1. THE SLABS

Nowadays, reinforced concrete slabs have become very common in the spanish construction market. Although, the traditional beam systems are still very used, other technologies gained the upper hand.

If we get a closer look at what is the trend around the world, beam slabs are still used in the countries where materials costs are higher than labour costs.

On the other hand, richer and industrialized countries, use deck plates.

Reinforced concrete slabs:

1. Are very solid. Thanks to side deformation prevention, they can't deform and the thickness can be reduced.
    a. Thickness reduction allows the economisation of materials
    b. Massing reduction, allows the maximisation of the ground surface exploitation, which is very important cost item.
2. Does not need beams:
    a. They allow the reduction of the volumetric footprint of the deck
    b. They avoid the scaffolding of the beams
    c. They facilitate the passage of installations, significantly reducing installation times
3. They are reinforced with meshes and straight bars :
    a. Reduction of the iron reinforcements costs. Wought iron is more expensive
    b. Meshes and straight bars are easier and faster to install
    c. It is possible to use pre-fabricated reinforced systems, in order to make the work faster (like BAMTEC layers of reinforcements)
4. They have an excellent fire and acoutic behaviour, thanks to their mass.

If we read the upper points, it looks like slab structures does not have any disadvantage, but, on the contrary, they also have some weak points that limit their use in respect to other more efficient methods:

They are massive structures:

- They consume an high quantity of concrete
- They are very heavy: there are large spans between the pillars, but the self-weight prevails and the result is very expensive

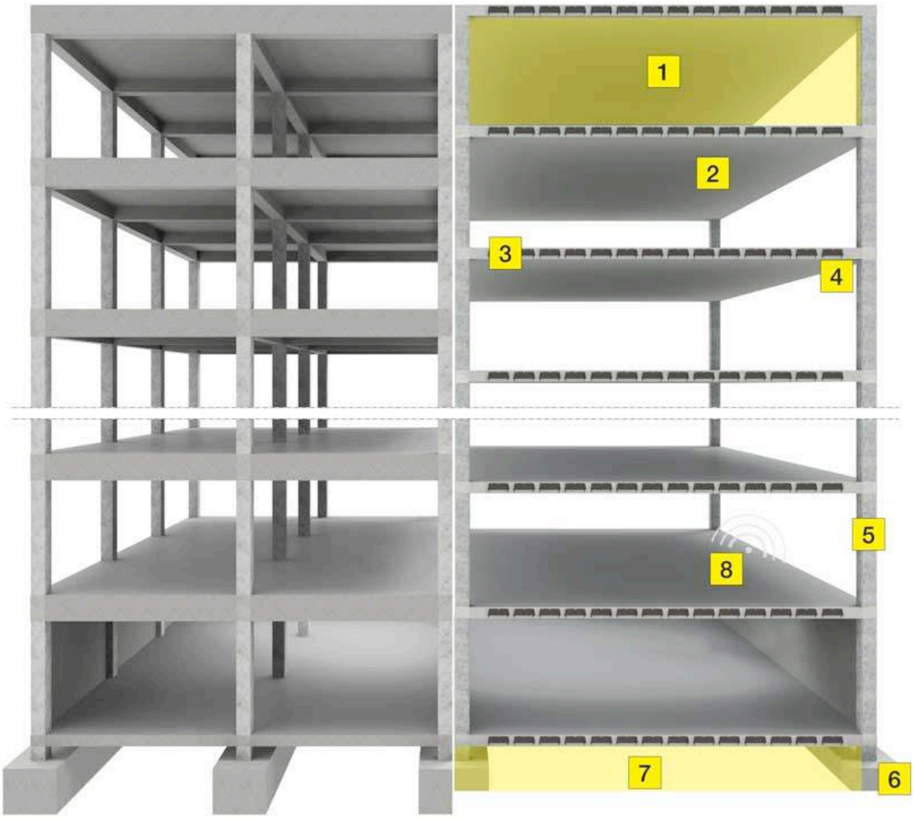
2. They are not flexible:
    - They can't be calculated as the classic structures
    - They need low structures

2. LIGHTENED SLABS

2.1. ADVANTAGES

They are structures with all the characteristics and strength points of standard slabs, but without their self-weight:

1. Limited volumes
2. No beams
3. Concrete is less expensive
4. Larger spans
5. Optimization of vertical structures
6. Reduced foundation load
7. Reduced excavation load



2.2. RETICULAR SLABS

The slabs mantain their bidirectional structure and create an orthogonal grid through the installation of disposable blocks (in concrete or terracotta) or reusable (in plastic or fibreglass). Massive capitals are embeded in the pillars for the punching.

2.2.1. ADVANTAGES

The advantages this type of solution offer, are multiple

1. They are slabs without beams
2. The quantity of concrete needed is reduced
3. They are very light
4. Less steel used

2.2.2. WEAK POINTS

These structures has also some disadvantages:

1. In comparison to reticular slabs, they consume more concrete and weight more.
2. They consume also more steel

2.2.3. CONCLUSIONS

This type of solution is ideal for narrow spans and low weight slabs. Apart from these applications they become less competitive.

LIGHTENED SLABS

Hollow articles are embeded in the pour. Usually they are made of cubic shaped polystyrene or plastic. Blocks remain embeded in the pour and create a grid of ribbings, which are enclosed between two massive upper and lower slabs.

ADVANTAGES

This solution is more efficient than most reticular slabs

5. The lower slab makes it perfect for all intents and purposes
6. The same thickness of full slabs can be mantained
7. They guarantee lightness and concrete savings
8. They can be reinforced in the same way as massive slabs
9. Steel is reduced
10. Great seismic behaviour
11. Great fire behaviour (up to REI 240’)
12. Does not need a false ceiling

2.2.4. WEAK POINTS

Even these structures have some disadvantages

3. In comparison to reticular slabs they consume more concrete and weight more
4. They consume more steel

2.2.5. CONCLUSIONS

3. This type of solution is ideal for narrow spans and low weight slabs. Apart from these applications they become less competitive.

On the contrary, it is extremely competitive if compared to a full slab, especially with a thickness from 28 to 60 cm and spans from 8 to 14 m.

3.1. LIGHTENED SLABS WITH HOLLOW ARTICLES IN PLASTIC

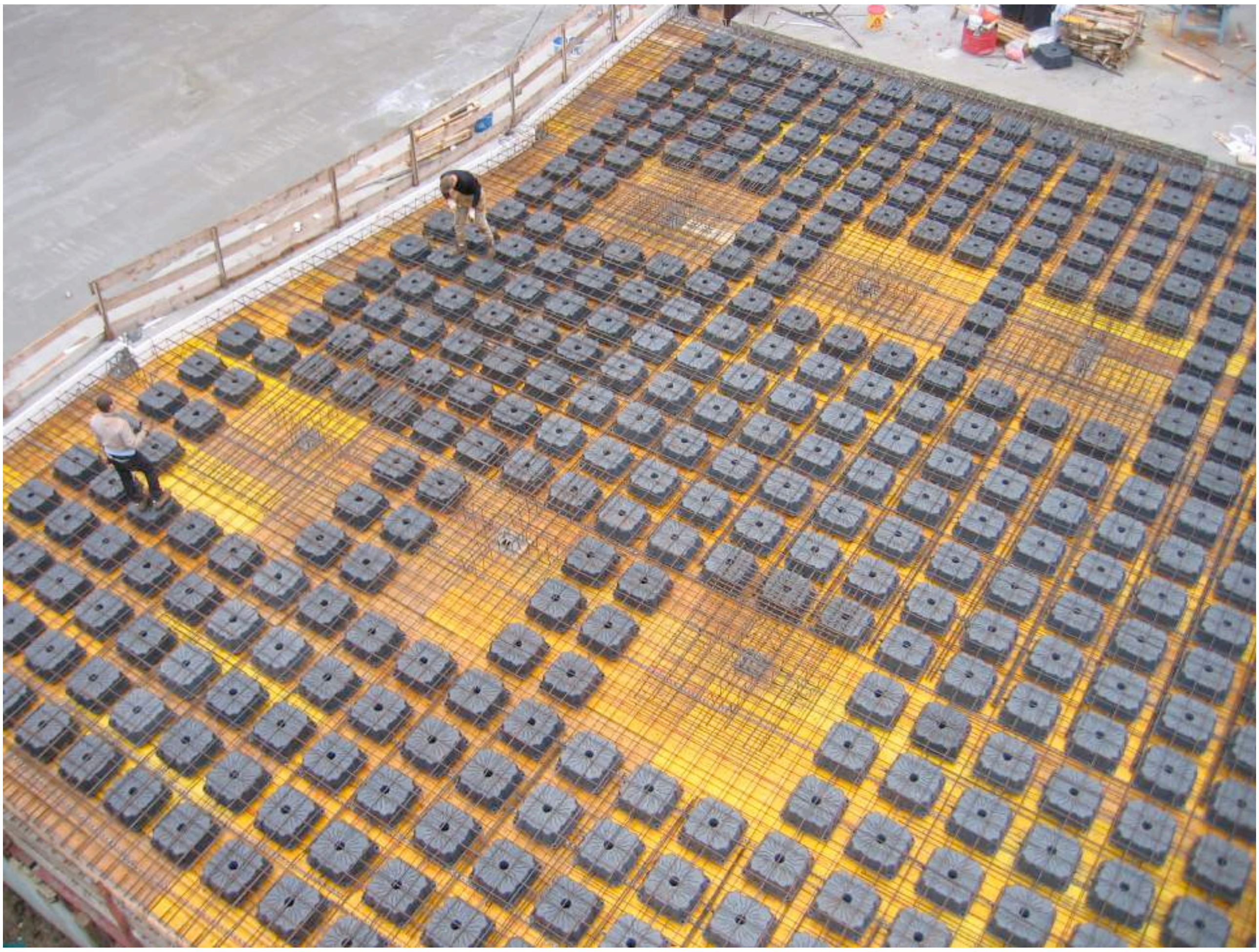
3.1.1. General Characteristics

Since 10-15 years ago, lightened slabs were created through the use of cubic blocks in polystyrene.

This contruction method had some disadvantages:

1. Blocks were fragile and suffer from weatherings
2. Blocks were bulky and did not facilitate worksite logistics
3. It was not easy to block them during the pour

   During recent years a new construction methods has arrived in the market. This solution allows the overrun of these limitations.



They are recycled polypropilene formworks, 52 x 52 cm with variable height. They can be “single”, or “double”, by putting together two “single”.

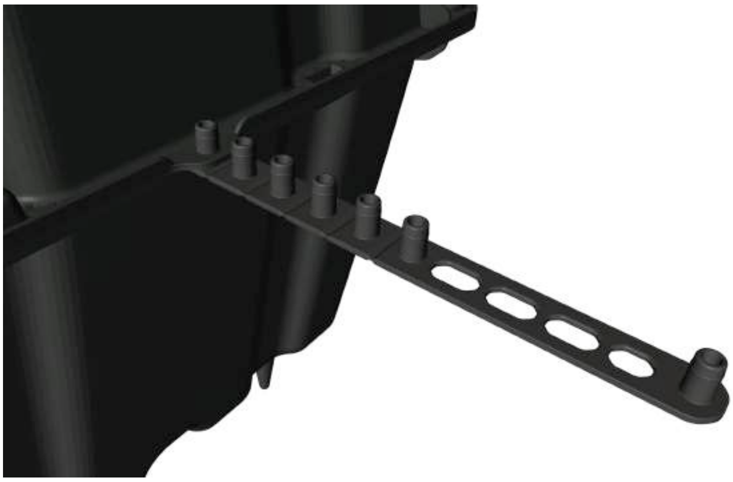
Figura 1 – Plastic lightening "single"type.

PLASTIC LIGHTENINGS HEIGHTS **« SINGLE »**
H10 cm
H13 cm
H16 cm
H20 cm
H24 cm
H28 cm

Figura 2 – Plastic Lightening "double" type

PLASTIC LIGHTENINGS HEIGHTS « DOUBLE »	
H23 cm	H37 cm
H26 cm	H38 cm
H29 cm	H40 cm
H30 cm	H41 cm
H32 cm	H44 cm
H33 cm	H48 cm
H34 cm	H52 cm
H36 cm	H56 cm

These formworks are stackable and can be transported and stored in small spaces. They are provided with cone shaped feet with variable height, from 5 to 10 cm and a spacer from 10 a 24 cm.



This peculiarity permits the installation of the elements right on the lower formwork, raising them from the reinforcements.

In this way, the slab che be reinforeced like a normal plate and the pour can be made during just one day.

The realisation times are the same of those of a massive slabs.

3.1.2. MODELLING AND STRESS CALCULATION

The overlapping of the plastic blocks created a grid of ribbing, with a variable thickness from 5 to 10 cm.

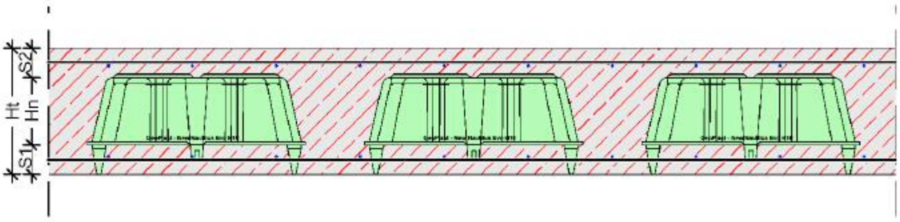


Figura 3 – A section of a typical lightened slab

Figura 4 -A section of lightened slab with "double"elements

Figura 5 – A section of lightened slab with "single" elements

There are different methods to create these types of structures and obtain the stresses they suffer:

3.1.2.1. TIMBER-FRAMED BEAMS MODEL

The structure is similiar to a grid of beams where the section is determine by the type of lightening.

The choice of the section is very important. According to the theory of De Saint Venant, if we decide to set a I section, opened profiles have no torsional stiffness. The bending and shear moment will be sufficiently accurate. The structure will have an higher deformability and the main reason we chose this type of structure will be lost. We will not obtain a slab

In alternative, we can model the grid by setting a rectangular and hollow section. In this way, it is possible to recover the torsional stiffness.

Another method is the modelling of the inverted T shaped beam grid, connected to a slab element equal to the upper hood.

This last method is correct, but there is the risk to lose the advantages of the slab structure. Moreover, the beams should be verified one at a time and this is very time-consuming.

3.1.2.2. PLATE MODEL

This is a slab for all intents and purposes. As a reference in the Eurocode 2 says, in chapter 5.3.1 (6):

"Ribbed or waffle slabs need not be treated as discrete elements for the purposes of analysis, provided that the flange or structural topping and transverse ribs have sufficient torsional stiffness. This may be assumed provided that:

- the rib spacing does not exceed 1500 mm

- the depth of the rib below the flange does not exceed 4 times its width.

- the depth of the flange is at least 1/10 of the clear distance between ribs or 50 mm,

whichever is the greater.

- transverse ribs are provided at a clear spacing not exceeding 10 times the overall depth of

the slab."

These plastic formworks always respects the prescriptions described above, because of their geometry and structure. Therefore, the final result will be a real slab.

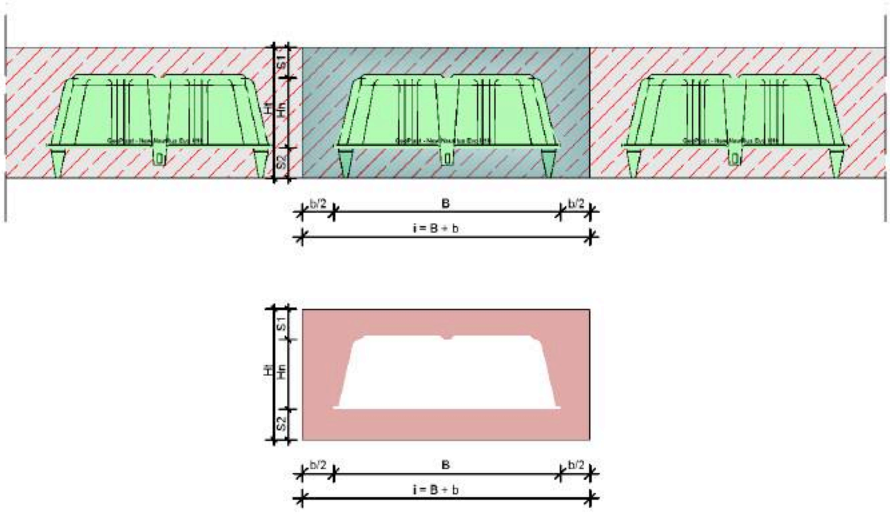


Figura 6 – Typical section of a plastic formwork

In the case we use a finite elements calculation, we should anlyze a full slab with the same characteristics of the lightened one.

