U-BOOT®
DESIGN PROCESS

U-Boot® Beton pre-dimensioning guide for lightened slabs

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INTRODUCTION

In the field of structural engineering, plates play a fundamental role in the construction of buildings and infrastructure in general. Due to their many advantages, such as high stiffness and simple construction, their use has become widespread and they have become a benchmark in the design and construction of horizontal structures.

The main disadvantage of solid slabs is their considerable weight, which becomes a limiting factor as the spans between vertical elements increases. This led to the development of lightened slabs, initially using polystyrene blocks, later upgraded by *recycled plastic formwork* such as **U-Boot® Beton**, to create a structure that keeps all the characteristics and strengths of a solid slab, while significantly reducing the weight.

The use of U-Boot® Beton formwork makes it possible to construct slabs without exposed beams, allowing the horizontal structural elements to be confined within the thickness of the slab. Dipping the U-Boot® Beton in the concrete casting, it is possible to form two flat slabs below and above the formwork, with variable dimensions thanks to the conical lifting feet.
The special spacers also make it possible to easily create an accurate grid of orthogonal ribs, connected to each other in both directions, which connect the two flat slabs at the intrados and extrados.

The purpose of this document is to provide a case study approach to the design of lightened slabs using a specific calculation example. The aim is therefore to assist the designer who intends to use this type of slab in relation to more traditional solutions such as frames and one-way slabs, or more simply for the transition between monolithic slabs and lightened slabs.

This is followed by an analysis of all the main design phases, starting with some simple rules for correct pre-sizing and ending with the necessary arrangements of reinforcement and construction details.
The free U-Boot® Beton Design Software, available on the Daliform website after registration, plays an important role in this process.

This document will give you all the practical tips you need to get the most out of the software during the design process.

PRE-SIZING - CASE STUDY

1. PRE-SIZING

Once the design has been analyzed and the vertical structures have been defined, it is possible to proceed with the pre-sizing of the horizon. For this purpose, as for beams, one-way slabs and monolithic slabs, an initial value based on the ratio between the maximum span and the thickness can be adopted.
Specifically, a ratio of L/27 can be considered, which is an excellent compromise compared to other solutions:

Structural Element	Preliminary dimensions
Beam	L/10
Monolithic plate slabs	L/25
Lightened plate slabs	L/27

The geometric ratio may, of course, depend on other factors, as will be seen in the following paragraphs, including the choice of reference thickness. In particular at this stage, it is possible to consider possible adjustments to the thickness if certain design conditions are known (e.g. fire resistance class, specific environmental exposures or loading conditions).

2. INPUT DATA

In relation to the example that will be developed in the following paragraphs, the relevant data for the correct dimensioning of the lightened slab with U-Boot® Beton formwork is given below:

- Maximum span between columns 8 x 8 m
- Permanent load 2 kN/sqm
- Accidental load 3 kN/sqm
- Pillar size 40 x 40 cm
- Concrete class C25/30
- Fire resistance R60
- Exposure class XC2
- Normative reference: Eurocode 2

If we consider a value of L_{max}/27 for the first test, we obtain:

$$800/27=29{,}6\ cm \rightarrow 30\ cm.$$

3. CHOOSING THE LIGHTENING FORMWORK

Once the 30 cm thickness has been determined, we need to choose the minimum slab thickness, the height of the formwork and the spacing between the formworks. The free **U-Boot® Beton Design Software** can be used to choose the type of formwork.

There are two ways to set cross-section parameters:
1) ***Free input:*** free input of all cross-section sizes
2) ***Simplified input:*** selection of possible solutions proposed for the total reference height.

The size of the slab depends itself on the minimum bar cover, which in turn also depends on the expected exposure class and any fire performance requirements.

