	6x6
3	0	0	6x6	6x6
4	0	6x6	6x6	6x6

Suppress the dofs related to supported nodes
Pay attention to the node numbers

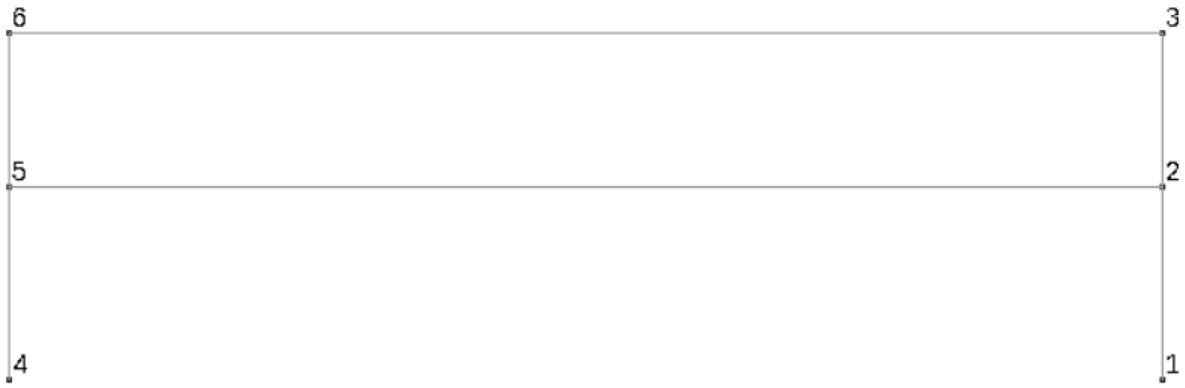
Take supports into account (example)

Attention: be careful with the nodes number

Geometry mode



Mesh mode



3. Modal properties

- Compute the modal mass and stiffness of each mode
  - $\mu_i = \psi_i^T . M . \psi_i$ Depends on the mode
- Compute the effective modal mass in both horizontal directions
  - $PM_{ik} = \frac{\left(\psi_i^T.M.e_k\right)^2.100}{(\psi_i^T.M.\psi_i).(e_k^T.M.e_k)}$ Depends on the mode and the seism direction
  - with the property : $\sum_{i=1}^{ndofs} PM_{ik} = 100\ \%$ for k = X, Y or Z
- Compute the modal share ratio for both horizontal directions
  - $RM_{ik} = \frac{\psi_i^T.M.e_k}{\psi_i^T.M.\psi_i}$ Depends on the mode and the seism direction

Where:

- M is the mass matrix
- ψ_i is the i^{th} eigen mode
- {e}k is a vector with 1 for each dof in the considered direction and 0 for the others

Definition of the ex, ey , ez vector

{e}k is a vector with 1 for each dof in the considered seism direction and 0 for the others

By node: 6 degrees of freedom (dofs) : x, y, z, θx, θy, θz

A total of 4 nodes ➔ vector 1 x 24

	node 1						node 2						node 3						node 4						
	x	y	z	θx	θy	θz	x	y	z	θx	θy	θz	x	y	z	θx	θy	θz	x	y	z	θx	θy	θz	
ex:	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	*Seism in x direction*
ey:	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	*Seism in y direction*
ez:	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	*Seism in z direction*

4. Parasismic calculation

- Establish the design acceleration spectrum according to EN 1998-1

  The building is located in Liege with a soil class C according EN 1998-1
  The building is an office building with meeting rooms
  The q factor is taken equal to 1.5

- Compute the response (displacements) of each mode in each direction

- Compute the maximum response in each direction (SSRS and CQC) of the building top
  - Which modes govern the total seismic response for each direction ?

- Compute the support forces

- Combine the support forces for both horizontal seism directions

Design Spectrum definition

According to EN 1998-1: chapter 3.2.2.5

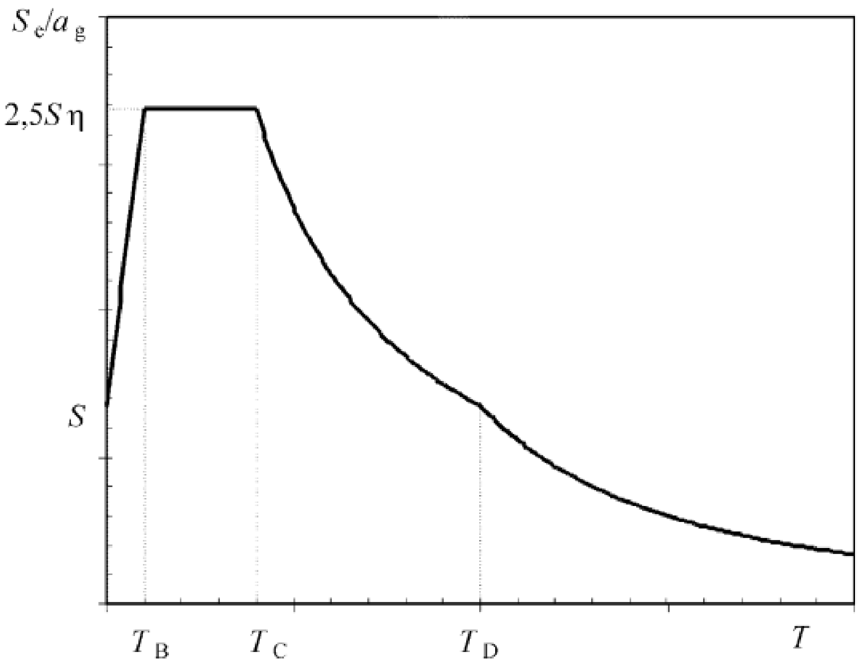
(4)P For the horizontal components of the seismic action the design spectrum, $S_d(T)$, shall be defined by the following expressions:

$$0 \le T \le T_B : S_d(T) = a_g \cdot S \cdot \left[\frac{2}{3} + \frac{T}{T_B} \cdot \left(\frac{2,5}{q} - \frac{2}{3}\right)\right] \quad (3.13)$$

$$T_B \le T \le T_C : S_d(T) = a_g \cdot S \cdot \frac{2,5}{q} \quad (3.14)$$

$$T_C \le T \le T_D : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C}{T}\right] \\ \ge \beta \cdot a_g \end{cases} \quad (3.15)$$

$$T_D \le T : S_d(T) \begin{cases} = a_g \cdot S \cdot \frac{2,5}{q} \cdot \left[\frac{T_C T_D}{T^2}\right] \\ \ge \beta \cdot a_g \end{cases} \quad (3.16)$$



where

a_g, S, T_C and T_D	are as defined in **3.2.2.2**;
$S_d(T)$	is the design spectrum;
q	is the behaviour factor;
β	is the lower bound factor for the horizontal design spectrum.

NOTE The value to be ascribed to β for use in a country can be found in its National Annex. The recommended value for β is 0,2.

Design Spectrum definition

Table 3.3: Values of the parameters describing the recommended Type 2 elastic response spectra

Ground type	S	T_B (s)	T_C (s)	T_D (s)
A	1,0	0,05	0,25	1,2
B	1,35	0,05	0,25	1,2
C	1,5	0,10	0,25	1,2
D	1,8	0,10	0,30	1,2
E	1,6	0,05	0,25	1,2

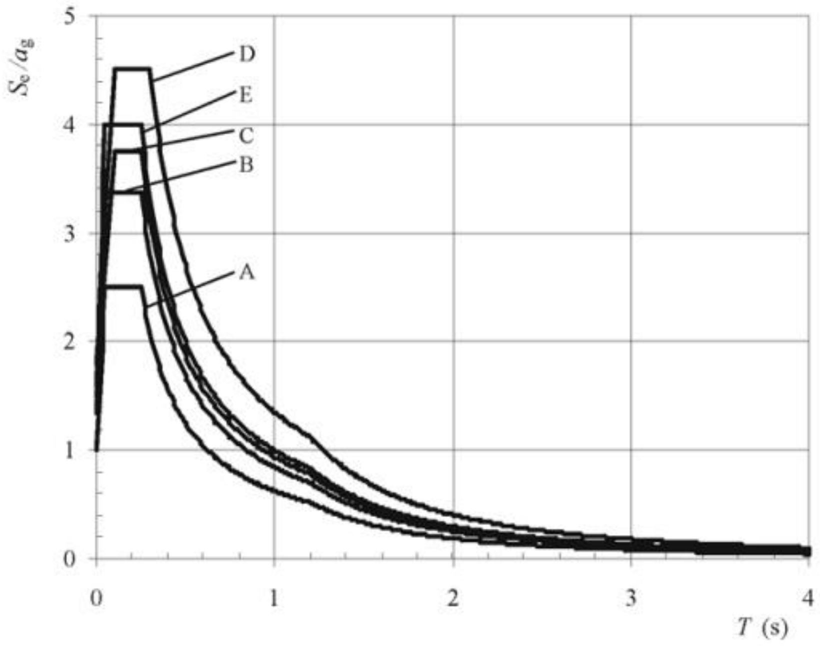


Figure 3.3: Recommended Type 2 elastic response spectra for ground types A to E (5% damping)

Design Spectrum definition

3.2 **Action sismique**
3.2.1 **Zones sismiques**

(2) La carte normative de zonage sismique de la Belgique est donnée à la Figure 1. La Belgique comporte 5 zones où l'accélération horizontale maximale de référence a_{gR} sur le rocher vaut respectivement :

Zone sismique 0 :	Pas d'accélération significative
Zone sismique 1 :	a_{gR} = 0,39 m/s^2 ou 0,04 g
Zone sismique 2 :	a_{gR} = 0,59 m/s^2 ou 0,06 g
Zone sismique 3 :	a_{gR} = 0,78 m/s^2 ou 0,08 g
Zone sismique 4 :	a_{gR} = 0,98 m/s^2 ou 0,10 g

a_{gr}=0.1*g

La liste des communes belges avec l'indication de la zone sismique à laquelle elles appartiennent est fournie en tableau en fin de la présente ANB.