If, on the other hand, we follow the theory of the orthotropic slab by Kirkhhoff, the following parameters should be taken into consideration:

Flexional stiffness (symmetric in comparison to the two orthogonal directions)

1. Flexional Stiffness
2. Cutting Stiffness

In addition, the slab will be lighter

3.1.2.2.1. FLEXIONAL STIFFNESS

According to Kirchhoff the flexional stiffness of a slab is:

$$R_f = \frac{E \cdot J}{(1-\mu)^2}$$

E = Elastic Module

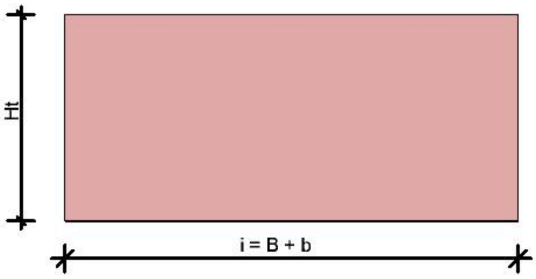
J = Moment of Inertia

m = Poisson's ratio

In the case of a full slab the flexional stiffness will be:

$$R_f = \frac{E \cdot H^3}{(1-\mu)^2}$$

H = thickness of the slab

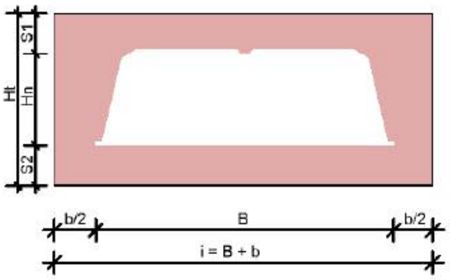


When we obtain the section of the slab embeded in the formwork, we can use Huygens theorem. In this way the Moment of Inertia will be of:

$$J' = \int_A r^2 \cdot dA$$

And the flexional stiffness of the lightness slab:

$$R'_f = \frac{E \cdot J'}{(1-\mu)^2}$$



It will depend on the thickness chosen. The thickness of the upper and lower slabs and of the ribbings will affect the Inertia of the slab. It should be:

$R_f = R'_f$

In order to model a full slab with the same flexional stiffness of the lightened one, it is necessary to reduce the Elastic Module or the Inertia Moment:

$$\alpha_{rf} = 12 \cdot \frac{J'}{i \cdot H^3}$$

i = Wheelbase of the lightenings (B+b)

The model between the Inertia Moments

3.1.2.2.2. TORSIONAL STIFFNESS

Even in this case, it is possible to calculate the torsional stiffness of the full section and of the lightened one.

The model is:

$$\alpha_{rt} = \frac{J'_t}{J_T}$$

It represents the factor of reduction of the torsional stiffness.

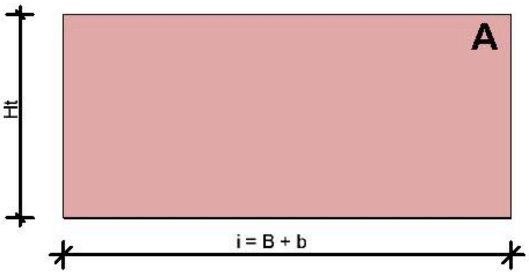
3.1.2.2.3. CUTTING STIFFNESS

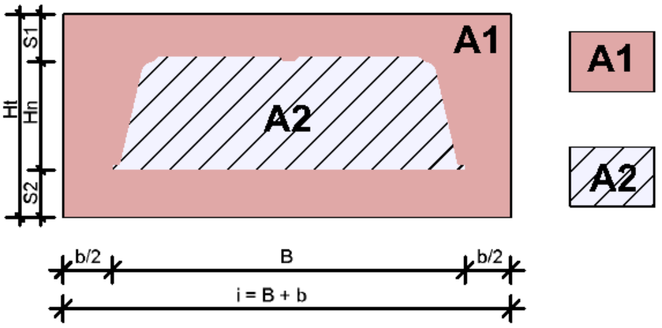
In this case the factor of reduction of stiffness, will be the relationship between the full area and the lightened area:

$$\alpha_t = \frac{A'}{A}$$

$A' = A_1 - A_2$

It can vary by changing the wheelbase of the lightenings. More specifically, the decrease or increase of the ribbing width.





3.1.2.2.4. SELF-WEIGHT CALCULATION

The self-weight of the lightened slab depends on the volume V of the lightening and of the chosen wheelbase. The wheelbase determine the unit impact of the lightenings:

$$n = \frac{1}{i^2} \text{ [pc/m}^2\text{]}$$

Concrete consumption of a lightened slab with thickness H (expressed in meters) will be:

$$C_a = 0{,}01 \cdot H - (n \cdot V) \text{ [m}^3\text{/m}^2\text{]}$$

Once again the relationship between this value and value C_m of the full slab will reduce the mass of the slab:

$$\alpha_m = \frac{C_a}{C_m}$$

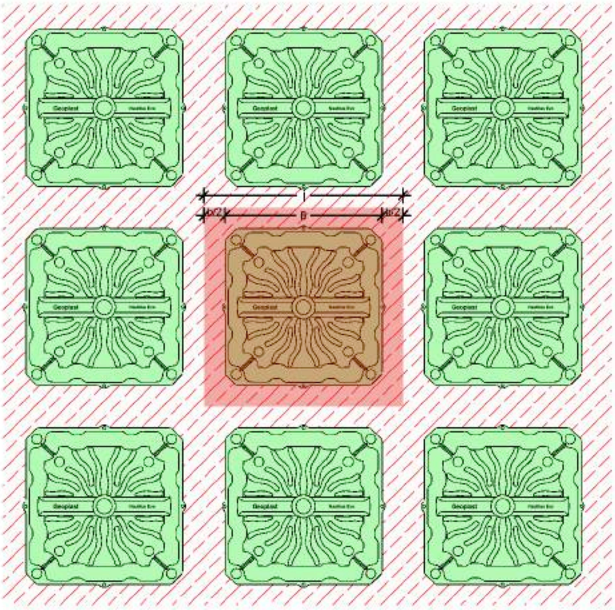


Figura 7 – Calculation of the formworks incidence per square meter

3.1.2.2.5. CONSTRUCTION OF THE CALCULATION MODEL

Now, we can model the structure. We need to assign the reduction coefficents to the lightened parts calculated above, while leaving unchanged the parts which will be made in full concrete.

The extension of the capitals over the pillars, can be calculated taking into consideration, as minimal extension the one in the punching perimeter. This can resist without any reinforcement and it is not lower than 2,75d from the edge of the pillar.

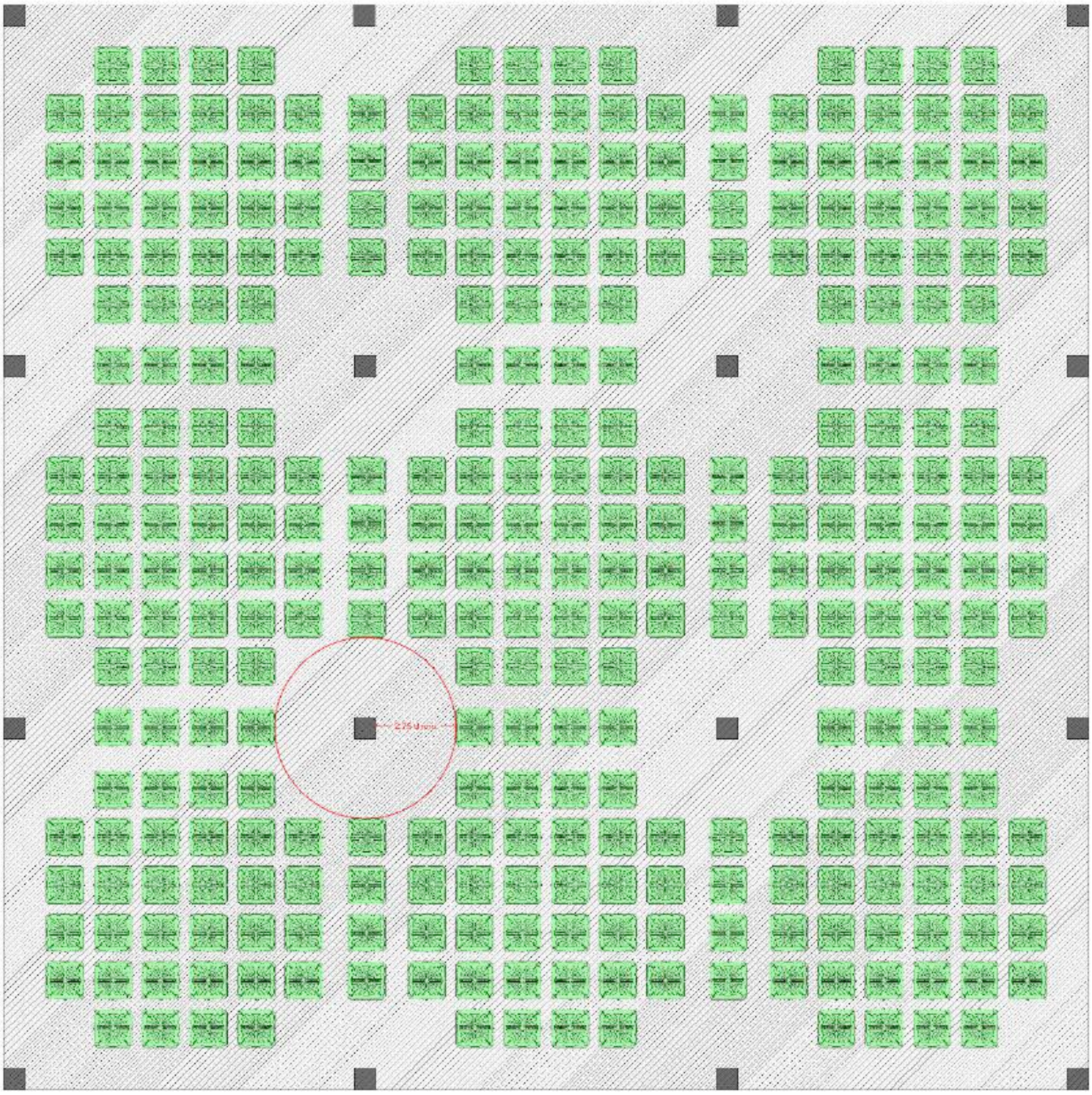


Figura 8 – Typical layout of lightenings with massive zones over the pillars

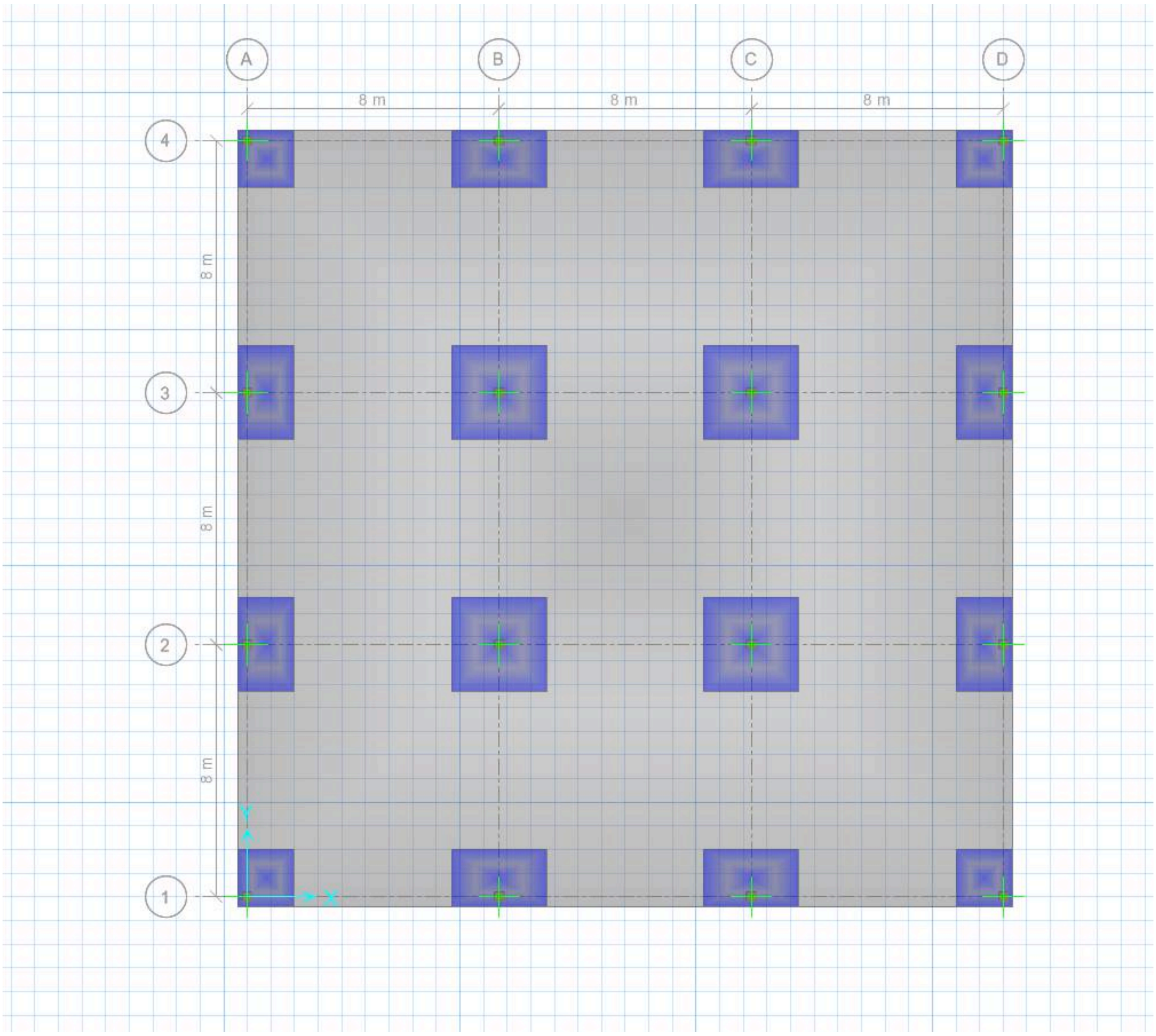


Figura 9 - FEM model for lightened slabs- in purple the massive zone, in grey the lightened zones

DIMENSIONING AND VERIFICATION OF THE REINFORCEMENTS

Once the calculation model is completed, it will be possible to obtain the stress value (N,M,V) that acts on the lightened slab.

Then, it is possible to dimension and verify the reinforcement, applying the usual methods of contruction and following the national regulations.

CHECK TO BENDING

For the check to bending it is possible to use two methods:

Method Wood-Armer: we take into consideration two artificial moments that follow two ortogonal directions, M^*_{xx} e M^*_{yy} they are calculated combining the moments adequately M_{xx} e M_{yy}. Usually, finite elements software calculate automatically the moments M^*_{xx} e M^*_{yy} to use for the calculation of the reinforcements.