For the proposed example, with fire performance R60 and exposure class XC2, a concrete cover of 3 cm is sufficient. (EN 1992-1-1-2004)

This assumes the use of a ø 12 mm rebar mesh, from which the minimum slab thickness to ensure the transmission of adhesion stresses is calculated as follows:

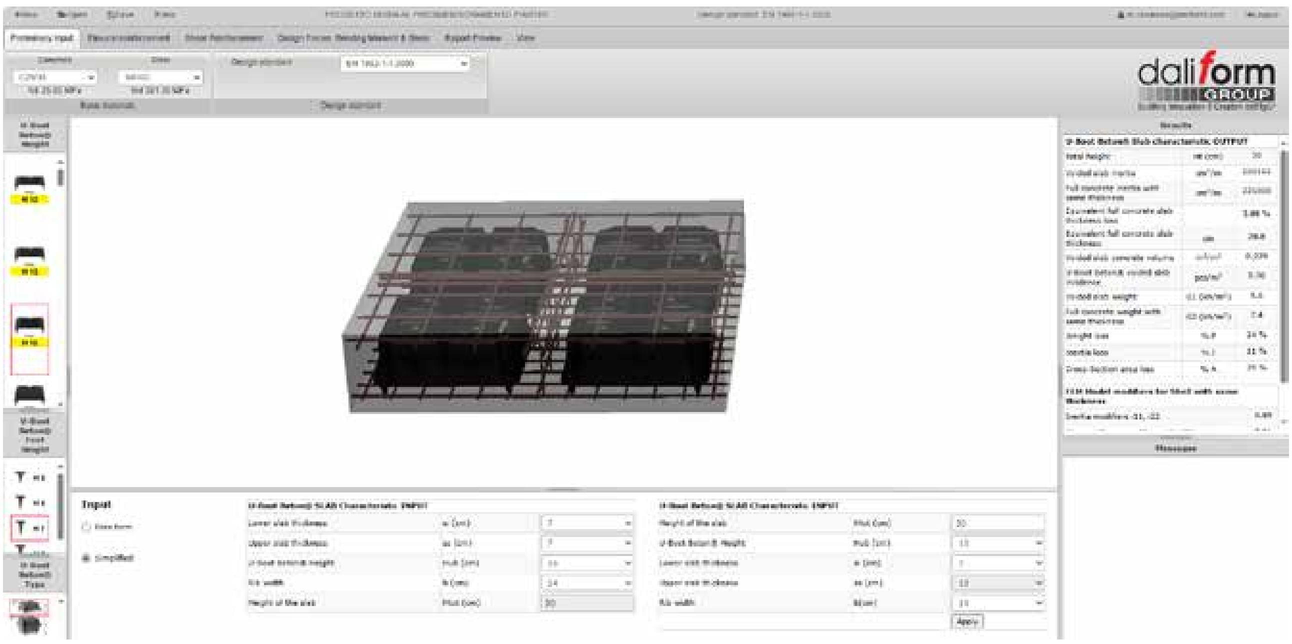
$$S_{min} = C_{min} + 2 \cdot ø + C_{(min,b)} = 3 + 2{,}4 + 1{,}2 = 6{,}6\ cm$$

A lower slab of 7 cm is therefore used.

To determine the width of the rib, we can first consider a value that ensures a ratio between the height of the floor slab and the width of the rib that varies between 2 and 2.5; in our case we can consider:

$$H/2{,}2 \text{ in this case: } 30\ cm / 2{,}2 = 13{,}6\ cm \rightarrow 14\ cm.$$

Having defined all the parameters of one of the possible solutions for lightening a 30 cm panel, we proceed to define the typical cross-section in the software:



Main screen of the U-Boot® Beton Design Software. In the ribbon bar you can find the tabs, organized from left to right in the successive steps of process development. At the bottom there is the interface for the cross-section input, which can be selected in free or simplified form, while in the right column there are the results related to the U-Boot® slab properties and modifiers for the FEM model. Iin the bottom right-hand column there is a box with eventually warnings about what has been entered.

U-Boot Beton® SLAB Characteristic INPUT		
Height of the slab	Htot (cm)	30
U-Boot Beton® Height	Hub (cm)	13
Lower slab thickness	si (cm)	7
Upper slab thickness	ss (cm)	10
Rib width	b(cm)	14
		Apply

INPUT Floor characteristics
Thanks to the simplified input interface, it is possible to define the characteristics of the lightened section of the floor, starting from the total thickness.
Once the total height is known, the thickness of the lower slab can be defined and the software automatically proposes a solution for the type of lightening to be used and the thickness of the upper slab.

4. CHECK ON PUNCHING

One of the sizing criteria for solid slabs, and therefore for lightened slabs, is the punching check; it is therefore useful to carry out a check to confirm the correctness of the chosen thickness.