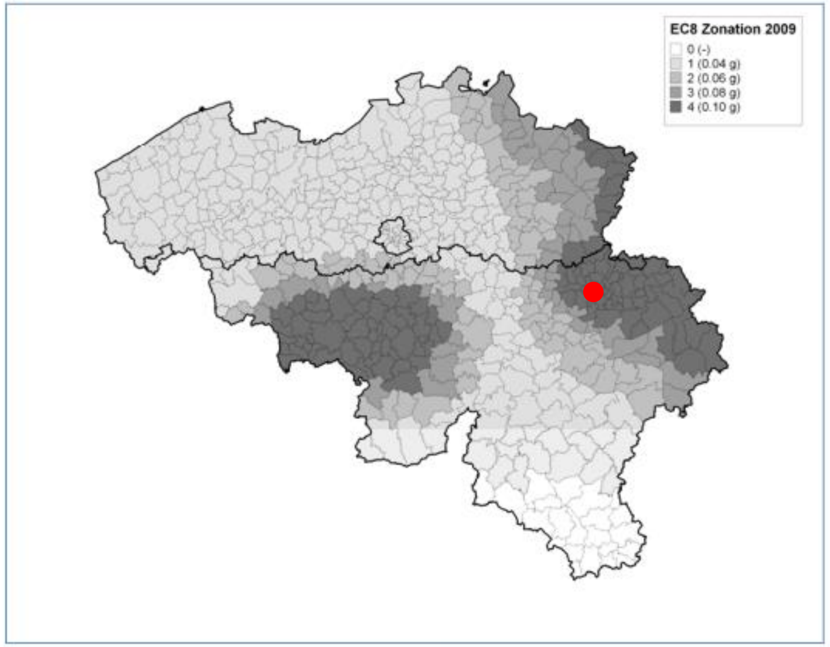


Figure 3.1-ANB : Carte de zonage sismique de la Belgique

$a_g = \gamma_i * a_{gr}$

4.2.5 Importance classes and importance factors

(1)P Buildings are classified in 4 importance classes, depending on the consequences of collapse for human life, on their importance for public safety and civil protection in the immediate post-earthquake period, and on the social and economic consequences of collapse.

(2)P The importance classes are characterised by different importance factors γ_I as described in **2.1(3)**.

(3) The importance factor γ_I = 1,0 is associated with a seismic event having the reference return period indicated in **3.2.1(3)**.

Table 4.3 Importance classes for buildings

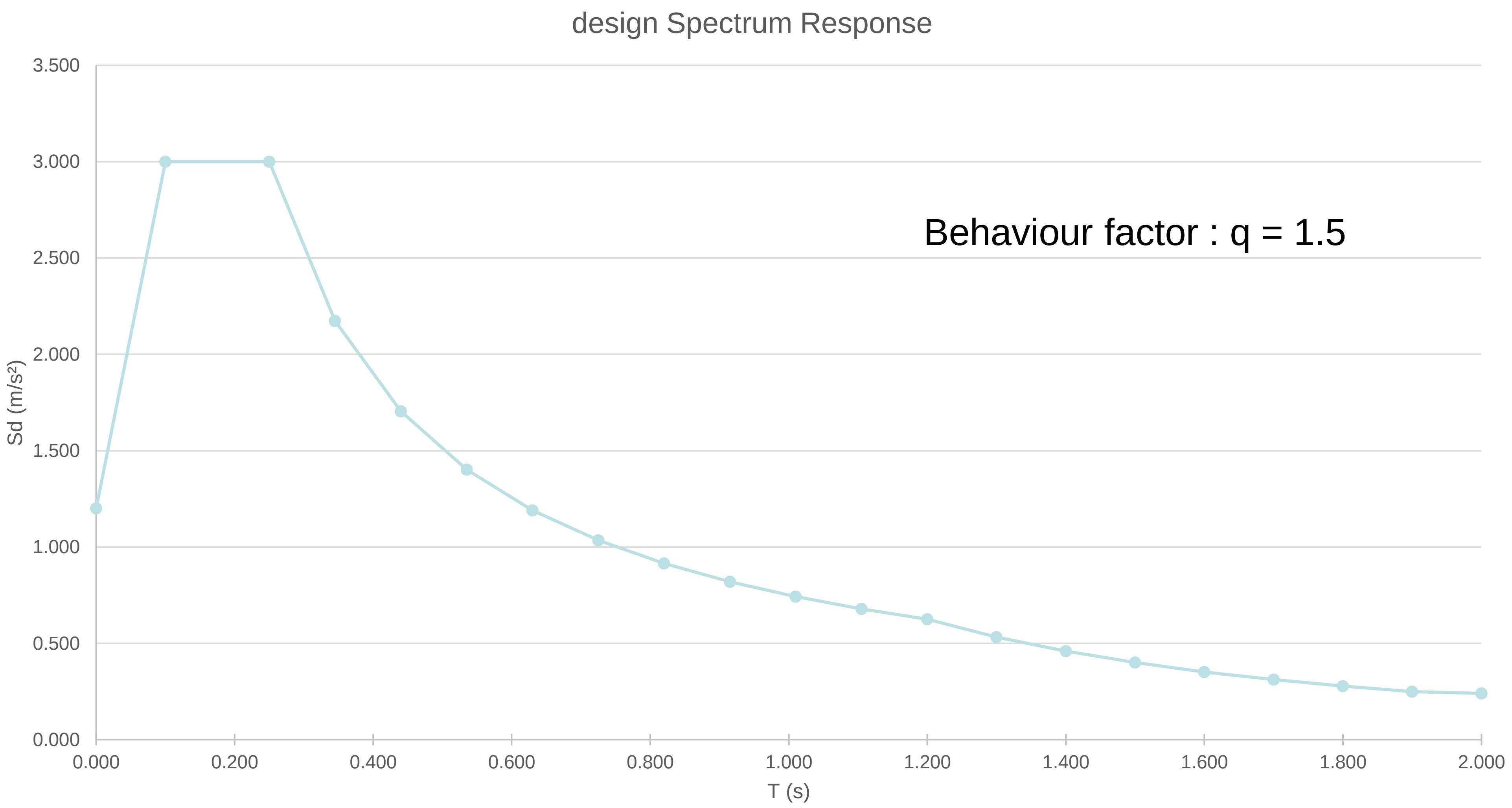
Importance class	Buildings
I	Buildings of minor importance for public safety, e.g. agricultural buildings, etc.
II	Ordinary buildings, not belonging in the other categories.
III	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions etc.
IV	Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc.