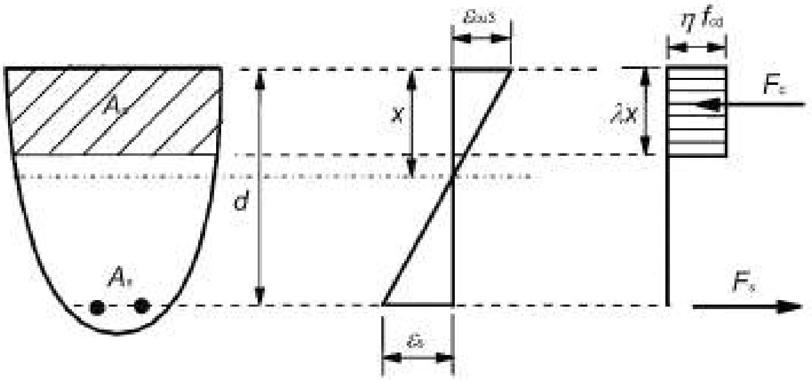
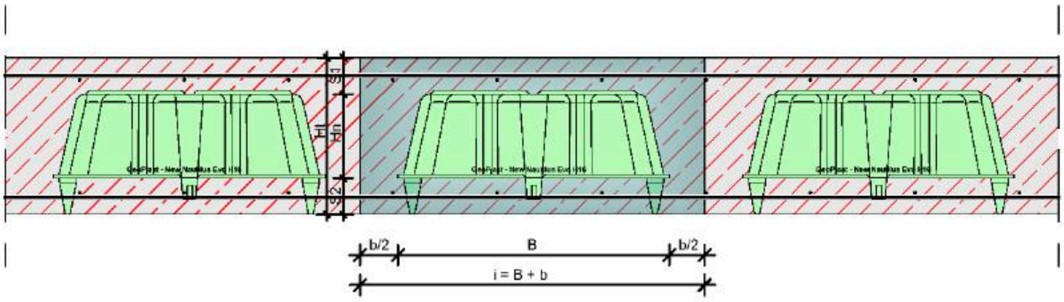
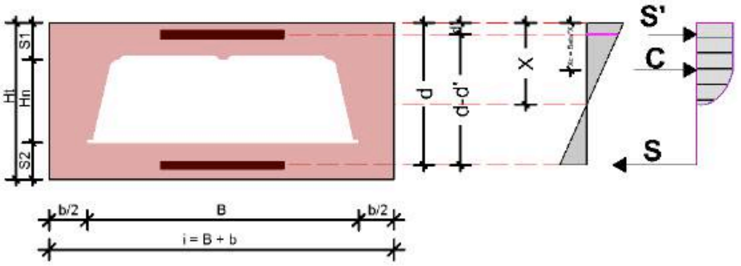
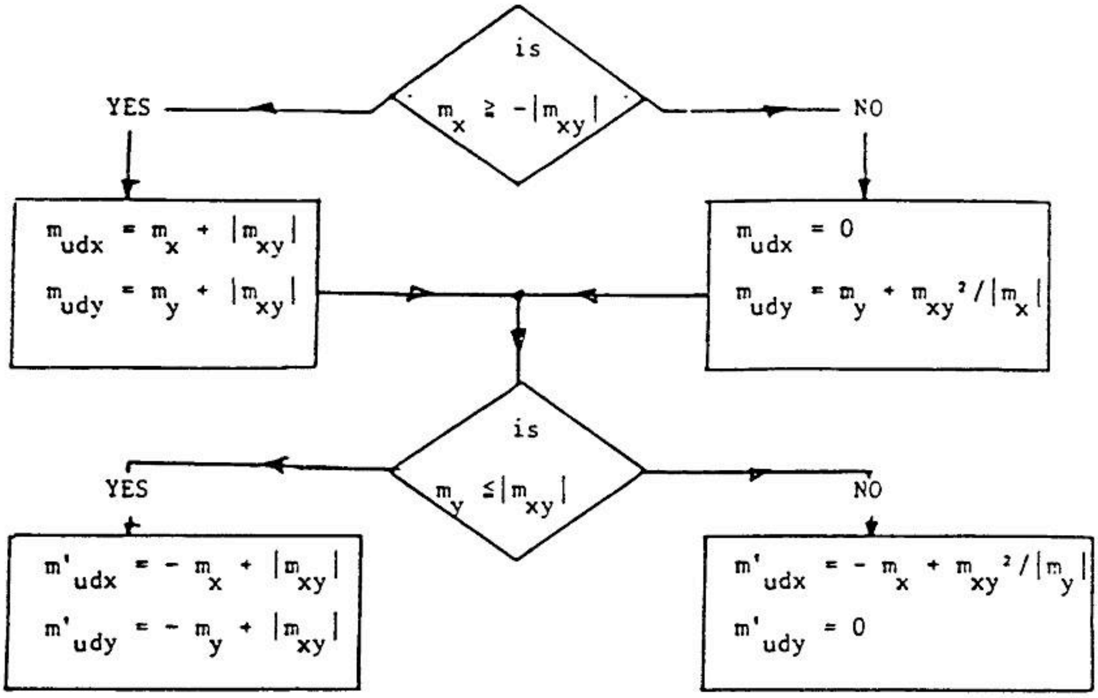


Figure 3.5: Rectangular stress distribution







1. Method Hillerborg: known also as stripes method. The slab is divided in strings/beams considered indipendent from one another. Then the reinforcement is dimensioned on the basis of the moments M_{xx} e M_{yy}.

Once the moments of stress have been calculated, the dimensioning and check of the reinforcement can be made. The calculation is called break at last limit and it is made taking into consideration the section a I or the section hollow rectangular.

The regulation of Eurocode 2 that need to be followed are the same of full slabs:

6.1 – Simple and compote flexion

- 6.6 –Anchoring and overlapping
- 7.3 –Cracking management
- 8.1 - Generality
- 8.2 –Space between the reinforcements
- 8.3 – Eligible diameters Mandrels for bent bars
- 8.4 – Anchoring length for the longitudinal reinforcements
- 9.2.1.1 – Minimal section of the reinforcements
- 9.3.1 – Flexion reinforcements (slabs)
- 9.4 –Honeycomb plates

3.1.2.3. SHEAR AND PUNCHING CHECK

The lightening reduces the shear section of the slab.

The shear reinforcement needs to be checked in proximity of the massive capitals.

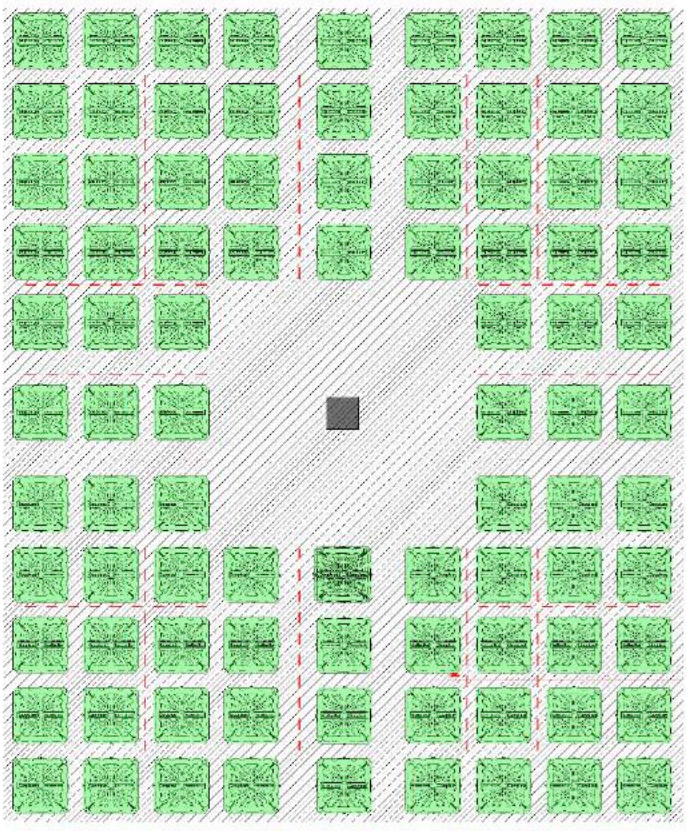
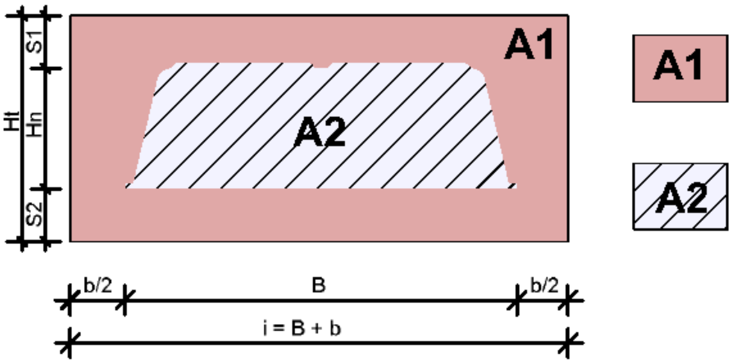


Figure 10 – Punching or reinforcements typical disposition

The shear check will be done while taking into consideration the hollow section of the lightened slab:



According to the hollow section which is wide:

i = (B+b)

The reinforcements resistance will be equal to:

$V_{rd,c} = \alpha_t \cdot v_{rd} \cdot l \cdot d$

With

$\alpha_t = \frac{A'}{A}$ ratio between lightened section's area and full section

$v_{rd,c} = C_{rd,c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^{\frac{1}{3}} \geq v_{min}$ according with EC2 6.6.2

At all points where this value is exceeded, normally close to the capitals and the supports on the sets, you should expect cutting armature, usually vertical pins. The cutting resistance of the section will therefore be the lowest value between

$$V_{rd,max} = \alpha_t \cdot \frac{\alpha_{cw} \cdot l \cdot z \cdot v_1 \cdot f_{cd} \cdot (cot\theta + cot\alpha)}{1 + cot^2\alpha}$$

And

$$V_{rd,s} = \frac{A_{sw}}{s} \cdot z \cdot f_{wy} \cdot (cot\theta + cot\alpha) \cdot sin\alpha$$

According with EC2 6.2.3 (4) expressions 6.13 and 6.14

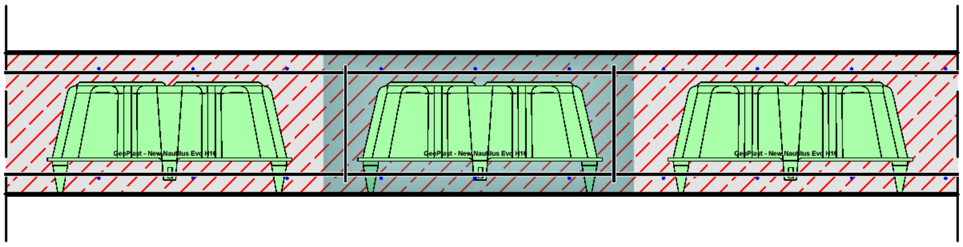


Figure 11 - Example of vertical brackets for cutting effort

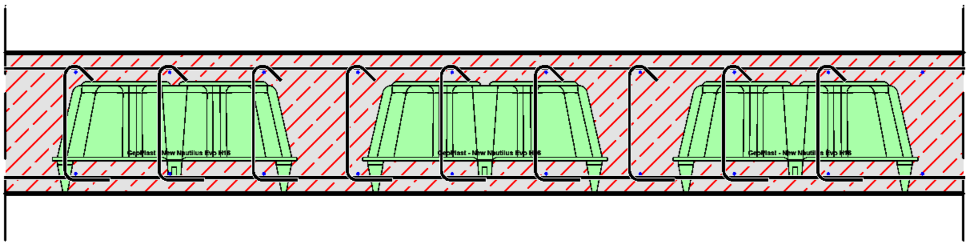


Figure 12- Cutting force brackets - Longitudinal section in the rib

As for punching, since massive areas are close to the supports, the normal sizing and checking methods used for massive plates are followed. Additional information is available at the following points in Eurocode 2:

- 6.2.1 – Cutting effort: general verification procedure
- 6.4.1 – Punching: general
- 8.5 – Anchoring of cutting armatures and other transverse reinforcements
- 9.3.2 – Cutting armatures

- 9.4.3 – Punching armatures

1.1.1.1. RETREAT AND FLUAGE

In this case you can easily follow the Eurocode 2 requirements:

- 2.3.2.2 – Retreat and fluage
- 5.8.4 - Fluage
- Annex B –Deformations due to retreat and fluage

1.1.1.2. CALCULATION OF INFLESSION AND CHECK OF ARROWS

The calculation of the inflection may be carried out in accordance with the requirements of Chapter 7.4.3 of the Eurocode 2.

Guidelines for checking the arrows are found in Chapter 7.4.

If you want to calculate the finite element arrows with nonlinear analysis, it should be noted that in the cracked phase the lightened slab has the same inertia as the full one only until the neutral axis does not intersect the rib.

It is therefore necessary to check the position of the neutral axis and to apply appropriate inertia modifiers, calculated in the same way as for the elastic section, but on the severed sections.

1.1.2. FIRE RESISTANCE

Fire resistance criteria are given in chapter 5.7.5 of EC2 part 1-2, tables 5.10 and 5.11:

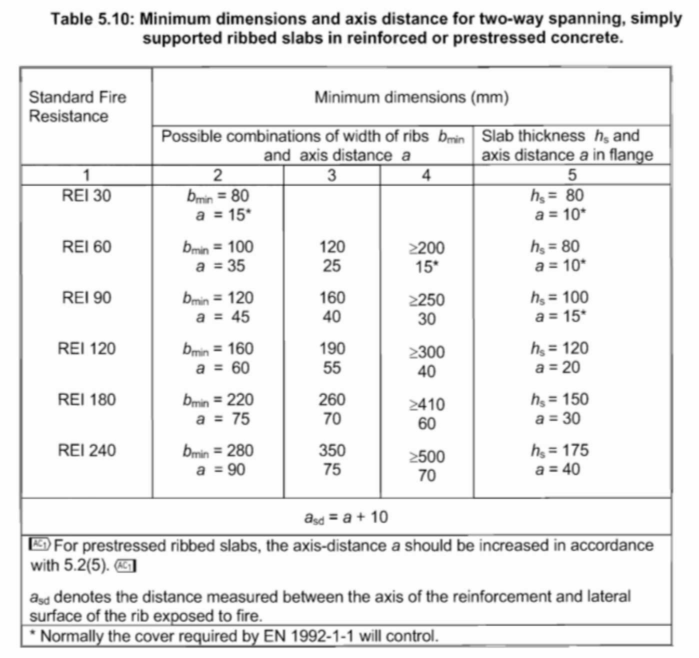


Table 5.10: Minimum dimensions and axis distance for two-way spanning, simply supported ribbed slabs in reinforced or prestressed concrete.

Standard Fire Resistance	Minimum dimensions (mm)			
	Possible combinations of width of ribs b_{min} and axis distance a			Slab thickness h_s and axis distance a in flange
1	2	3	4	5
REI 30	b_{min} = 80 a = 15*			h_s = 80 a = 10*
REI 60	b_{min} = 100 a = 35	120 25	≥200 15*	h_s = 80 a = 10*
REI 90	b_{min} = 120 a = 45	160 40	≥250 30	h_s = 100 a = 15*
REI 120	b_{min} = 160 a = 60	190 55	≥300 40	h_s = 120 a = 20
REI 180	b_{min} = 220 a = 75	260 70	≥410 60	h_s = 150 a = 30
REI 240	b_{min} = 280 a = 90	350 75	≥500 70	h_s = 175 a = 40
$a_{sd} = a + 10$				

AC1 For prestressed ribbed slabs, the axis-distance a should be increased in accordance with 5.2(5). AC1

a_{sd} denotes the distance measured between the axis of the reinforcement and lateral surface of the rib exposed to fire.

* Normally the cover required by EN 1992-1-1 will control.