Assuming that we are going to lighten 70% of the slab, the on-line software will allow us to obtain the dead weight of the lightened areas for the chosen solution:

U-Boot Beton® Slab characteristic OUTPUT		
Total height	Ht (cm)	30
Voided slab inertia	cm^4/m	200165
Full concrete inertia with same thickness	cm^4/m	225000
Equivalent full concrete slab thickness loss		3.86 %
Equivalent full concrete slab thickness	cm	28.8
Voided slab concrete volume	m^3/m^2	0.229
U-Boot Beton® voided slab incidence	pcs/m^2	2.30
Voided slab weight	G1 (kN/m^2)	5.6
Full concrete weight with same thickness	G2 (kN/m^2)	7.4
Weight loss	% P	24 %
Inertia loss	% I	11 %
Cross-Section area loss	% A	39 %

FEM Model modifiers for Shell with same thickness	
Inertia modifiers i11, i22	0.89
Shear stiffness modifiers t13, t23	0.61
Weight modifier	0.76

OTPUT: Characteristics of the U-Boot® slab. *In the right column of the initial page of the software, this window allows gives the essential data to proceed with the structural calculation.*
The weight of the lightened zone can be determined, as well as the reduction with respect to a solid plate of equivalent thickness.
The values of the inertia modifiers to be used in the subsequent phases of the project are then calculated and returned within the calculation software.

This gives the average weight of the plate:

$$P_m = 5{,}6 \cdot 0{,}7 + 7{,}4 \cdot 0{,}3 = 6{,}14\ kN/m^2$$

Note: In order to calculate a P_{ed} value for the first trial, we assume that 70% of the area is bright and 30% is dark (typical values for this type of structure).

You can then evaluate V_{ed} on the pillar:

$$P_{ed} = (1{,}3 \cdot 6{,}14 + 1{,}3 \cdot 2 + 1{,}5 \cdot 3) \cdot (8 \cdot 8) = 965\ kN$$

$$V_{ed} = \frac{(ß \cdot P_{ed})}{(U_i \cdot d)} = \frac{(1{,}15 \cdot 965)}{(16 \cdot 25{,}8)} = 2{,}69 \frac{N}{mm^2}$$

The maximum shear/puncture resistance at the control perimeter is:

$$V_{rd,max} = 0{,}4 \cdot \nu \cdot f_{cd}$$

With ν=0,5 up to class C70/85

So:

$$V_{rd,max} = 2{,}83 \frac{N}{mm^2} > V_{ed}$$

so that the thickness chosen is appropriate.

5. DETERMINATION OF FULL AND LIGHTENED ZONES

The basic principle is that the size of the solid zone is at least 2 times the useful height, and in any case the verification perimeter U_{out} extends all the way to the solid zone (EC2 6.4.5 (4)). According to:

$$U_{out} = \frac{ß \cdot V_{ed}}{\nu_{rd,c} \cdot d} = 712{,}64\ cm$$

This results in a minimum width of the solid zone C of more than 227 cm.

With the 66 cm spacing between formworks, a plausible size of the solid area could be:

$$C = I \cdot nub + T = 66 \cdot 4 + 14 = 278\ cm > 227\ cm$$

Note: *In general, C can also be derived from the maximum span, allowing for a drop expansion of approximately 35%:*
$C = 0{,}35 \cdot L_{max} = 0{,}35 \cdot 800 = 280\ cm \approx 278\ cm$

6. DETERMINATION OF DESIGN STRESSES

The behaviour of a lightened plate subjected to vertical loads can be simulated and analysed in various ways, in a more or less simplified way. In the following example and for structural analyses, one of the main references is to model the elements in fem software as bidirectional 'plates'.

This type of modelling is the simplest and quickest and the results are easy to analyse; however, attention must be paid to the delimitation of the lightened zones and to the management of the results in the most critical areas (full-lightened zone transitions and nodes on vertical supports).

To take into account the voids in the plate, it will be necessary to set some modifiers to the weight matrix, or otherwise assign to the lightened zone the weight of the plate.

This difference generally changes between different software, so it's not possible to generalize a solution; however, the quality of the results has no effect on the type of modifiers used.
The **U-Boot® Beton Design software** is used to determine the parameters for modifying the lightened zones; after entering the characteristics of the lightened section, it provides the parameters to be used for define the rafts.