NOTE Importance classes I, II and III or IV correspond roughly to consequences classes CC1, CC2 and CC3, respectively, defined in EN 1990:2002, Annex B.

(5)P The value of γ_I for importance class II shall be, by definition, equal to 1,0.

NOTE The values to be ascribed to γ_I for use in a country may be found in its National Annex. The values of γ_I may be different for the various seismic zones of the country, depending on the seismic hazard conditions and on public safety considerations (see Note to **2.1(4)**). The recommended values of γ_I for importance classes I, III and IV are equal to 0,8, 1,2 and 1,4, respectively.

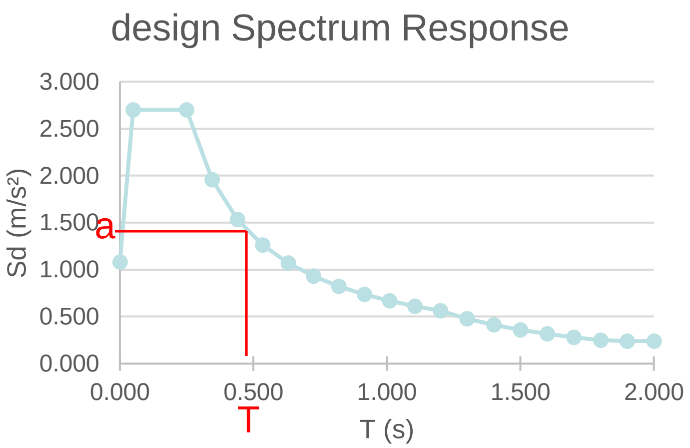
Design Spectrum definition



Seismic response of one mode

1 dof system

$$\ddot{x} + 2\xi\omega\dot{x} + \omega^2 x = -\ddot{x_g}$$



$\ddot{x}_{max}$ = acc_{max} = Sd(ω,ξ)

Generaly ξ = 5%

x_{max} = Sd(ω,ξ)/ω^2

ω = 2.π.freq = 2.π/T

n dof system

(modal base)

$$\ddot{z_i} + 2\xi\omega\dot{z_i} + \omega^2 z_i = -RM_{ik} * \ddot{x_g}$$

Attention: modal share ratio are different for each seismic direction and mode

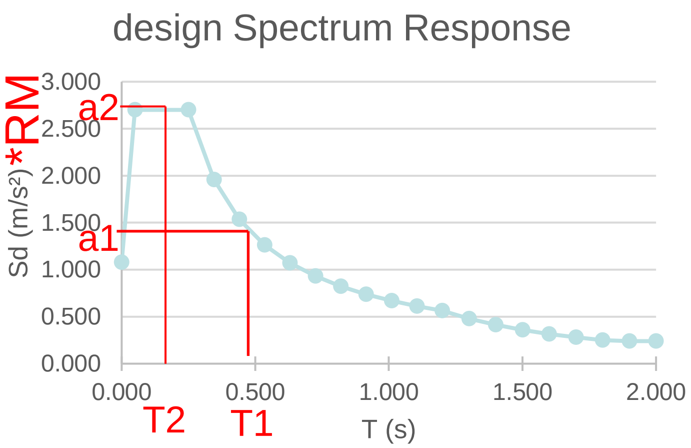
$acc_{max,i,k}$ = RM_{ik} * Sd(ω,ξ)

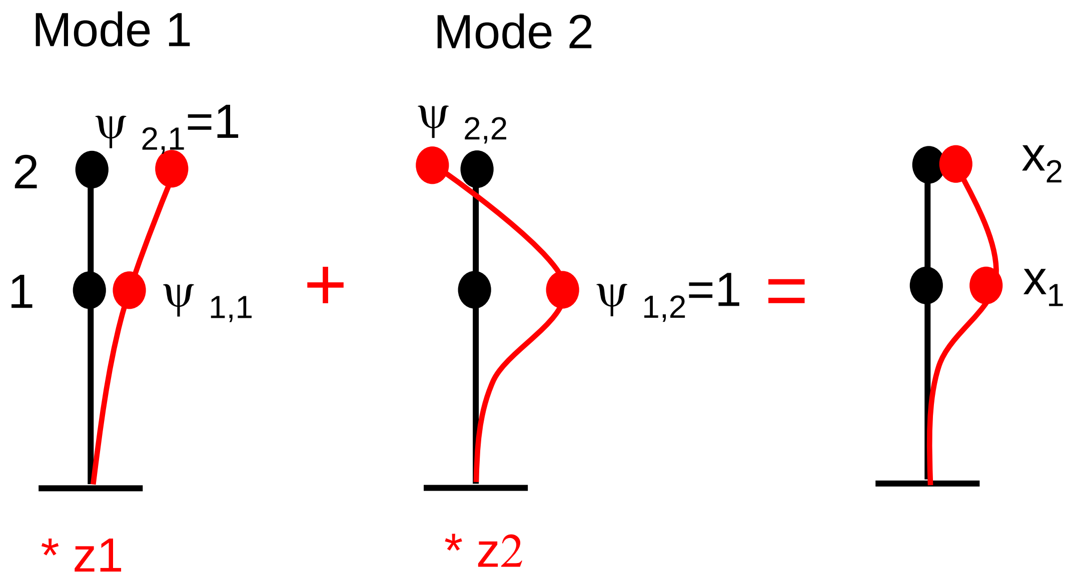
$z_{max,i,k}$ = RM_{ik} * Sd(ω,ξ)/ω^2

Where z_i is the i^{th} eigen mode amplitude
And k the seism direction

Seismic response of all modes

For each mode i with an amplitude z_i; the maximum displacement $x_{j,i}$ (displacement of the node (dof) j in the mode i -) is equal to: $x_{ji} = \psi_{ji} * z_i$, where ψ_{ji} is the modal displacement of mode i at node(dof) j.