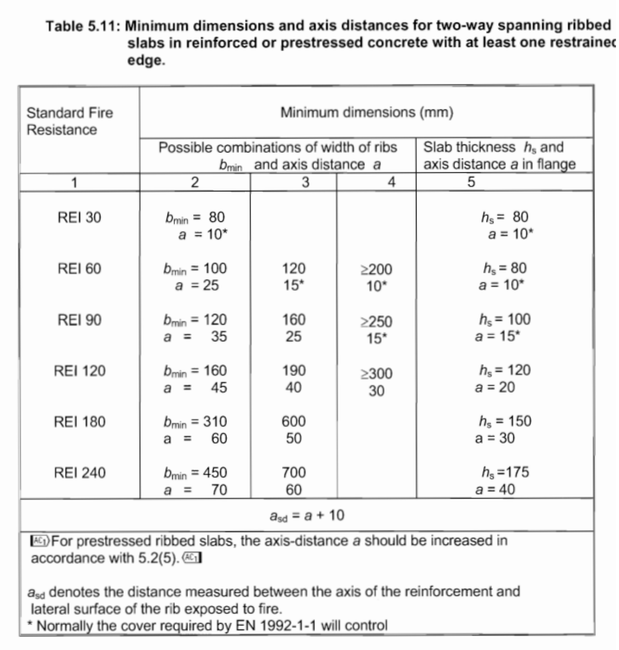


Table 5.11: Minimum dimensions and axis distances for two-way spanning ribbed slabs in reinforced or prestressed concrete with at least one restrainec edge.

Standard Fire Resistance	Minimum dimensions (mm)			
	Possible combinations of width of ribs b_{min} and axis distance a			Slab thickness h_s and axis distance a in flange
1	2	3	4	5
REI 30	b_{min} = 80 a = 10*			h_s = 80 a = 10*
REI 60	b_{min} = 100 a = 25	120 15*	≥200 10*	h_s = 80 a = 10*
REI 90	b_{min} = 120 a = 35	160 25	≥250 15*	h_s = 100 a = 15*
REI 120	b_{min} = 160 a = 45	190 40	≥300 30	h_s = 120 a = 20
REI 180	b_{min} = 310 a = 60	600 50		h_s = 150 a = 30
REI 240	b_{min} = 450 a = 70	700 60		h_s =175 a = 40
$a_{sd} = a + 10$				

AC1 For prestressed ribbed slabs, the axis-distance a should be increased in accordance with 5.2(5). AC1

a_{sd} denotes the distance measured between the axis of the reinforcement and lateral surface of the rib exposed to fire.

* Normally the cover required by EN 1992-1-1 will control

Alternatively, it is possible to conduct an analytical calculation to the finite elements using a standard temperature curve according to the requirements of chapter 4.3 of EC2 part 1-2.

1.1.3. ACOUSTIC PERFORMANCE

Normally lightening suppliers provide on-demand laboratory or on-site testing of the acoustic performance of the construction system, based on which you can estimate the slab performance you are designing.

1.1.4. CONCRETE CASTING METHODOLOGY

The lightening caissons are watertight, as the air clamped inside them prevents the entrance of the concrete.

For this reason they tend to float during the casting, developing a vertical force such that it is possible to lift the upper armature.

The cast has to be run in two phases, both in the same day: a first strut of the lift leg, then the completion layer, to be performed after 2-4 hours (depending on the outside temperature).

In case the cast is run several hours later, it is necessary to calculate and provide a suitable shot armor.

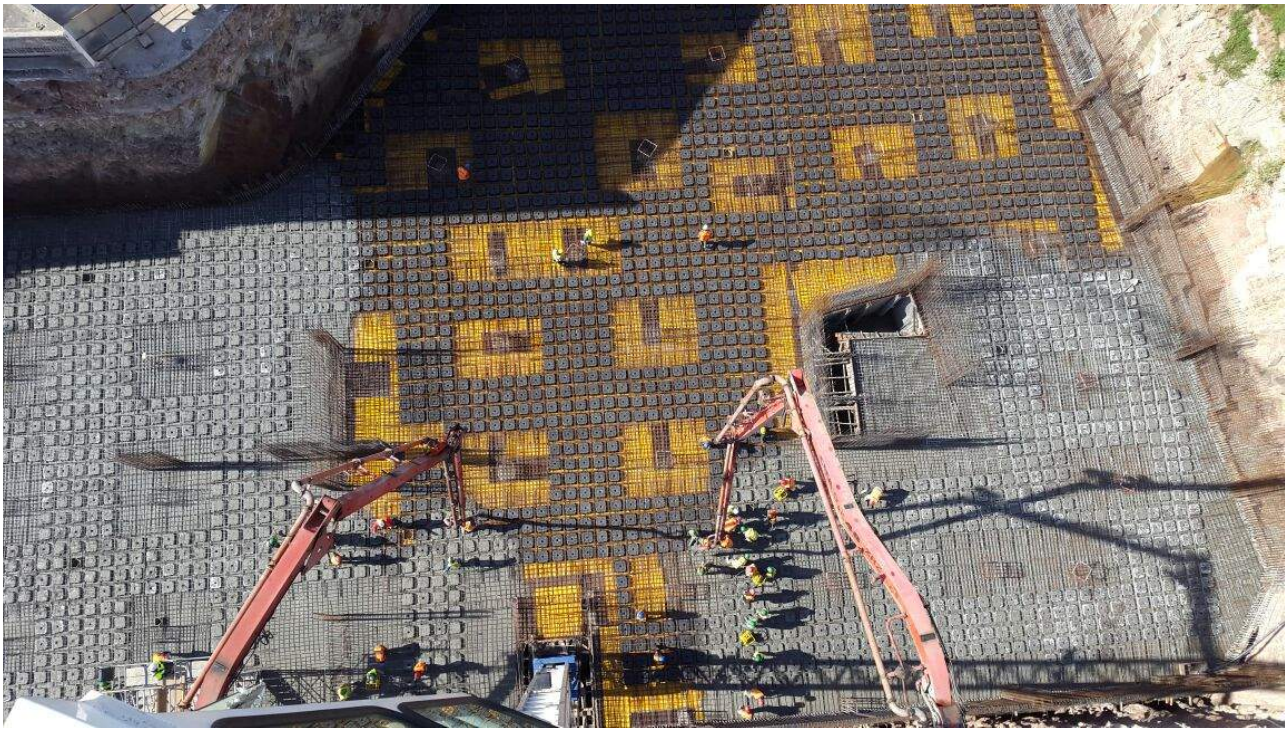


Figure 13 - Cast of the first layer

Figure 14 - Cast of the completion layer

1.2. COMPARISON WITH THE FULL PLATES

Lightened plates retain all the features and benefits of their massive structures:

1. Thicknesses reduced
2. No beams
3. High rigidity and reduced arrows
4. Good fire behavior

5. Ease of operation thanks to the use of basically straight bars and electrowelded nets for the armor.

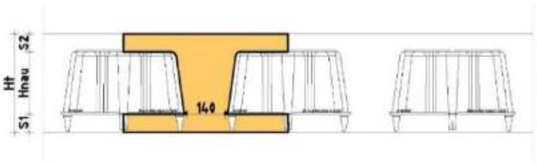
Obviously, the reduction of material obtained through the interposition of lightening in the casting results in a reduction of the rigidity of the structure, but is compensated by the greater lightness.

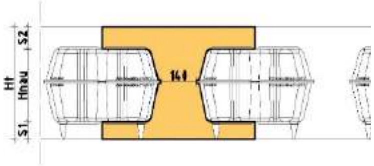
1.2.1. PREDIMENSIONING

As for the first predimensioning of the thickness, lightened plates follow the same criteria and practical rules normally used for full plates:

1. Lightened plate on pillars: $L/25 < S < L/30$ depending on the ELU load
2. Lightened plate on lowered beams or capitals: $L/30 < S < L/35$

Below is a table that provides an idea of the predimensioning of a lightened plate according to the span between the pillars and in the case of a load $G'_k+Q_k = 5,0$ kN/m^2





SPANS SPACING L_x x L_y	LOADS G'_k + Q_k	PROPOSED THICKNESS	S_1	$H_{nautilus}$	S_2	INERTIA NAUTILUS SLAB J_{nau}	INERTIA FLAT SLAB J_{full}	SELF WEIGHT NAUTILUS SLAB P_{nau}	SELF WEIGHT FLAT SLAB P_{full}	INERTIA LOSS	WEIGHT/CONCRETE REDUCTION	LOADS/REINFORCEMENT REDUCTION
[m]	[kN/m^2]	[cm]	[cm]	[cm]	[cm]	[cm^4]	[cm^4]	[kN/m^2]	[kN/m^2]	%	%	%
5	5.00	20	5	10	5	60821.26	66666.67	3.63	5.00	-8.77%	-27.4	-13.0
6	5.00	23	5	13	5	88537.95	101391.67	4.15	5.75	-12.68%	-27.8	-14.2
7	5.00	25	6	13	6	117362.62	130208.33	4.65	6.25	-9.87%	-25.6	-13.6
8	5.00	28	6	16	6	158952.73	182933.33	5.18	7.00	-13.11%	-26.0	-14.5
9	5.00	32	7	20	5	226197.71	273066.67	5.78	8.00	-17.16%	-27.8	-16.4
10	5.00	34	7	20	7	280664.38	327533.33	6.28	8.50	-14.31%	-26.1	-15.8
11	5.00	36	7	24	5	307772.12	388800.00	6.38	9.00	-20.84%	-29.1	-18.0
12	5.00	40	8	24	8	452305.45	533333.33	7.38	10.00	-15.19%	-26.2	-16.8
13	5.00	44	8	28	8	581150.55	709866.67	7.98	11.00	-18.13%	-27.5	-18.2
14	5.00	50	7	36	7	779649.39	1041666.67	8.48	12.50	-25.15%	-32.2	-22.3
15*	5.00	58	10	41	7	1236413.18	1625933.33	9.98	14.50	-23.96%	-31.2	-22.5
16*	5.00	64	8	48	8	1561851.26	2184533.33	10.73	16.00	-28.50%	-32.9	-24.4
17**	5.00	68	10	48	10	1997584.59	2620266.67	11.73	17.00	-23.76%	-31.0	-23.4
18**	5.00	72	10	52	10	2317962.12	3110400.00	12.43	18.00	-25.48%	-30.9	-23.6

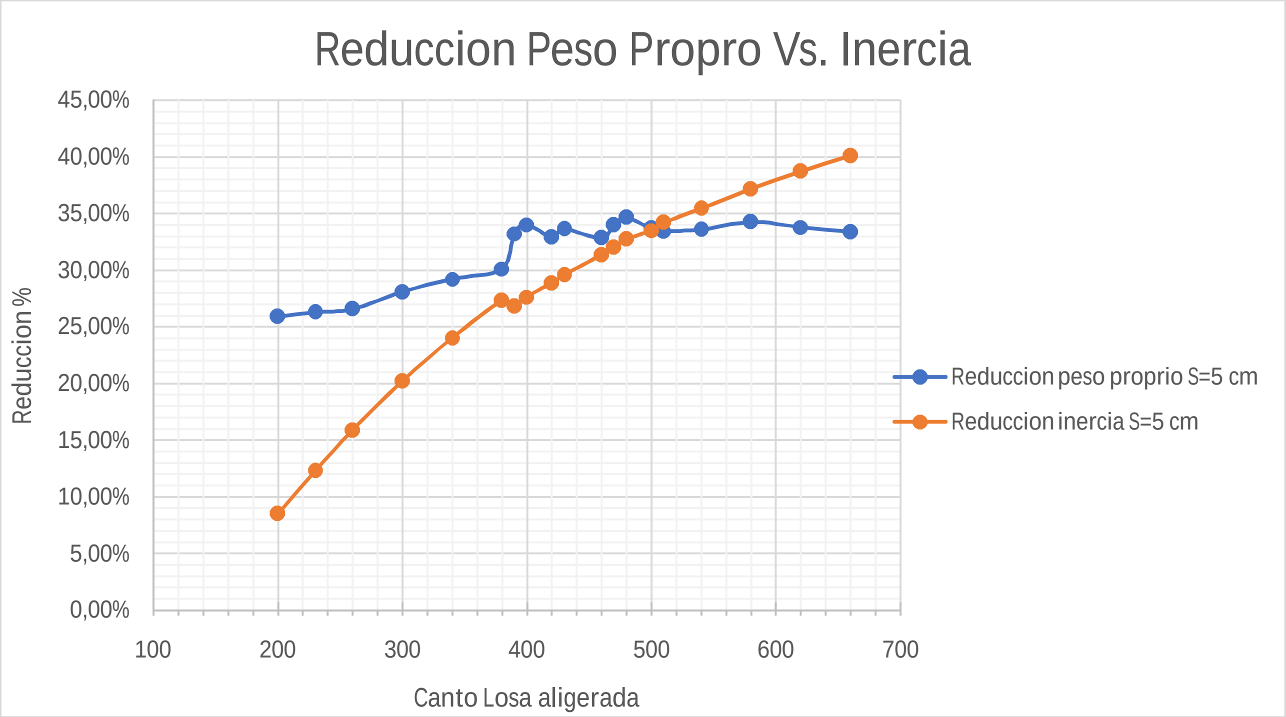
19**	5.00	74	10	56	8	2386739.39	3376866.67	12.65	18.50	-29.32%	-31.6	-24.3
20**	5.00	76	10	56	10	2668006.06	3658133.33	13.15	19.00	-27.07%	-30.8	-23.8
*High performances concrete reccomended - **Post tensioning reccomended												

1.2.2. EFFECTS OF THE REDUCTION OF STIFFNESS

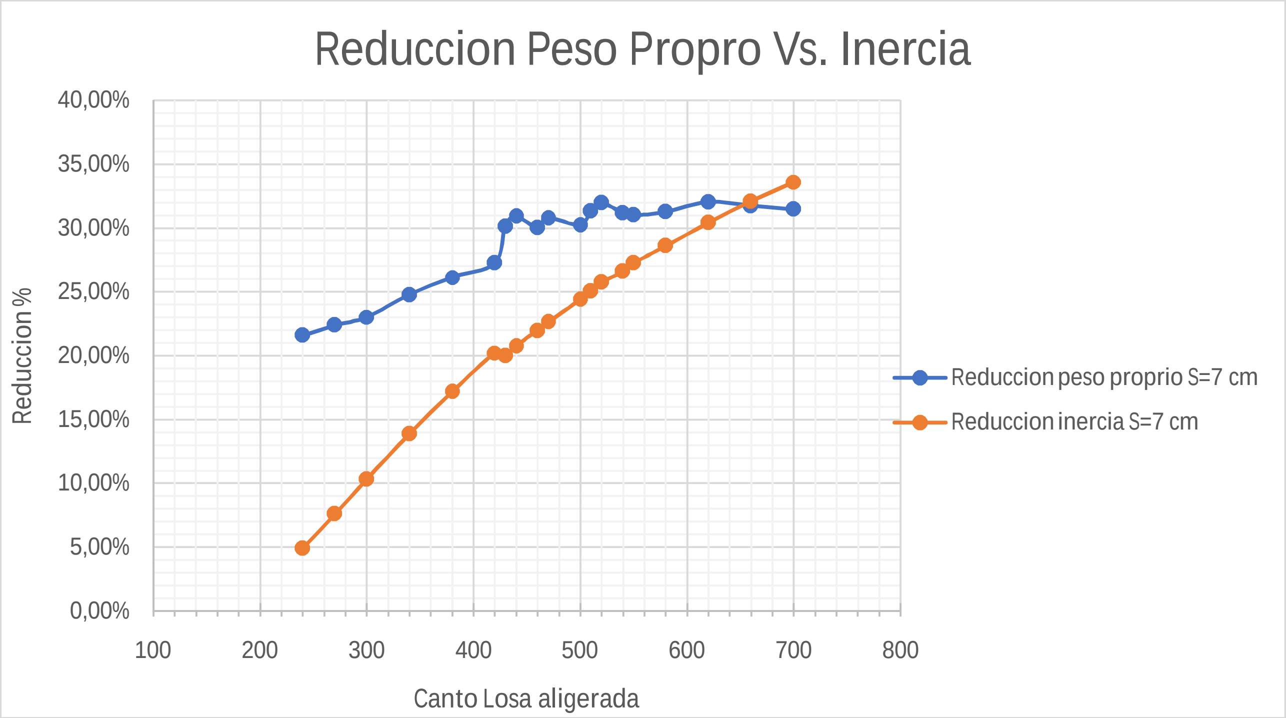
Reduction of rigidity is a function of the lightening geometry and is not linear with its height, it is also influenced by the thickness of the lower plate and, to a lesser extent, by the distance between the lightenings.