U-Boot Beton® Slab characteristic OUTPUT			
Total height	H_t	[cm]	30
Voided slab inertia		[cm^4/m]	200.165
Full concrete inertia with same thickness		[cm^4/m]	225.000
Equivalent full concrete slab thickness loss			3,86 %
Equivalent full concrete slab thickness		[cm]	28,84
Voided slab concrete volume		[m^3/m^2]	0,23
U-Boot Beton® voided slab incidence		[pcs/m^2]	2,30
Voided slab weight	G_1	[kN/m^2]	5,61
Full concrete weight with same thickness	G_2	[kN/m^2]	7,36
Weight loss		% P	23,77
Inertia loss		% I	11,04
Cross-Section area loss		% A	38,80
FEM Model modifiers for Shell with same thickness			
Inertia modifier		i11, i22	0,89
Shear stiffness modifier		T13, T23	0,61
Weight modifier			0,76

Parameter	Value
Name	C25/30 LIGHTENED (EN1992-2)
Type	Concrete
Unit mass [kg/m3]	1900
E mod [MPa]	2,8014e+04
Poisson - nu	0.2
G mod [MPa]	0,8000e+04
fck(28) [MPa]	25,00
fcm(28) [MPa]	33,00
fcm(28) - fck(28) [MPa]	8,00
fctm(28) [MPa]	2,28
fctk 0,05(28) [MPa]	1,60
fctk 0,95(28) [MPa]	2,97

Example of the insertion of modified parameters in a calculation software.
In this case, where SCIA Engineering was used, we proceed with the creation of a fictitious material to be assigned to the brightened areas of the plate.
In particular, we will highlight the modification of the density, the modulus of elasticity (E) and the parameters related to the tensile strength of the material: fctm, fctk

As can be seen from the summary table above, which is typical of the input of a material into a calculation programme, the FEM modifiers obtained from the **U-Boot® Beton Design Software** are used to modify the parameters:

$$E_{mod} = E \cdot i11 = 31476 \cdot 0{,}89 = 28014\ MPa$$

$$\gamma_{ub} = 2500 \cdot 0{,}76 = 1900\ kg/m^3$$

$$G_{mod} = G \cdot T13 = 13115 \cdot 0{,}61 = 8000\ MPa$$

$$f_{ctm,\ mod} = f_{ctm} \cdot 0{,}89 = 2{,}56 \cdot 0{,}89 = 2{,}28\ MPa$$

Once the correct parameters have been set for the zones where u-boot are placed, the calculation model can be managed in the same way as a solid plate and the calculation stresses can then be derived.
The following are the design moment and shear values for the example proposed in this guide.