Mode 1: $\omega 1$ ➔ T1 ➔ a1➔ $z1 = a1/(\omega 1)^2$

Mode 2: $\omega 2$ ➔ T2 ➔ a2➔ $z2 = a2/(\omega 2)^2$

zi = maximal amplitude of mode i

Seismic displacements	**Mode 1**	**Mode 2**
Node 1	$z1 * \psi_{1,1}$	$z2 * \psi_{1,2}$
Node 2	$z1 * \psi_{2,1}$	$z2 * \psi_{2,2}$

Seismic response of all modes

All the modes i are not maximum at the same time

➔ total displacement ≠ $\sum_{i=1}^{n} x_{ji}$

➔ total displacement = $\sqrt{\sum_{i=1}^{n} x_{ji}^2}$; Square Root of the Sum of the Squares = SRSS

➔ Total displacement = $\sqrt{\sum_{k=1}^{N} \sum_{l=1}^{N} C_{kl} . d_{ki} . x_{li}}$; complete quadratic combination = CQC

$$C_{kl} = \frac{8\, \xi^2\, r^{1.5}}{(1+r)(1-r)^2 + 4\, \xi^2\, r(1+r)}$$

$$r = \frac{T_k}{T_l}$$

Where: x_{ji} = displacement j for mode i

ξ = damping ratio (default value = 0.05)

T_k , T_l = Periods of ***k*** et ***l***.

Be careful not to add the modal amplitude but to add the nodal displacements at the same nodes

How many modes ?

Eurocode recommends that the total effective mass of retained modes > 90 %

The effective modal mass in both horizontal directions

- $PM_{ik} = \frac{(\psi_i^T.M.e_k)^2.100}{\psi_i^T.M.\psi_i \; e_k^T.M.e_k}$ Depends on the mode and the seism direction
- with the property : $\sum_{i=1}^{ndofs} PM_{ik} = 100\,\%$

With all the modes $\sum_{i=1}^{NDOFS} PM_{ik} = 100\,\%$ for k = X, Y or Z

Maximum of modes = number of dofs

With n modes $\sum_{i=1}^{n} PM_{ik} \geq 90\,\%$

Bearing Forces

For each mode i:

$[K_{glo}] * \psi_i = \{F_i\}$ where F_i = nodal forces

If we have a support, the nodal force F_i: support forces R_i

The maximum support force under earthquake:

$$R_{SRSS} = \sqrt{\sum_{i=1}^{n} R_i^2} \text{ or } R_{CQC} = \sqrt{\sum_{k=1}^{N} \sum_{l=1}^{N} C_{kl}.R_k.R_l}$$

To combine, the 2 horizontal directions :

(3) As an alternative to b) and c) of **(2)** of this subclause, the action effects due to the combination of the horizontal components of the seismic action may be computed using both of the two following combinations:

a) E_{Edx} "+" $0{,}30E_{Edy}$ (4.18)

b) $0{,}30E_{Edx}$ "+" E_{Edy} (4.19)