It is important to calibrate the lightened section so that the stiffness reduction is compensated by the lightness of the plate, calibrating the thicknesses of the slabs.

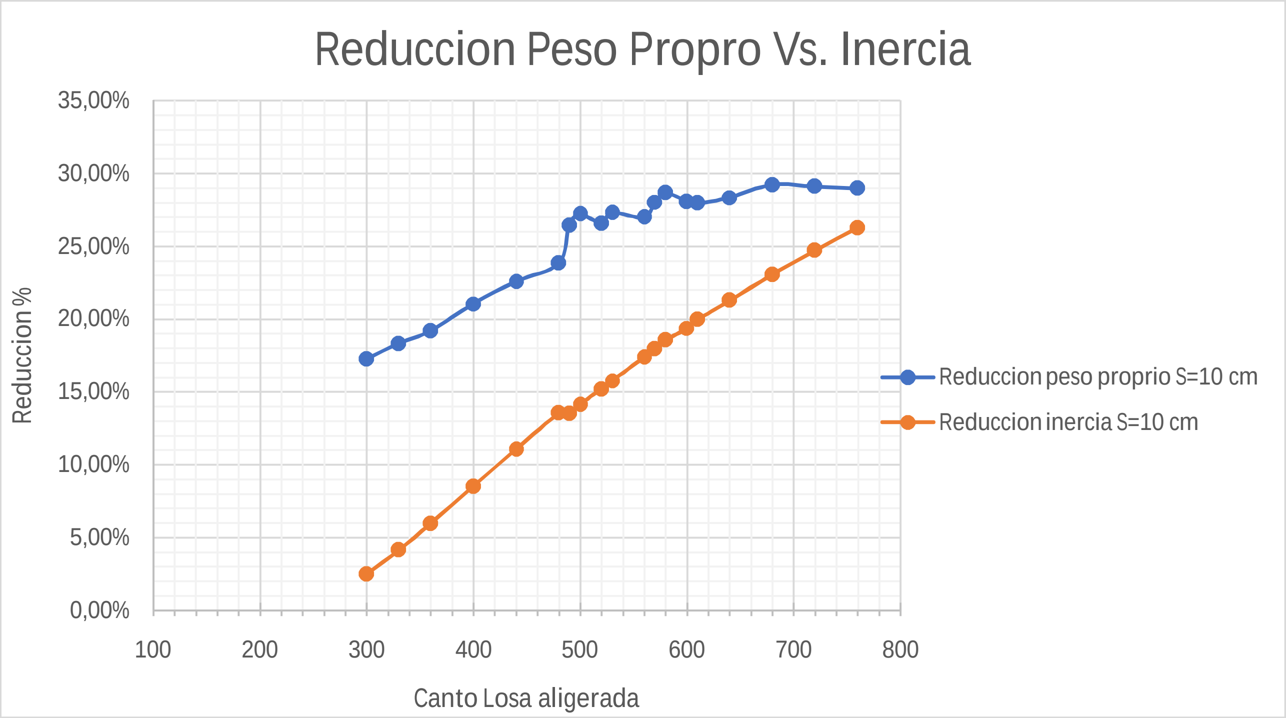
The following charts show how, when the height of the lightening and therefore the thickness of the plate is altered, and a distance is fixed, by increasing the thickness of the hoods, it is always possible to make the weight reduction superior to the loss of stiffness, thus keeping the performance of the lightened plate unaltered with respect to the full equivalent.



Graph 1 - Loss of flexural strength Vs. Weight reduction for lightweight plates with top and bottom 5 cm thickness



Graph 2 - Loss of flexural strength Vs. Weight reduction for lightweight plates with top and bottom 7 cm thickness



Graph 3 - Loss of flexural strength Vs. Weight reduction for lightweight plates with top and bottom 10 cm thickness

1.2.2.1. CONCLUSIONS

If you dimension the section appropriately, choosing the lightening height depending on the desired thickness and the appropriate thickness of the upper and lower plates, it is always possible to ensure that the loss of inertia is clearly compensated by the weight reduction.

By doing this, plates are obtained which have an average weight of 25% less than the full equivalent, losing only an 8-15% stiffness.

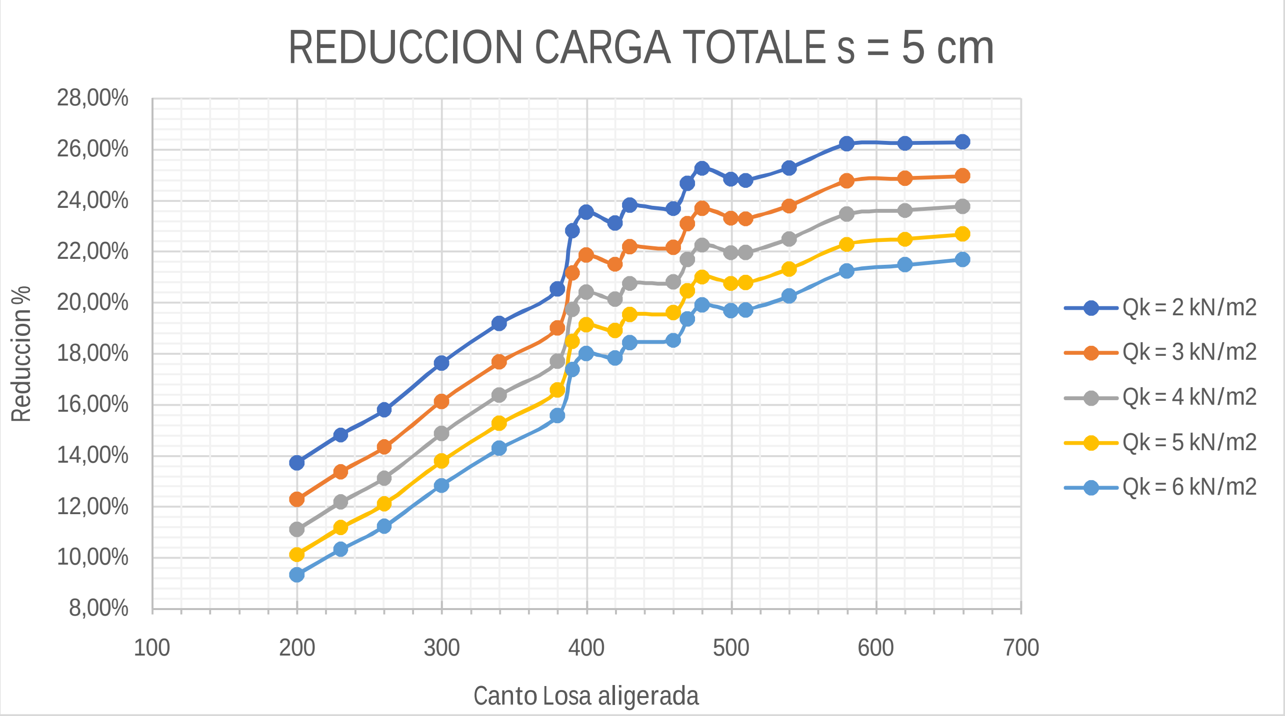
1.2.3. STRESSING LOAD REDUCTION

The first consequence of weight reduction of the same thickness as the homogeneous mass plate is that the slab and vertical structures all benefit from a reduction in load to the ultimate state which is the function of decreasing the proper weight of the plate and the size of the loads of the project.

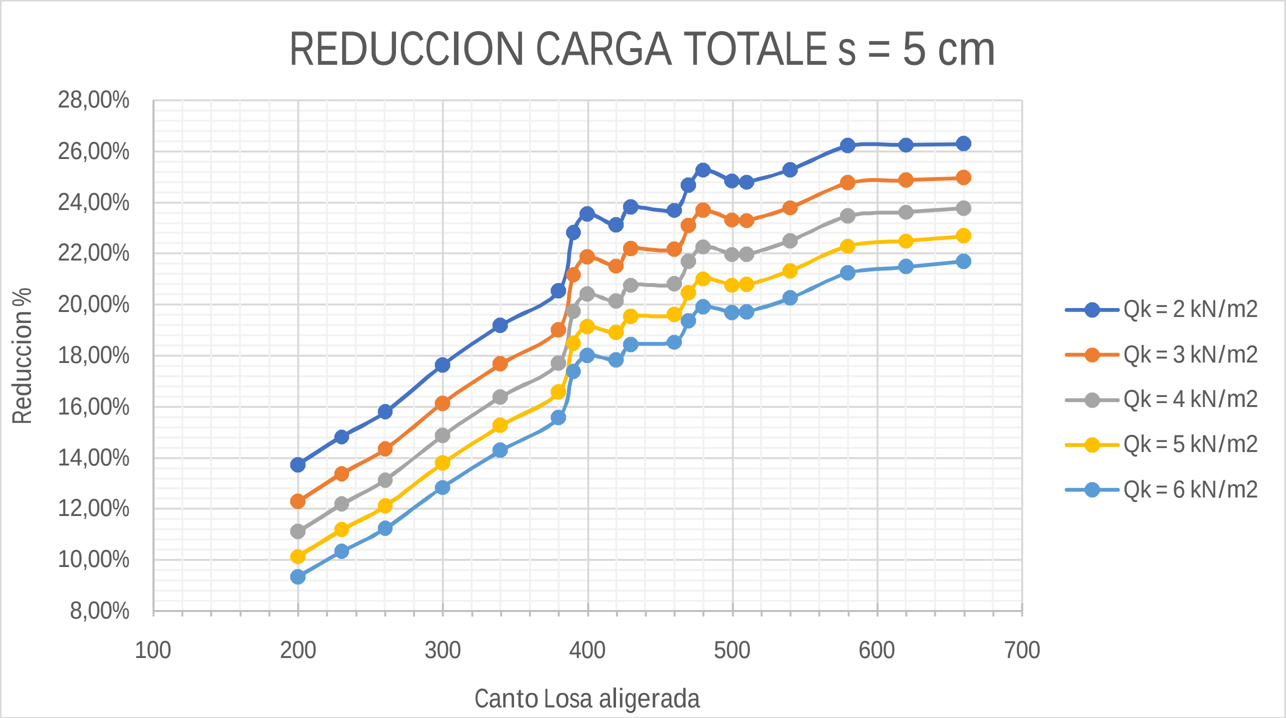
The following graphs show that, as the thickness of the upper and lower plates varies, the vertical load reduction to the Ultimate Limit State is variable from 8 to 10% minimum, up to 25%.

The graphs show the magnitude of the benefit in the case of a fixed G_k permanent load of 2,0 kN/m^2 at the variation of the plate thickness and variable load Q_k. Also the width of the rib is assumed invariable.

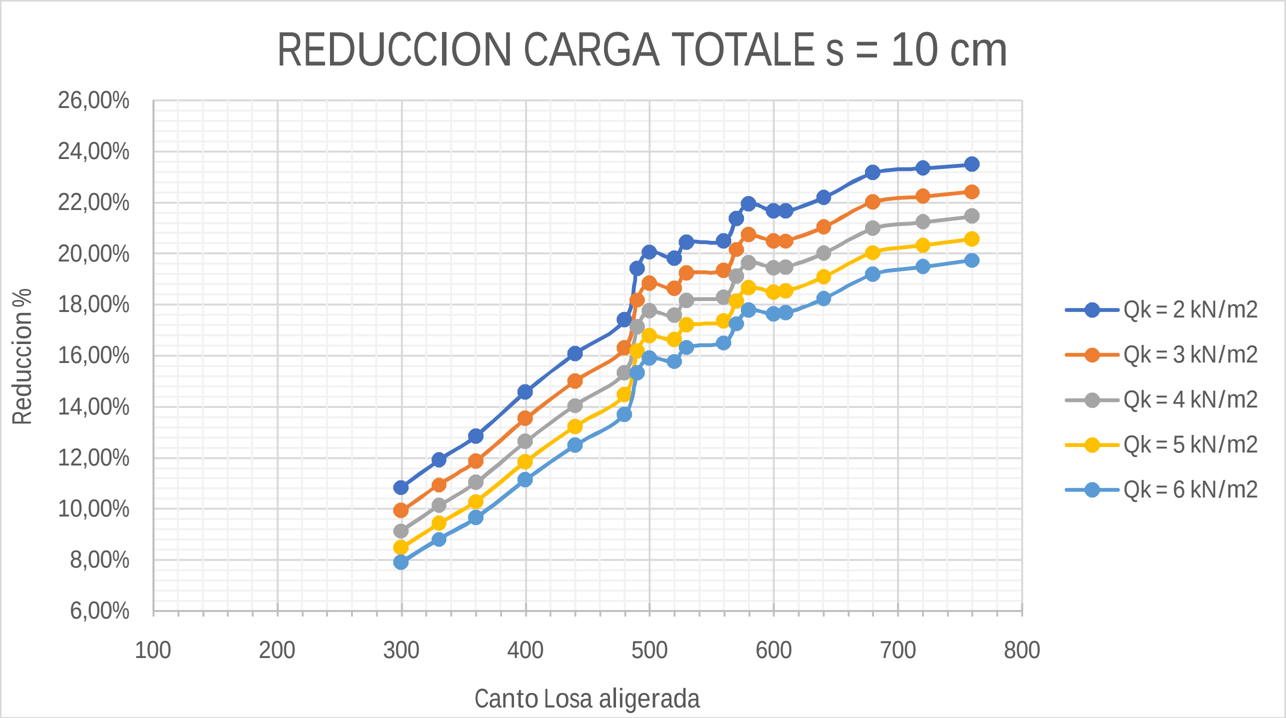
The vertical load reduction allows for direct savings of reinforcing steel in the slab, but also indirect savings on sizing of pillars. This savings helps to further lighten the entire structure, resulting in benefits to the foundation structures.



Graph 4 - ELU Load reduction depending on the thickness of the slab in the case of bottom and top plates of 5 cm thickness



Graph 5 - ELU Load reduction depending on the thickness of the slab in the case of bottom and top plates of 7 cm thickness



Graph 6 - ELU Load reduction depending on the thickness of the slab in the case of bottom and top plates of 10 cm thickness

1.2.4. SEISMIC MASS REDUCTION

Lightening the slabs and consequently the entire structure has important consequences on the seismic behavior of the structure.

Although it is not possible to give generic indications of the extent of the benefits on the seismic level as seismic acceleration is given by the response spectrum curve which is the function of the particular vibration period of the structure, which must be assessed case by case, it remains undeniable that the active seismic force is a direct function of the mass of the building.

The lightening of the slabs and consequently of the vertical structures therefore results in a significant reduction of the seismic force acting on the building.

1.2.5. COMPARISON ON TYPE BUILDINGS

By way of example we have made a comparison between two identical buildings, one with massive slabs and one with lightweight slabs.