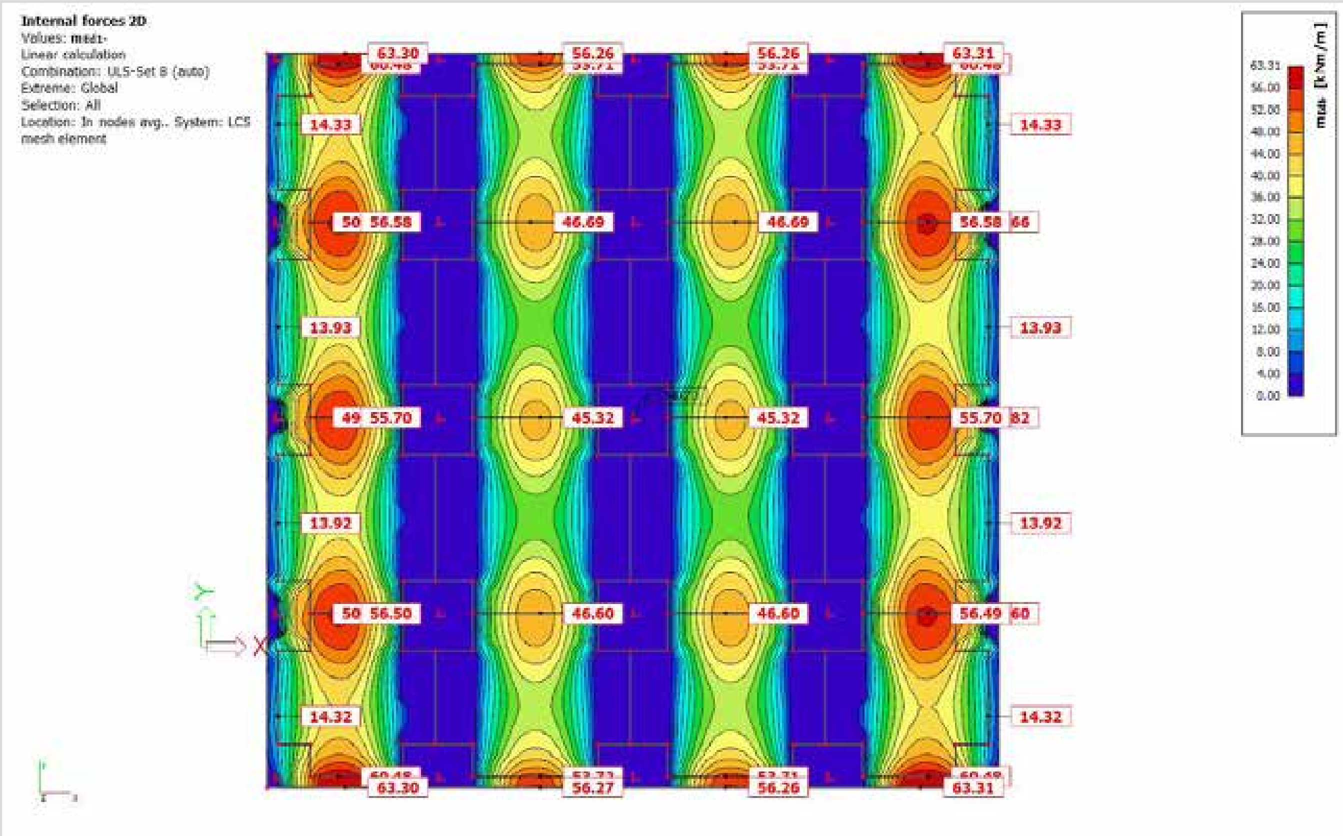


Figure 1 M_{ed} lower X

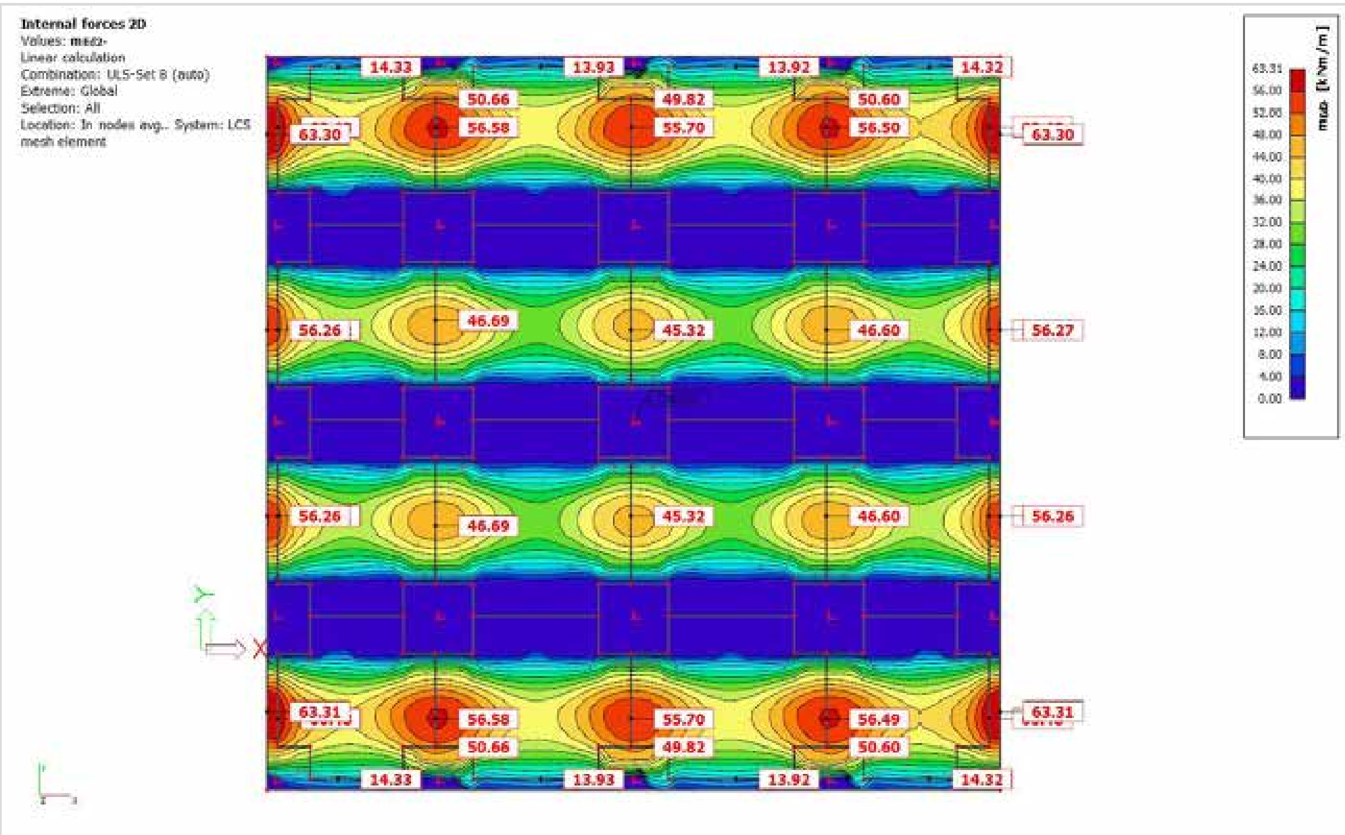


Figure 2 M_{ed} lower Y