where

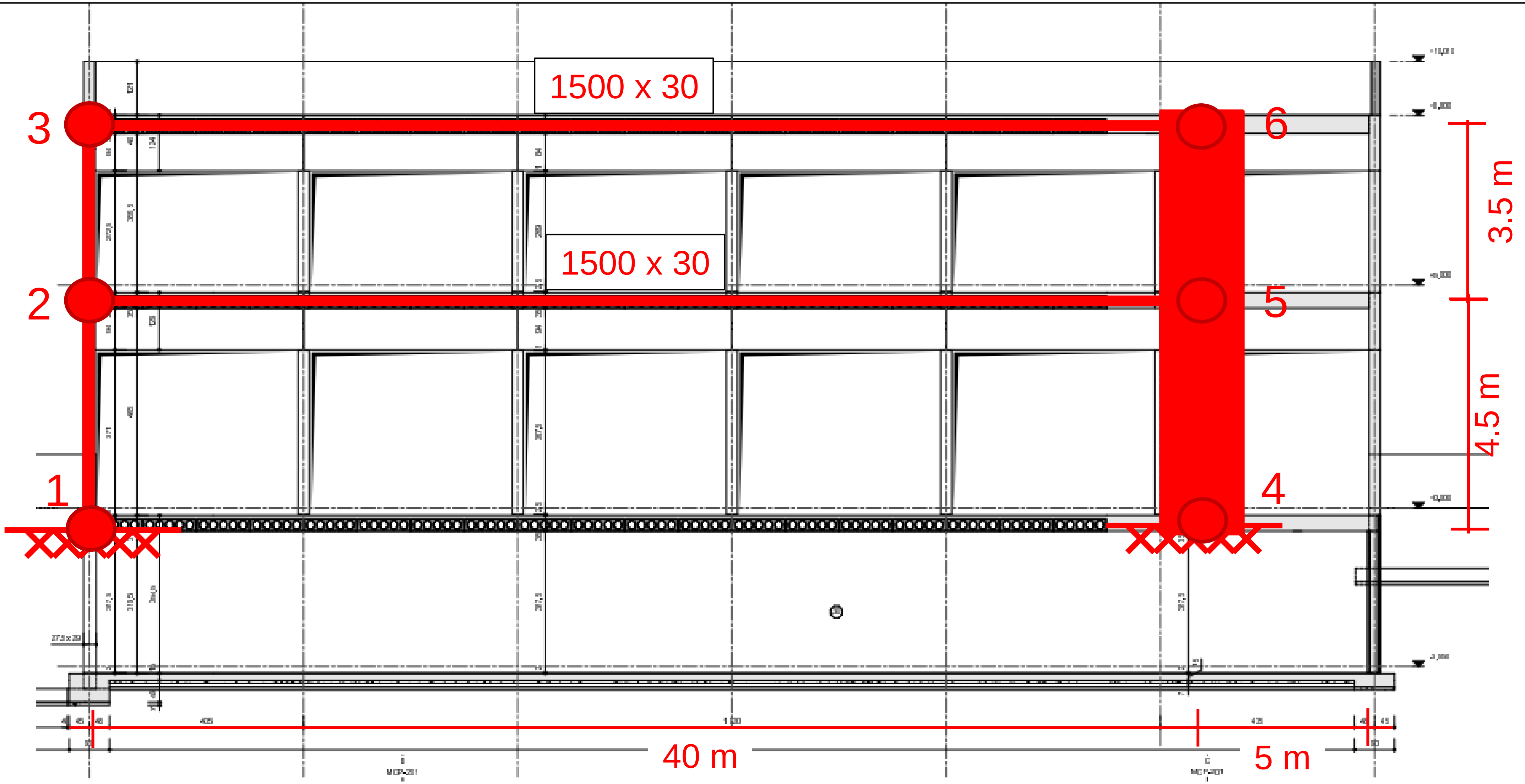
"+" implies "to be combined with";

E_{Edx} represents the action effects due to the application of the seismic action along the chosen horizontal axis *x* of the structure;

E_{Edy} represents the action effects due to the application of the same seismic action along the orthogonal horizontal axis *y* of the structure.

Stiffness Matrix (36x36)

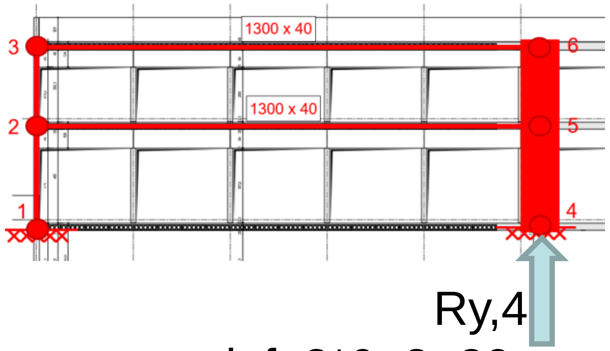
Nodes number



bearing reactions

ψi = Eigenmode i (36x1)