The starting hypotheses are the following:

1. Slabs 28 cm thick and with a surface of about 500 m^2
2. Span between pillars 8 x 8 m
3. 10 storey building
4. Pillars automatically dimensioned by FEM software to appreciate load savings on the verticals
5. Project loads: $G_k = 2,0\ kN/m^2$ - $Q_k = 3,0\ kN/m^2$
6. Seismic acceleration peak at reference ground: 0,257g

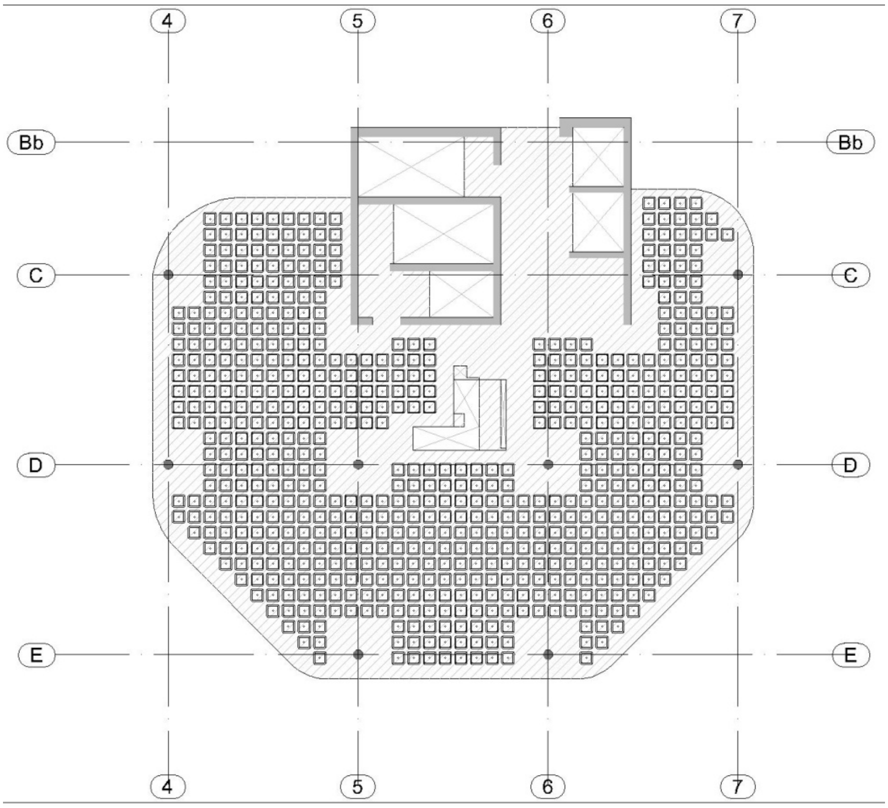


Figure 15 - Plant of lightweight slab type

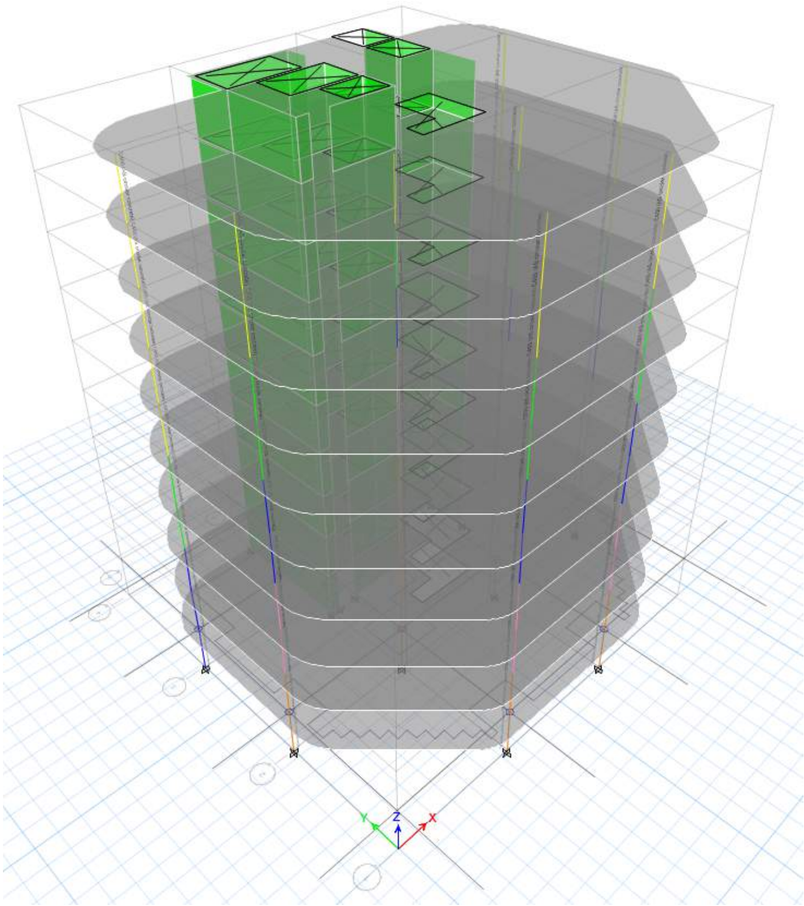


Figure 16 - Building calculation model

		FULL PLATE	LIGHTENED PLATE
TOTAL THICKNESS	H [mm]	280	280
THICKNESS LOWER PLATE	S_1 [mm]		60
THICKNESS UPPER PLATE	S2[mm]		60
LIGHTENING HEIGHT	H [mm]		160
RIB WIDTH	B [mm]		140
DISTANCE	I [mm]		660
SLAB INERTIA	J [cm^4/m]	182.933	158.844
CONCRETE CONSUMPTION	C [m^3/m^2]	0.280	0.207
OWN WEIGHT	P [kN/m^2]	7,0	5,18

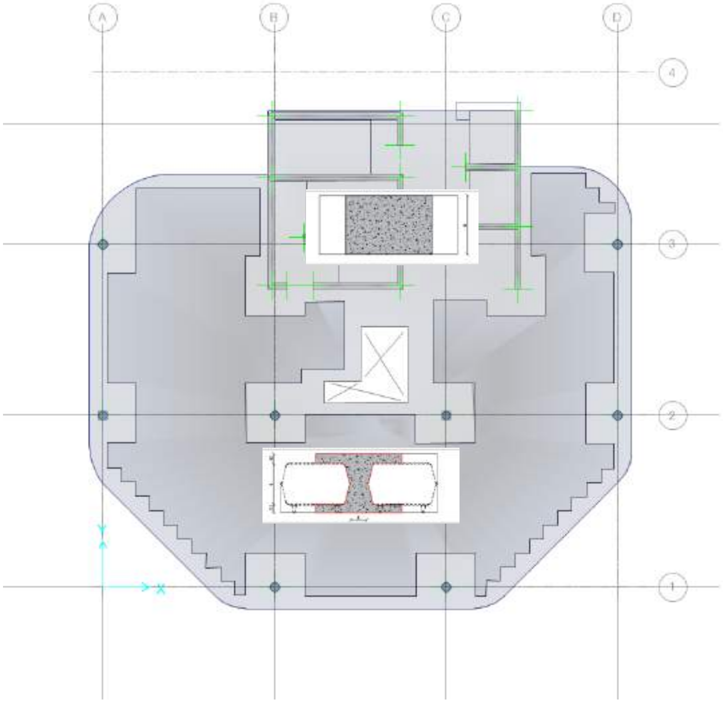


Figure 1 - FEM model of the type plate

1. In dark grey: shaped plate as lightened
    a. Bending flexibility reduction factor: 0,87
    b. Cutting stiffness reduction factor: 0,60
    c. Mass reduction factor: 0,74
2. In light grey: shaped plate as full
    a. Bending flexibility reduction factor: 1,00
    b. Cutting stiffness reduction factor: 1,00
    c. Mass reduction factor: 1,00

1.2.6. COMPARISON OF THE DEFORMED

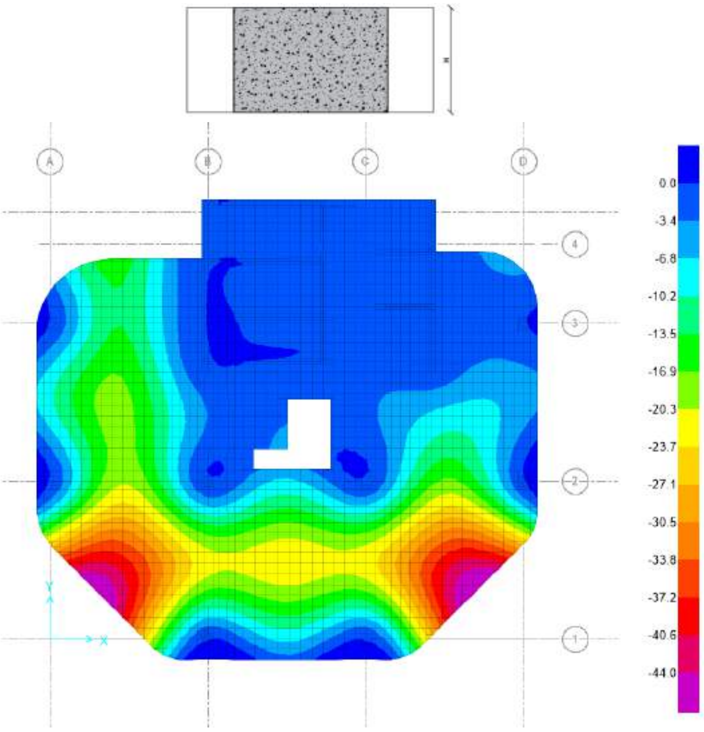


Figure 2 - Long-term arrow: 49,76 mm

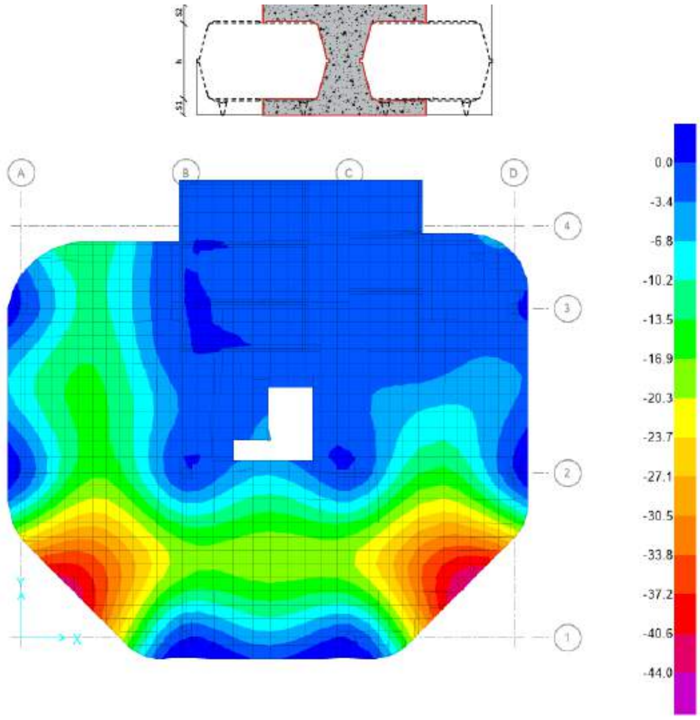


Figure 3 - Long-term arrow: 42,77

1.2.7. COMPARISON OF BENDING MOMENTS

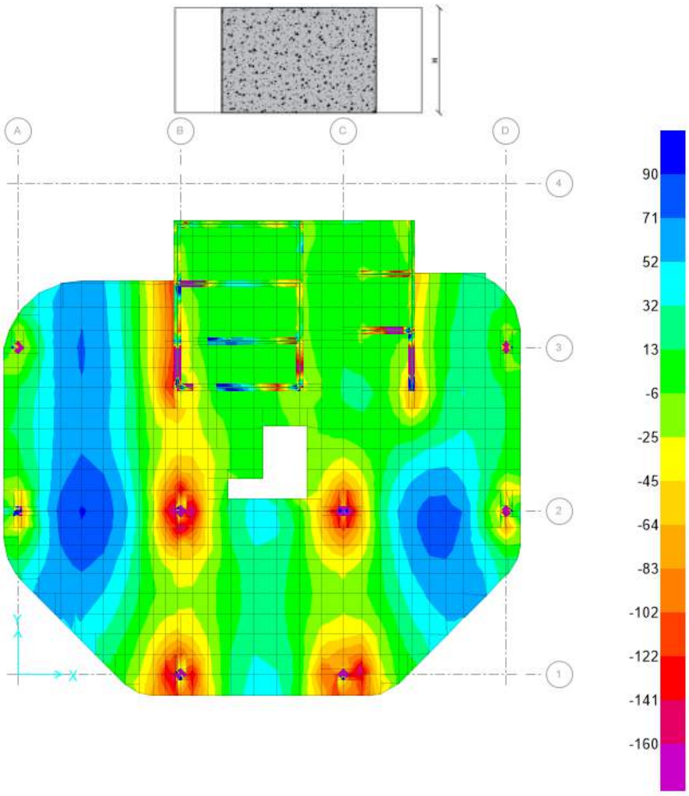


Figure 4 - Full plate – Mxx

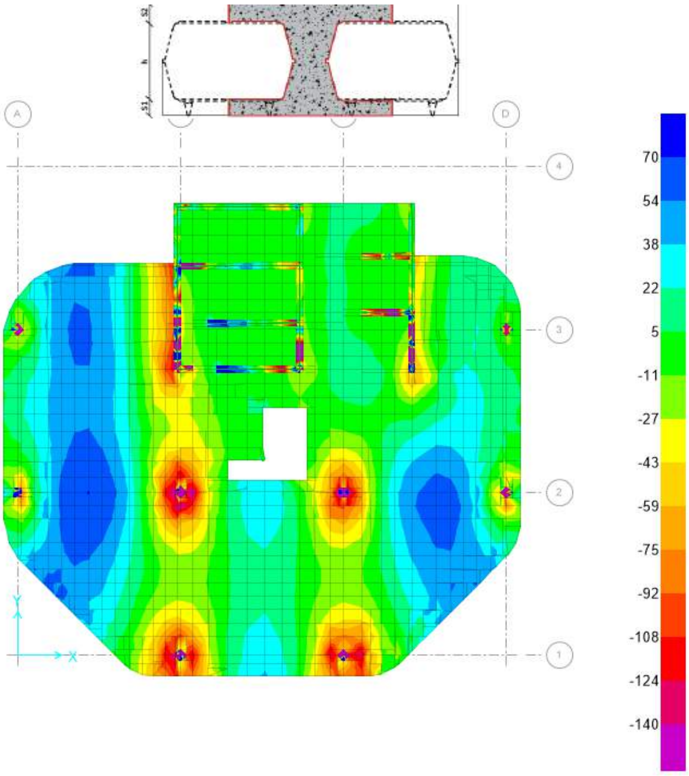


Figure 5 - Lightened plate - Myy

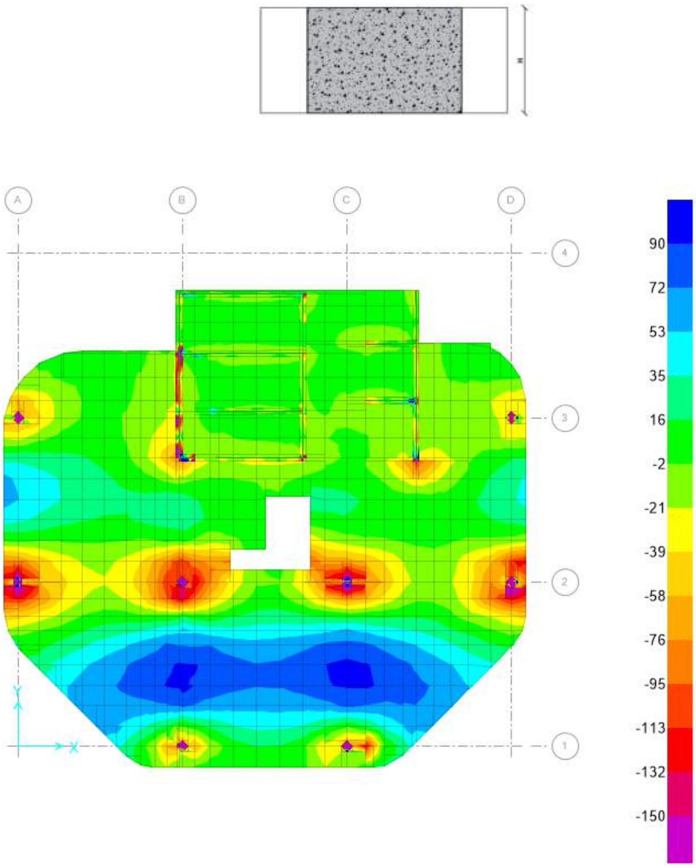


Figure 4 - Full plate: Myy

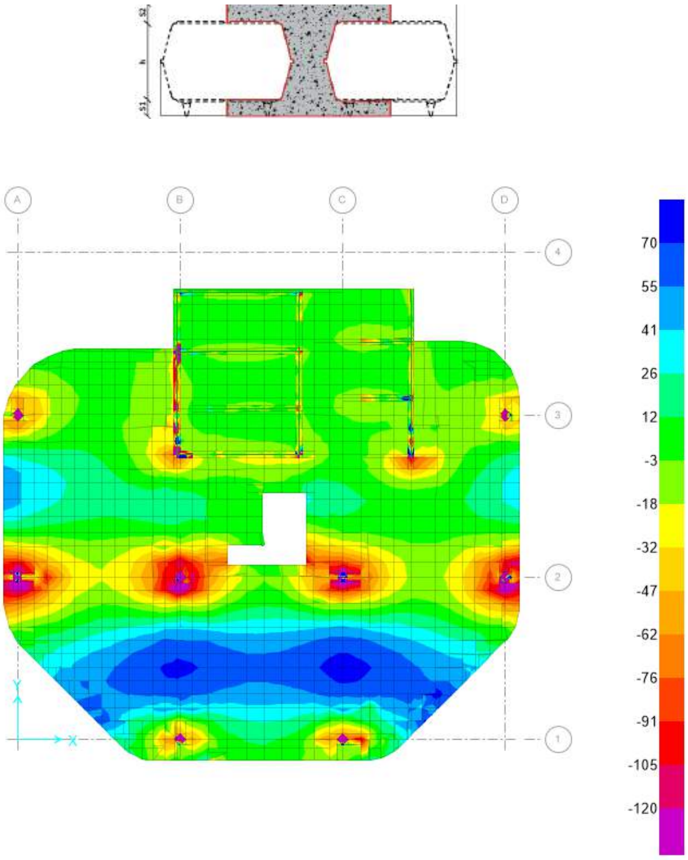


Figure 5 - Lightened plate: Myy

1.2.8. CONCLUSIONS

	FULL	**LIGHTENED**	**DIFF. %**
ARROW [mm]	49.76	42.77	-14%

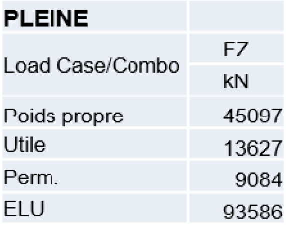
	FULL	**LIGHTENED**	**DIFF. %**
M_{xx}^{+} [kNm]	115.02	73.56	-36.05%
M_{xx}^{-} [kNm]	-425.06	-229.75	-45.95%
M_{yy}^{+} [kNm]	91.84	98.87	7.65%
M_{yy}^{-} [kNm]	-346.82	-287.99	-16.96%