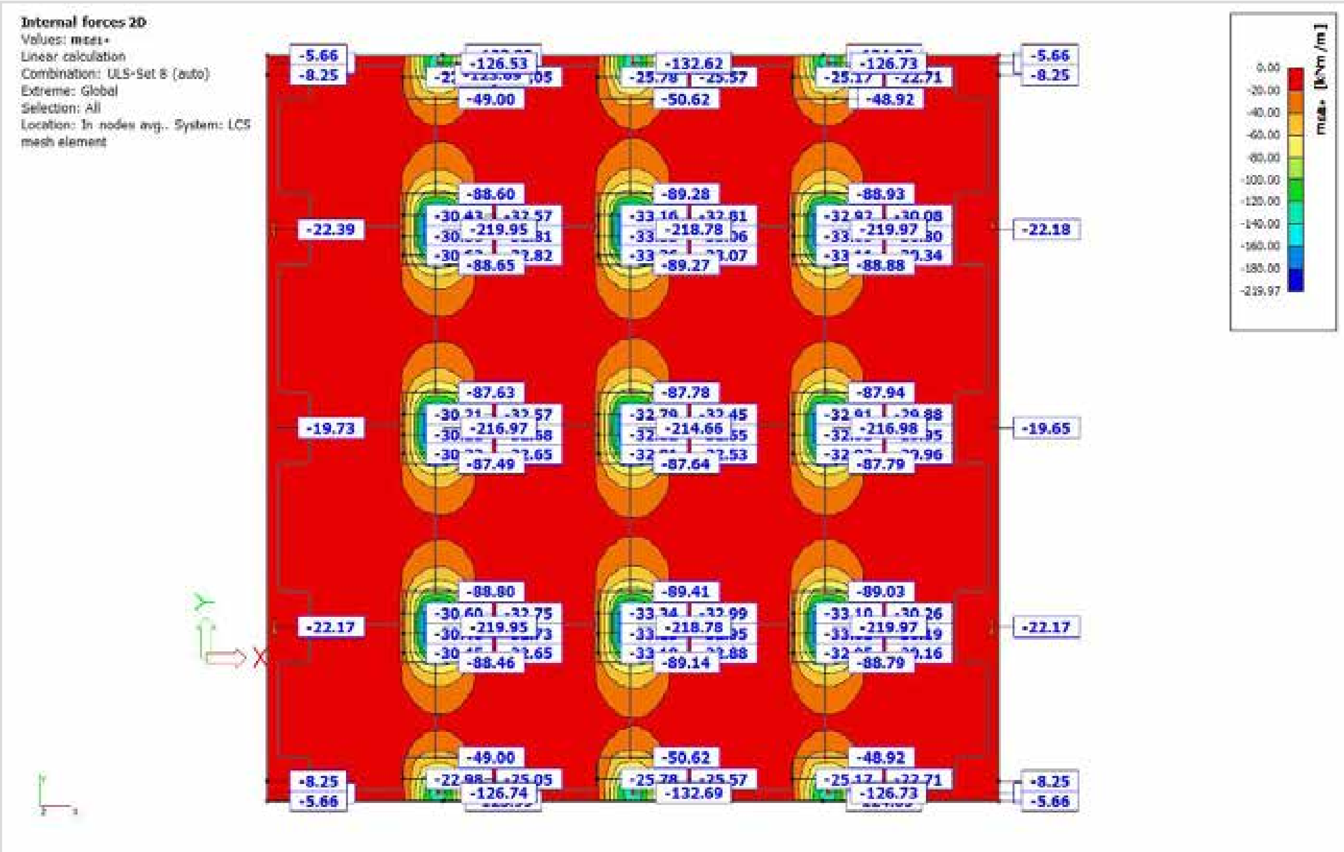


Figure 3 M_{ed} upper X

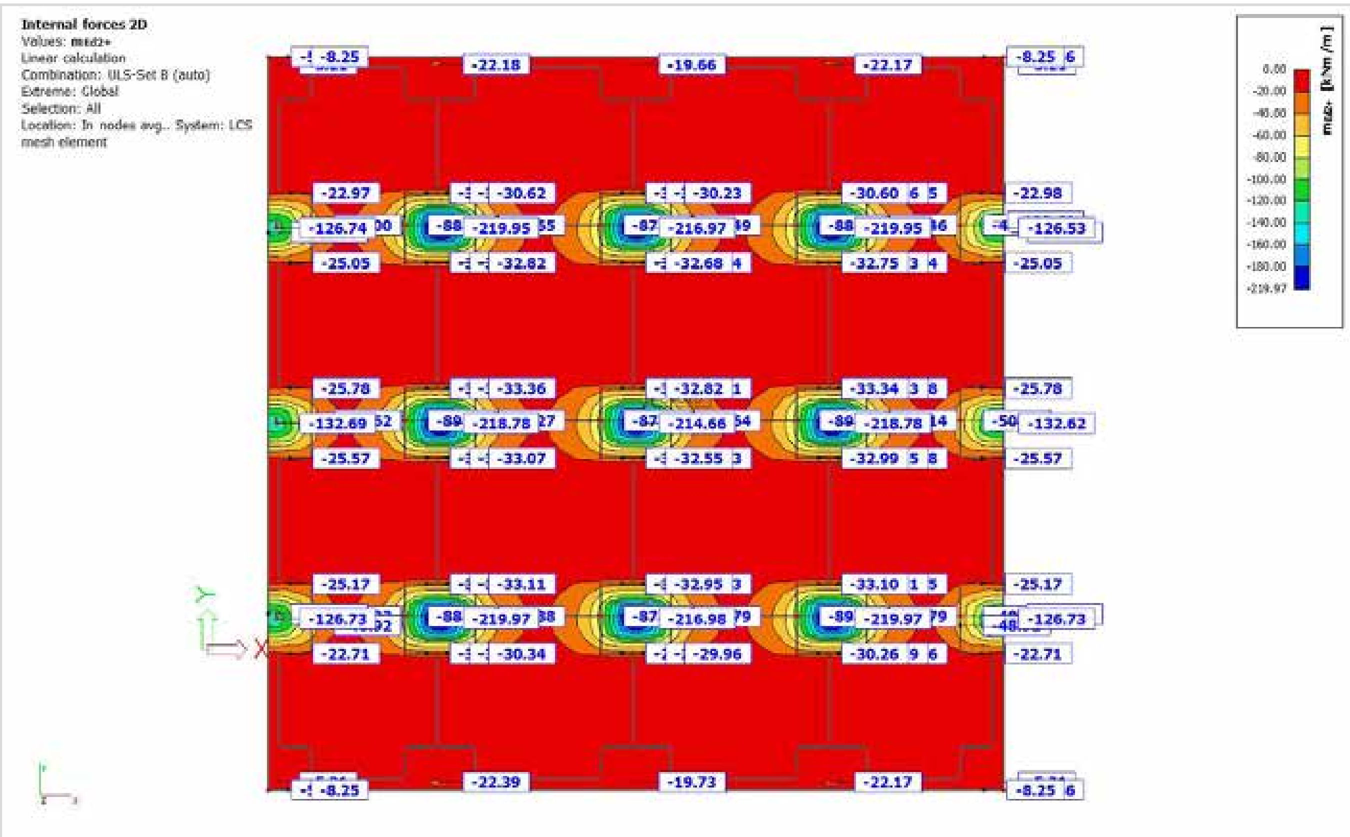