zi = amplitude under seism of mode i



Ry,4

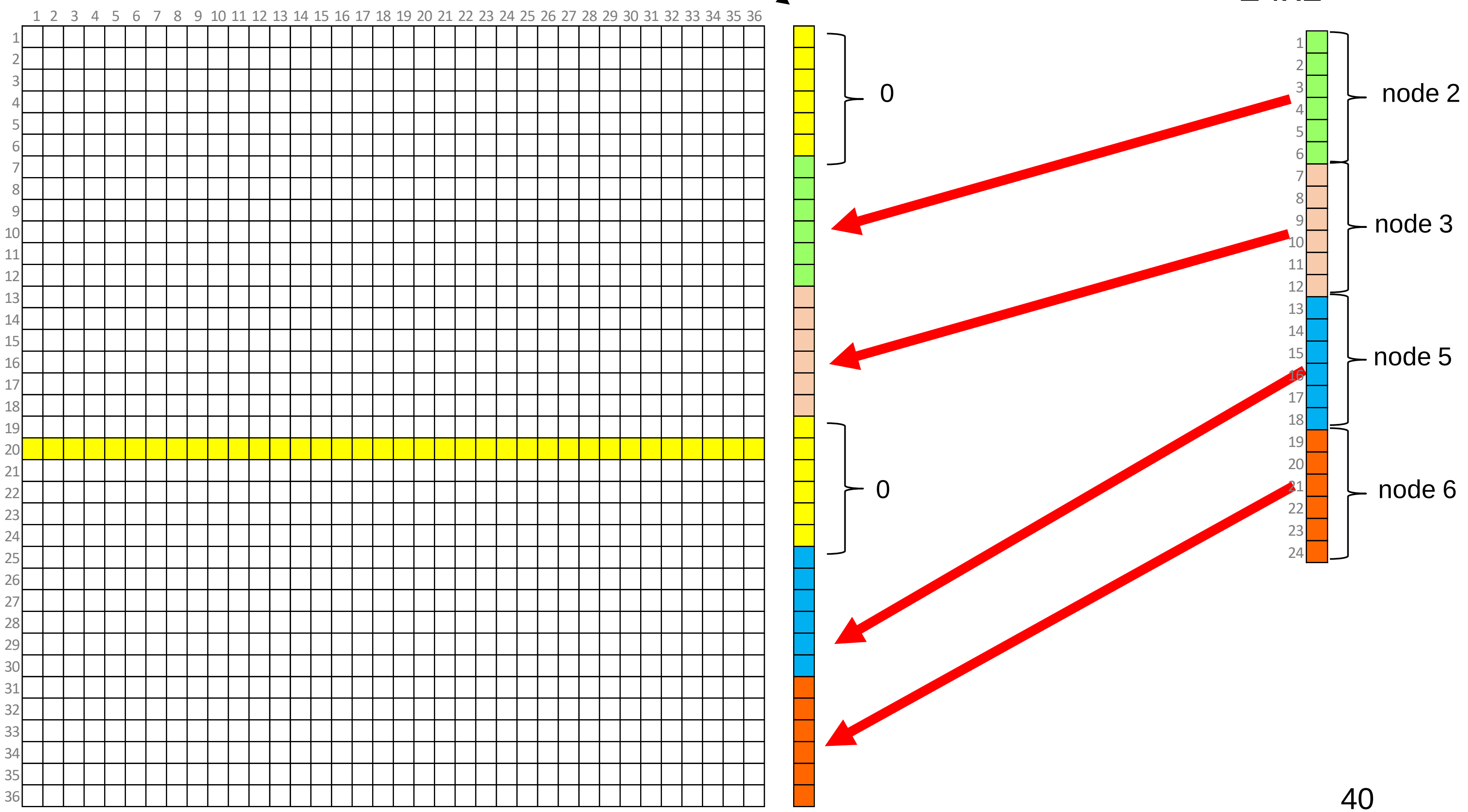
dof: 3*6+2=20

$R_{y,4,i}$ (mode i) =
K(line 20) * ψi * zi
(1x36) (36x1) (1x1)

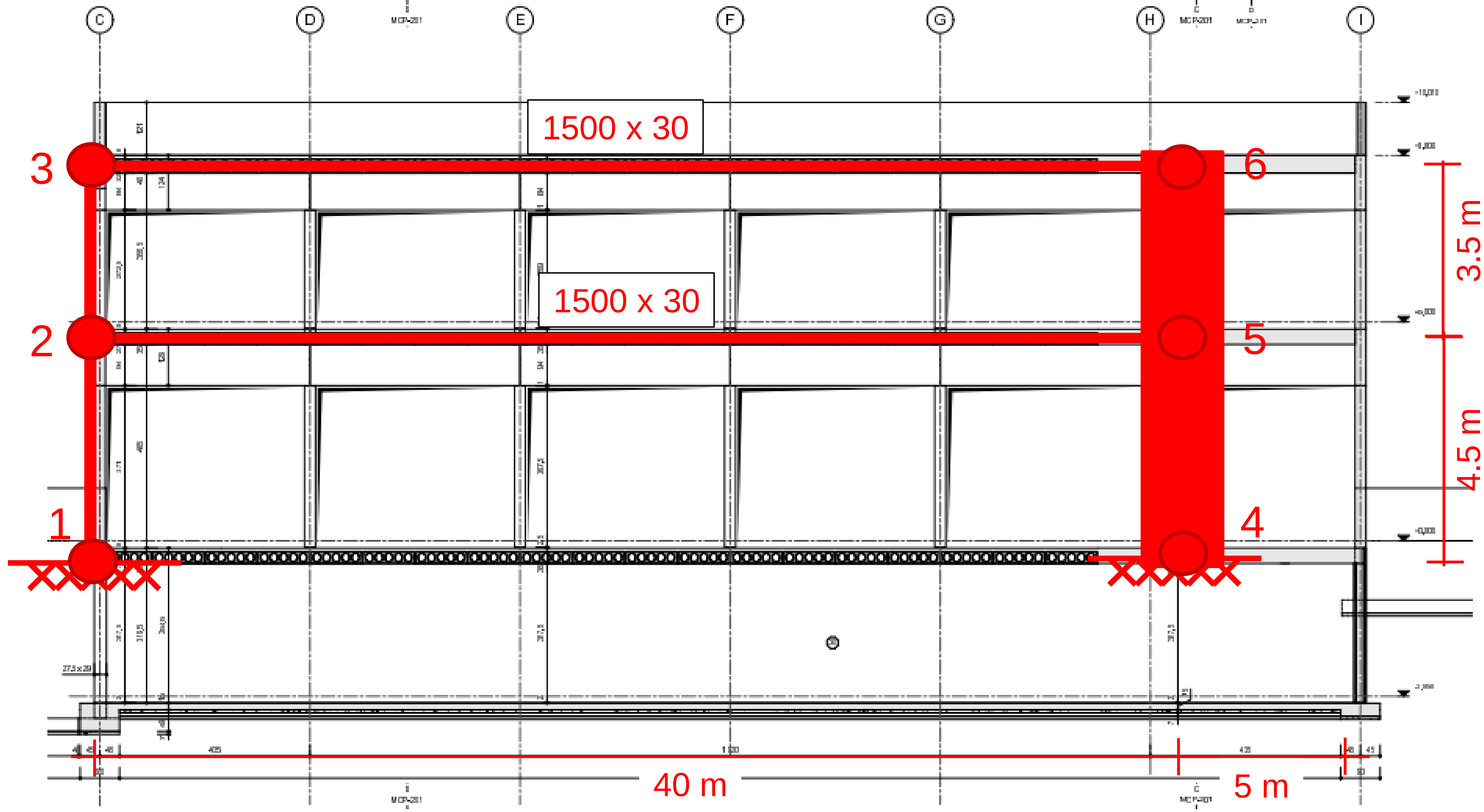
$$R_{y,4,SRSS} = \sqrt{\sum_{i=1}^{n} R_{y,4,i}^{2}}$$