Bending moments obviously result from redistribution due to the fact that the full plate has constant stiffness while the lightened is more rigid to the supports, thus resulting in a negative moment migration.

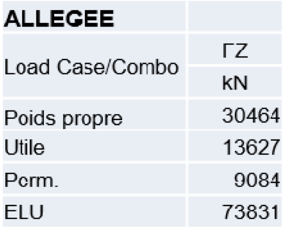
The average reduction of bending moment is around 17%.

1.2.9. OVERALL LOAD REDUCTION

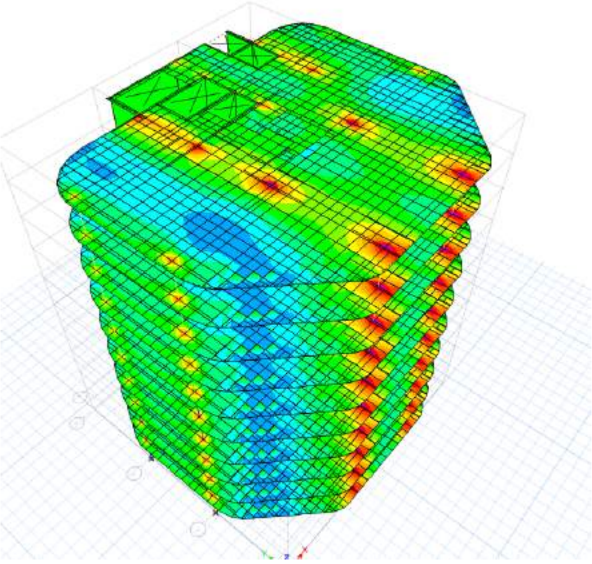
If we go to evaluate the weight and load reduction of each slab, added to the weight reduction due to the optimization of vertical structures subject to lower load, the overall benefit is even greater than not simply on the slab:



PLEINE	
Load Case/Combo	FZ
	kN
Poids propre	45097
Utile	13627
Perm.	9084
ELU	93586



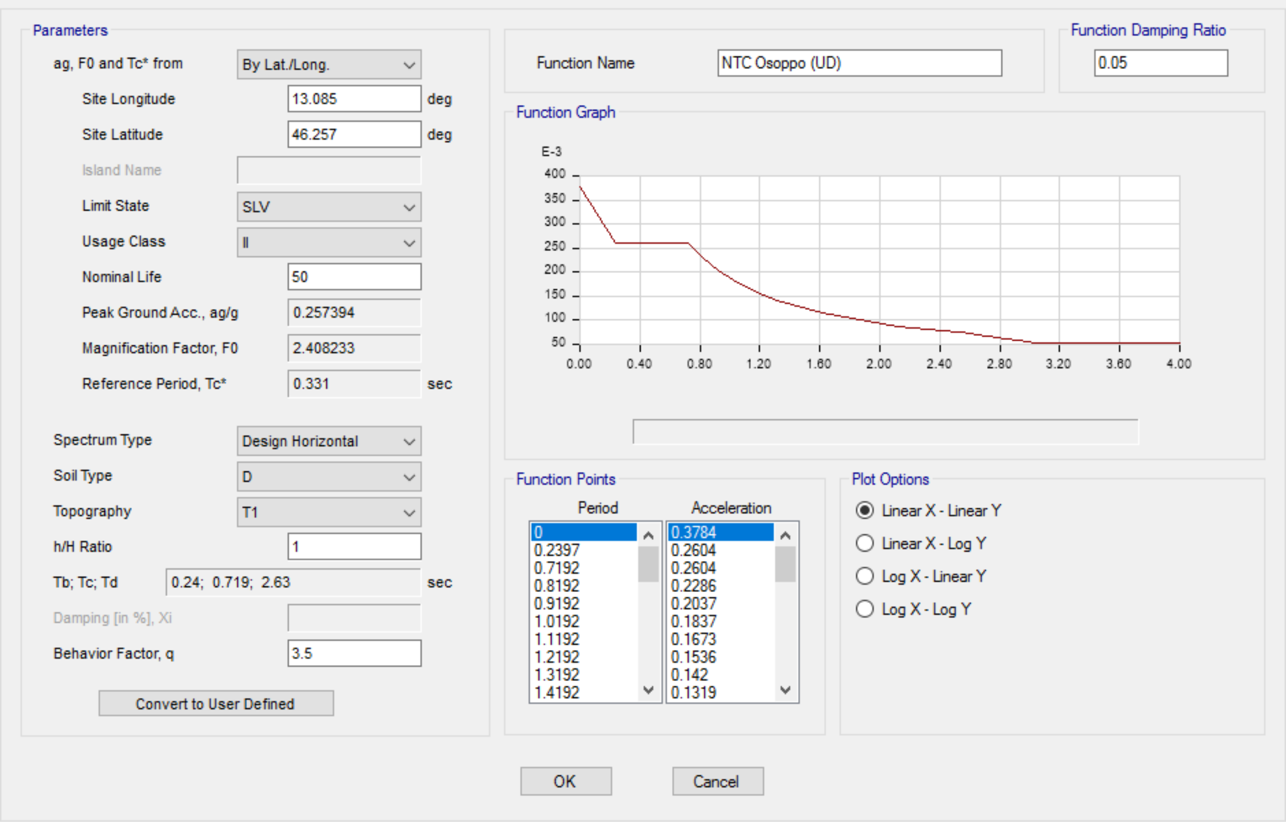
ALLEGEE	
Load Case/Combo	FZ
	kN
Poids propre	30464
Utile	13627
Perm.	9084
ELU	73831



1. -26% on the weight of the slabs
2. -32% of the total building weight
3. -21% of global load in foundation

1.2.10. REDUCTION OF SEISMIC LOAD

We made a comparison between the two buildings also from the seismic point of view, taking as reference the curve of the response spectrum of the Italian standard, in a highly seismic zone and in the pessimistic hypothesis of a type D soil.



Parameters

ag, F0 and Tc* from	By Lat./Long.	
Site Longitude	13.085	deg
Site Latitude	46.257	deg
Island Name		
Limit State	SLV	
Usage Class	II	
Nominal Life	50	
Peak Ground Acc., ag/g	0.257394	
Magnification Factor, F0	2.408233	
Reference Period, Tc*	0.331	sec
Spectrum Type	Design Horizontal	
Soil Type	D	
Topography	T1	
h/H Ratio	1	
Tb; Tc; Td	0.24; 0.719; 2.63	sec
Damping [in %], Xi		
Behavior Factor, q	3.5	

Function Name: NTC Osoppo (UD)

Function Damping Ratio: 0.05

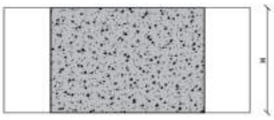
Function Points

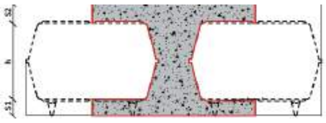
Period	Acceleration
0	0.3784
0.2397	0.2604
0.7192	0.2604
0.8192	0.2286
0.9192	0.2037
1.0192	0.1837
1.1192	0.1673
1.2192	0.1536
1.3192	0.142
1.4192	0.1319

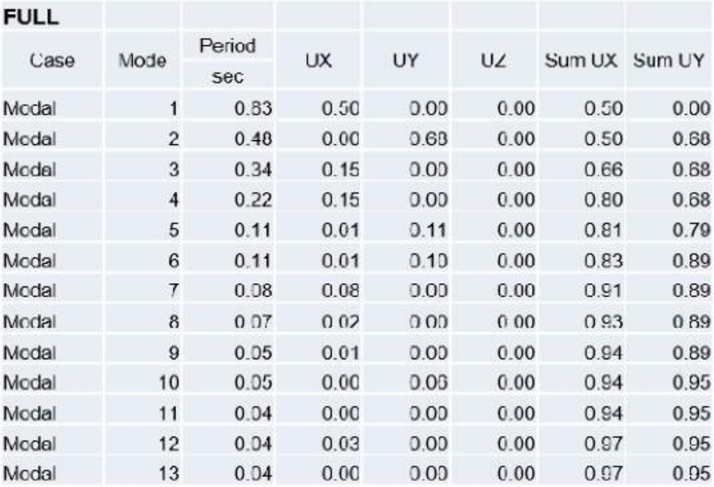
Plot Options

● Linear X - Linear Y
○ Linear X - Log Y
○ Log X - Linear Y
○ Log X - Log Y

The tables below show the different modal participation masses in the case of a building with a full or all-round plate:

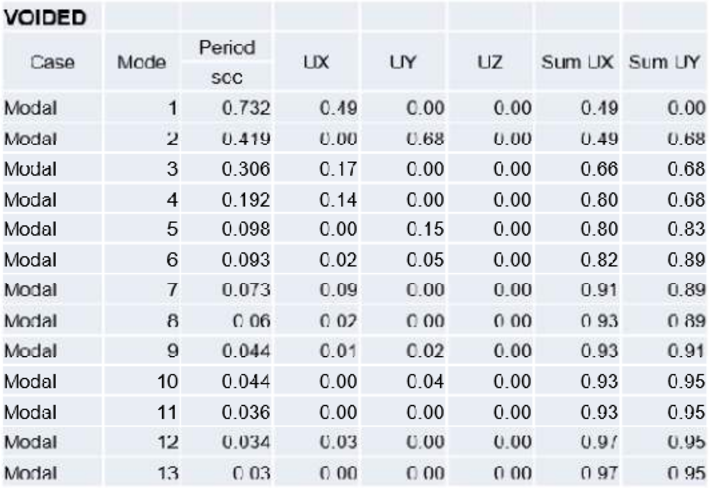






FULL

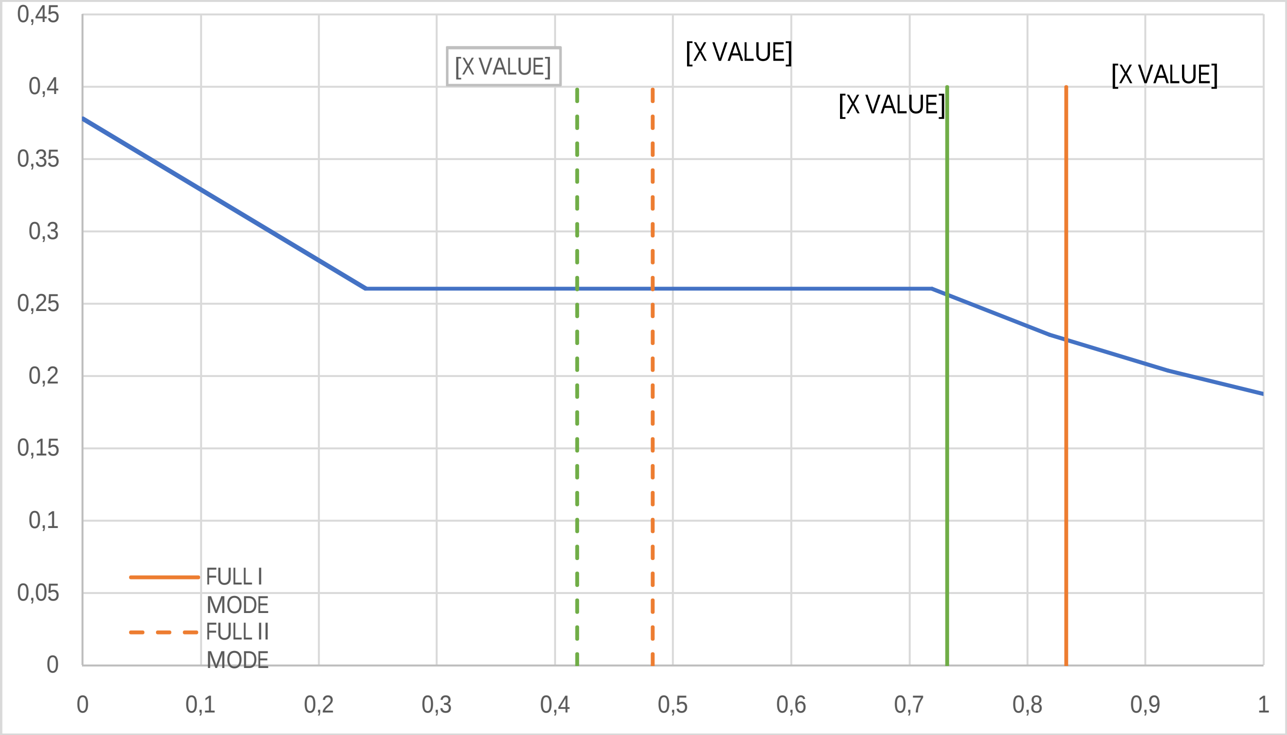
Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY
		sec					
Modal	1	0.83	0.50	0.00	0.00	0.50	0.00
Modal	2	0.48	0.00	0.68	0.00	0.50	0.68
Modal	3	0.34	0.15	0.00	0.00	0.66	0.68
Modal	4	0.22	0.15	0.00	0.00	0.80	0.68
Modal	5	0.11	0.01	0.11	0.00	0.81	0.79
Modal	6	0.11	0.01	0.10	0.00	0.83	0.89
Modal	7	0.08	0.08	0.00	0.00	0.91	0.89
Modal	8	0.07	0.02	0.00	0.00	0.93	0.89
Modal	9	0.05	0.01	0.00	0.00	0.94	0.89
Modal	10	0.05	0.00	0.06	0.00	0.94	0.95
Modal	11	0.04	0.00	0.00	0.00	0.94	0.95
Modal	12	0.04	0.03	0.00	0.00	0.97	0.95
Modal	13	0.04	0.00	0.00	0.00	0.97	0.95