K matrix: 36x36

Calculated eigenmode 24x1



Results



Results – modal properties

Frequencies

fill in the yellow cells

mode n°	freq (Hz)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	

EFFECTIVE MODAL MASS

====================================

Number	freq (Hz)	MASS along. X	MASS along. Y	MASS along. Z
1	0.0000			
2	0.0000			
3	0.0000			
4	0.0000			
5	0.0000			
6	0.0000			
7	0.0000			
8	0.0000			
9	0.0000			
10	0.0000			
11	0.0000			
12	0.0000			

MODAL SHARE RATIO

==============================

Number	freq (Hz)	RM. X	RM. Y	RM. Z	MODAL MASS	MODAL STIFFNESS
1	0.00000					
2	0.00000					
3	0.00000					
4	0.00000					
5	0.00000					
6	0.00000					
7	0.00000					
8	0.00000					
9	0.00000					
10	0.00000					
11	0.00000					
12	0.00000					

Results – Displacements

Response under X seims

MODAL RESPONSE
==============

Number	freq (Hz)	PERIODE	ACCELERAT.	modal mass	RM. X	MODAL RESPONSE
1	0.0000	#DIV/0!		0.00E+00	0.00000	
2	0.0000	#DIV/0!		0.00E+00	0.00000	
3	0.0000	#DIV/0!		0.00E+00	0.00000	
4	0.0000	#DIV/0!		0.00E+00	0.00000	
5	0.0000	#DIV/0!		0.00E+00	0.00000	
6	0.0000	#DIV/0!		0.00E+00	0.00000	
7	0.0000	#DIV/0!		0.00E+00	0.00000	
8	0.0000	#DIV/0!		0.00E+00	0.00000	
9	0.0000	#DIV/0!		0.00E+00	0.00000	
10	0.0000	#DIV/0!		0.00E+00	0.00000	
11	0.0000	#DIV/0!		0.00E+00	0.00000	
12	0.0000	#DIV/0!		0.00E+00	0.00000	

Response under Z seims

MODAL RESPONSE
==============

Number	freq (Hz)	PERIODE	ACCELERAT.	modal mass	RM. Y	MODAL RESPONSE
1	0.0000	#DIV/0!		0.00E+00	0.00000	
2	0.0000	#DIV/0!		0.00E+00	0.00000	
3	0.0000	#DIV/0!		0.00E+00	0.00000	
4	0.0000	#DIV/0!		0.00E+00	0.00000	
5	0.0000	#DIV/0!		0.00E+00	0.00000	
6	0.0000	#DIV/0!		0.00E+00	0.00000	
7	0.0000	#DIV/0!		0.00E+00	0.00000	
8	0.0000	#DIV/0!		0.00E+00	0.00000	
9	0.0000	#DIV/0!		0.00E+00	0.00000	
10	0.0000	#DIV/0!		0.00E+00	0.00000	
11	0.0000	#DIV/0!		0.00E+00	0.00000	
12	0.0000	#DIV/0!		0.00E+00	0.00000	

TOP displacements

Modal deformation at top

mode	node3 - X	node3 - Z	node6 -X	node 6 - Z
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				

Top displacements under seism along X

mode	node3 - X	node3 - Z	node6 -X	node 6 - Z
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
SRSS				
CQC				

Top displacements under seism along Z

mode	node3 - X	node3 - Z	node6 -X	node 6 - Z
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
SRSS				
CQC				

Results – Reactions

Support Reactions

fill in the yellow cells

Seims X

node 1

	Support Reaction					
	Rx	Ry	Rz	Mx	My	Mz
mode	[N]	[N]	[N]	[Nm]	[Nm]	[Nm]
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
SRSS						
CQC						

Seims Y

node 1

	Support Reaction					
	Rx	Ry	Rz	Mx	My	Mz
mode	[N]	[N]	[N]	[Nm]	[Nm]	[Nm]
SRSS						
CQC						

Seims X

node 4

	Support Reaction					
	Rx	Ry	Rz	Mx	My	Mz
mode	[N]	[N]	[N]	[Nm]	[Nm]	[Nm]
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
SRSS						
CQC						

Seims Y

node 4

	Support Reaction					
	Rx	Ry	Rz	Mx	My	Mz
mode	[N]	[N]	[N]	[Nm]	[Nm]	[Nm]
SRSS						
CQC						

Your report: pptx

1. Establish the static scheme of the structure
   a. Simplify the structure to the lowest number of dofs possible to represent the dynamic behavior under earthquake. Use beam element.
   b. Make some modification to improve the torsion behavior
2. Frequencies and eigen modes
   a. Establish and Compute the stiffness matrix of the system
   b. Establish and Compute the mass matrix of the system
   c. Compute the eigen modes and the frequencies
   d. Draw the deformed shape of the first 2 modes
3. Modal properties
   a. Compute the modal stiffness and mass of each mode
   b. Compute the effective modal mass in both horizontal direction
   c. Compute the modal share ratio for both horizontal direction
   d. Notation between lecture slides and Eurocode are different. So make a correspondence table between both notations
4. Parasismic calculation
   a. Establish the design acceleration spectrum according to EN 1998-1
   b. Compute the response (displacements) of each mode in each direction
   c. Compute the maximum response in each direction (SSRS and CQC) of the building top
   d. Compute the support forces
   e. Combine the support forces in the X and Y direction
   f. Compare results from different static schemes