VOIDED

Case	Mode	Period	UX	UY	UZ	Sum UX	Sum UY
		sec					
Modal	1	0.732	0.49	0.00	0.00	0.49	0.00
Modal	2	0.419	0.00	0.68	0.00	0.49	0.68
Modal	3	0.306	0.17	0.00	0.00	0.66	0.68
Modal	4	0.192	0.14	0.00	0.00	0.80	0.68
Modal	5	0.098	0.00	0.15	0.00	0.80	0.83
Modal	6	0.093	0.02	0.05	0.00	0.82	0.89
Modal	7	0.073	0.09	0.00	0.00	0.91	0.89
Modal	8	0.06	0.02	0.00	0.00	0.93	0.89
Modal	9	0.044	0.01	0.02	0.00	0.93	0.91
Modal	10	0.044	0.00	0.04	0.00	0.93	0.95
Modal	11	0.036	0.00	0.00	0.00	0.93	0.95
Modal	12	0.034	0.03	0.00	0.00	0.97	0.95
Modal	13	0.03	0.00	0.00	0.00	0.97	0.95

The building with full plates has a slightly longer vibration period, while the lightweight slab building is located on the plateau of the curve:



However, the reduction of global mass plays a much more relevant effect on the resulting seismic force:

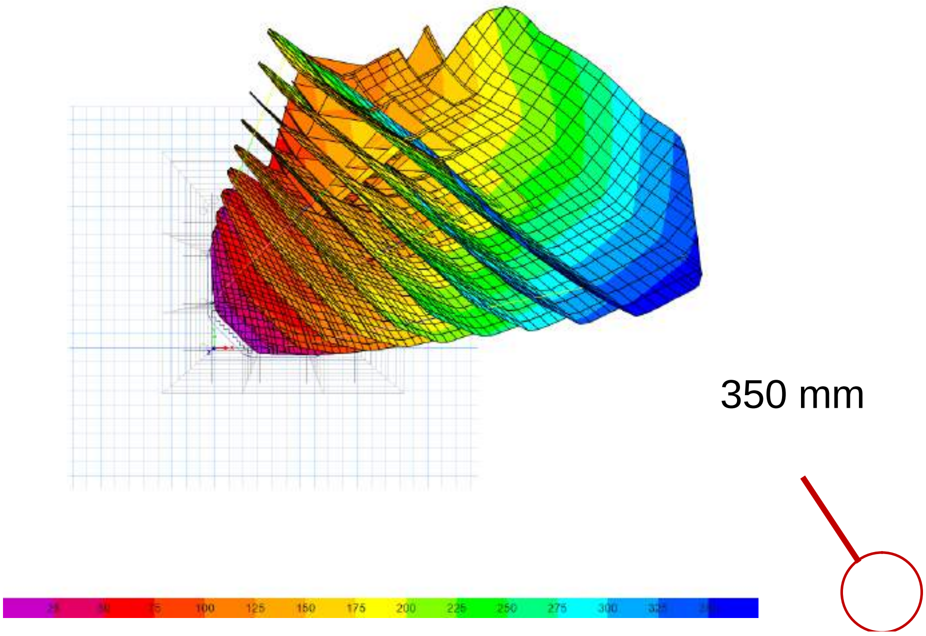


Figure 6 - Displacement due to seismic forces - full plate building

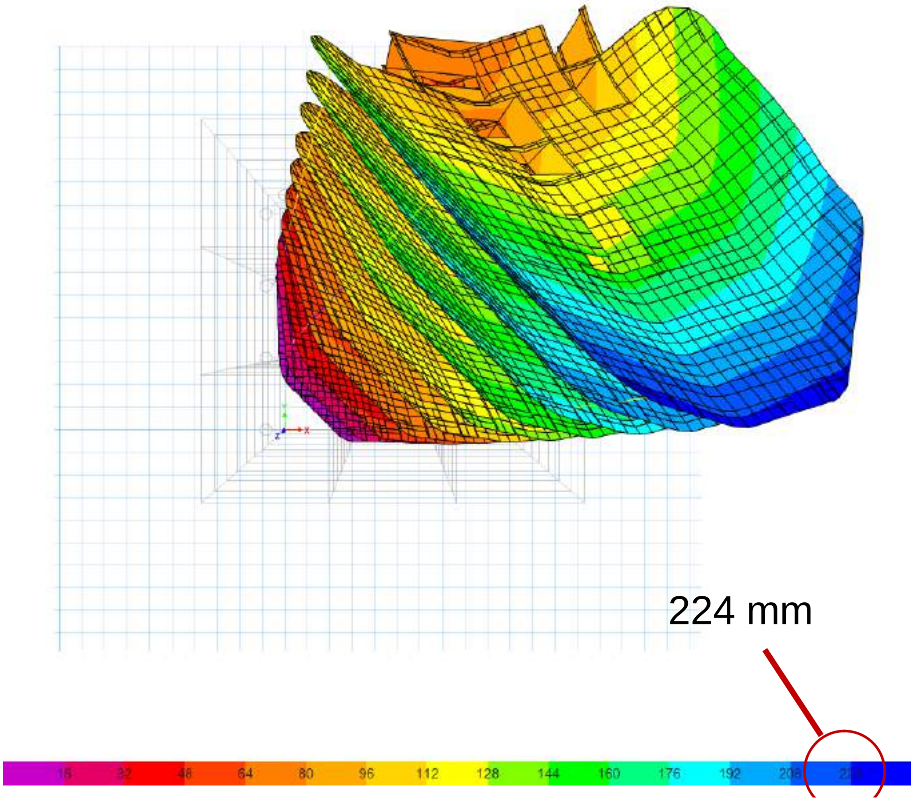
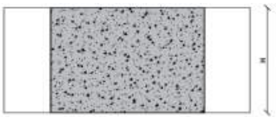


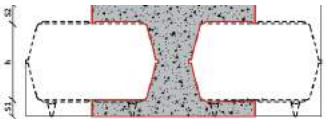
Figure 7 - Displacement due to seismic forces - lightweight building

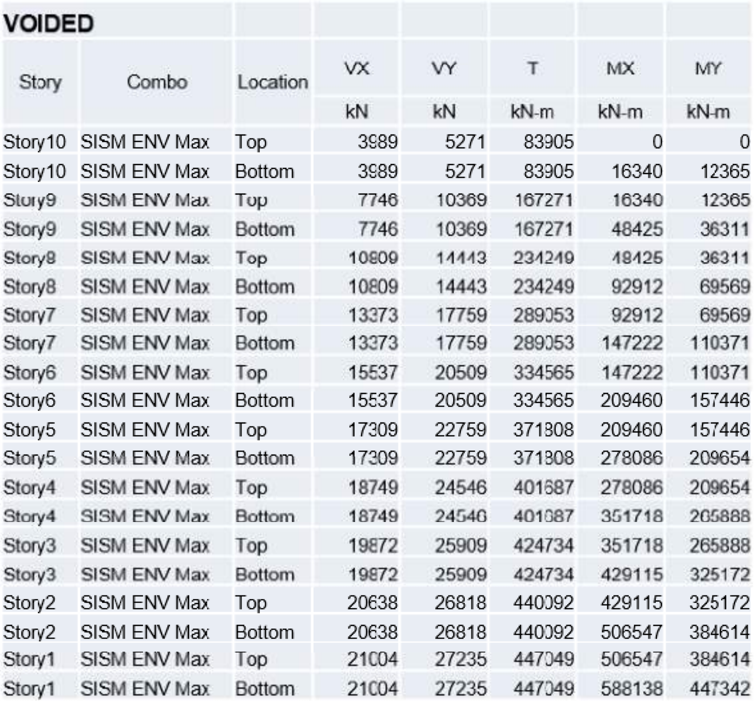
The displacement is 36% lower in case of lightweight slabs.

1.2.10.1. REDUCTION OF SEISMIC STRESSES



FULL							
Story	Combo	Location	VX kN	VY kN	T kN-m	MX kN-m	MY kN-m
Story10	SISM ENV Max	Top	6624	8491	131852	0	0
Story10	SISM ENV Max	Bottom	6624	8491	131852	26324	20534
Story9	SISM ENV Max	Top	12362	16163	252730	26324	20534
Story9	SISM ENV Max	Bottom	12362	16163	252730	76339	58755
Story8	SISM ENV Max	Top	16931	22274	349612	76339	58755
Story8	SISM ENV Max	Bottom	16931	22274	349612	144945	110856
Story7	SISM ENV Max	Top	20760	27247	429263	144945	110856
Story7	SISM ENV Max	Bottom	20760	27247	429263	228241	173971
Story6	SISM ENV Max	Top	24216	31379	495901	228241	173971
Story6	SISM ENV Max	Bottom	24216	31379	495901	323377	246246
Story5	SISM ENV Max	Top	27037	34762	550577	323377	246246
Story5	SISM ENV Max	Bottom	27037	34762	550577	428035	326638
Story4	SISM ENV Max	Top	29229	37455	594336	428035	326638
Story4	SISM ENV Max	Bottom	29229	37455	594336	540161	413830
Story3	SISM ENV Max	Top	30919	39516	627928	540161	413830
Story3	SISM ENV Max	Bottom	30919	39516	627928	657940	505905
Story2	SISM ENV Max	Top	32153	40886	650204	657940	505905
Story2	SISM ENV Max	Bottom	32153	40886	650204	775759	598300
Story1	SISM ENV Max	Top	32774	41511	660294	775759	598300
Story1	SISM ENV Max	Bottom	32774	41511	660294	899933	696001





VOIDED							
Story	Combo	Location	VX kN	VY kN	T kN-m	MX kN-m	MY kN-m
Story10	SISM ENV Max	Top	3989	5271	83905	0	0
Story10	SISM ENV Max	Bottom	3989	5271	83905	16340	12365
Story9	SISM ENV Max	Top	7746	10369	167271	16340	12365
Story9	SISM ENV Max	Bottom	7746	10369	167271	48425	36311
Story8	SISM ENV Max	Top	10809	14443	234249	48425	36311
Story8	SISM ENV Max	Bottom	10809	14443	234249	92912	69569
Story7	SISM ENV Max	Top	13373	17759	289053	92912	69569
Story7	SISM ENV Max	Bottom	13373	17759	289053	147222	110371
Story6	SISM ENV Max	Top	15537	20509	334565	147222	110371
Story6	SISM ENV Max	Bottom	15537	20509	334565	209460	157446
Story5	SISM ENV Max	Top	17309	22759	371808	209460	157446
Story5	SISM ENV Max	Bottom	17309	22759	371808	278086	209654
Story4	SISM ENV Max	Top	18749	24546	401687	278086	209654
Story4	SISM ENV Max	Bottom	18749	24546	401687	351718	265888
Story3	SISM ENV Max	Top	19872	25909	424734	351718	265888
Story3	SISM ENV Max	Bottom	19872	25909	424734	429115	325172
Story2	SISM ENV Max	Top	20638	26818	440092	429115	325172
Story2	SISM ENV Max	Bottom	20638	26818	440092	506547	384614
Story1	SISM ENV Max	Top	21004	27235	447049	506547	384614
Story1	SISM ENV Max	Bottom	21004	27235	447049	588138	447342

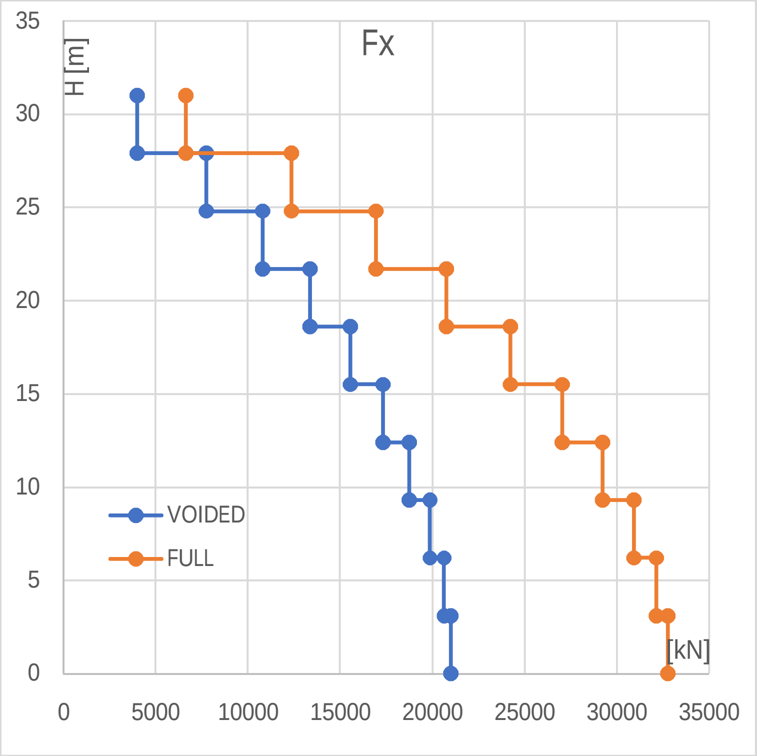


Figure 26 - Horizontal seismic force per plane - direct. X

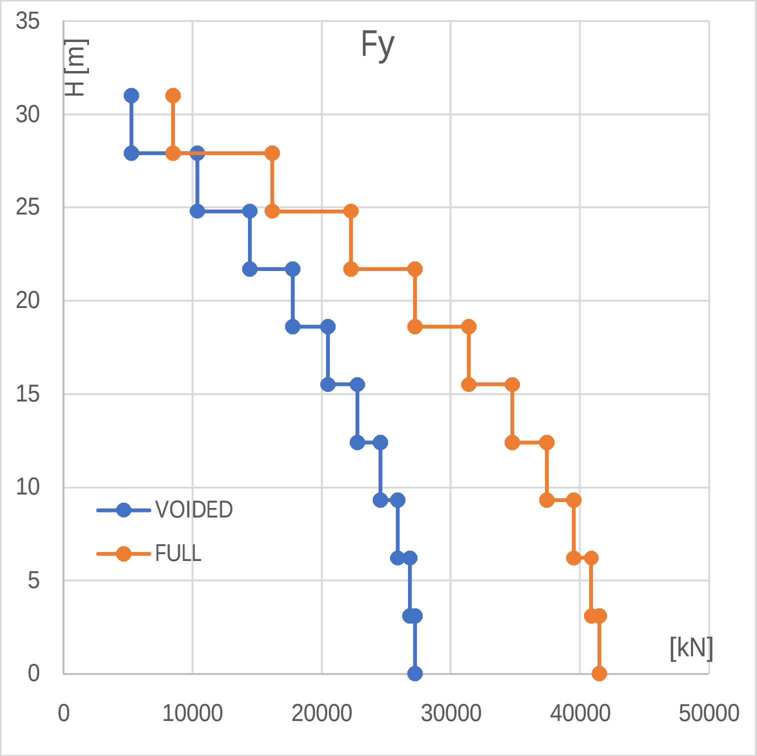


Figure 27- Horizontal seismic force per plane - direct. Y

Even in this case, the reduction of the soliciting force is important and in the order of 36% less.

1.2.11. CONCLUSIONS

To lighten the plates of a building has as immediate impact on the steel reduction of armor on the plates themselves, that we have seen to be average in the 12-15 order%.

Greater lightness also reduces the overall weight of the building as horizontal structures can be reduced due to the increased lightness of the slabs.

The benefit obviously grows as the number of floors in the building increases, and can lead to a reduction in the overall building weight of 30% and a reduction in the foundation load by 20%.

Similarly, the seismic forces decrease significantly, in the case example, a 36% less.

It remains to assess the burden of buying lightening and putting them into operation.

Depending on the cost of concrete, which varies not only from nation to nation, but also from region to region or city to city (especially in large urban centers it is usually much more expensive due to logistical burdens), the impact of the lightening on the cost of the lightened plate is greater or lesser.

On average, the cost of the lightening is largely offset by the savings of concrete generated by it, the remainder being largely compensated by the steel savings that are obtained on the totality of the building.

The time and consequent cost of laying workmanship is rather reduced (30-40 m^2 / h per worker) and is largely offset by the fact that saving steel on the slabs reduces the laying time of the same, and that time can be used for laying the lightening.

This implies that the productivity of a lightened plate is also the same as a full plate.