Figure 4 M_{ed} upper Y

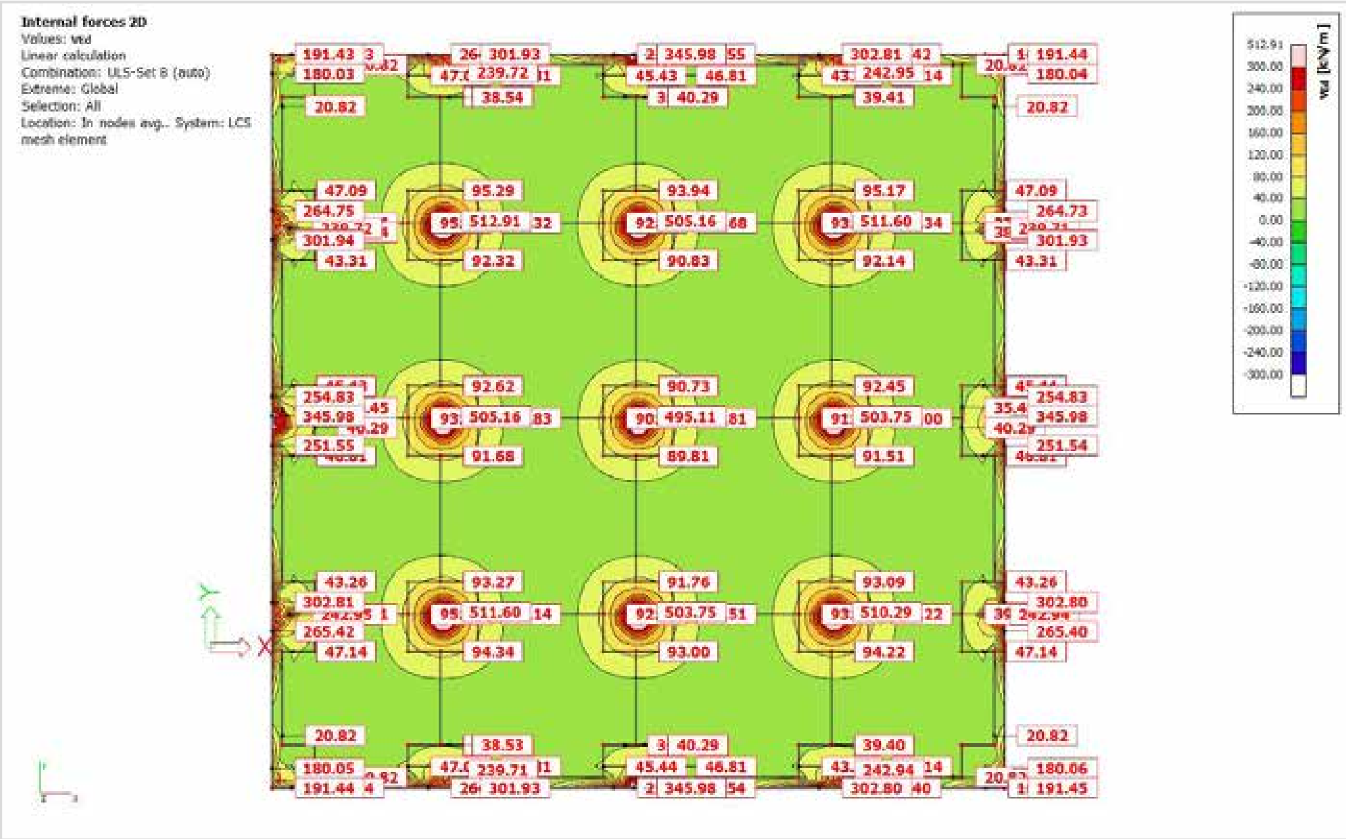


Figure 5 stress shear V_{ed}

To summarise the previous figures, a table of maximum stress values by zone is given:

		Med X	Med Y	Ved
		kNm/m	kNm/m	kNm/m
Lightened span	Lower	64	64	94
Lightened zone	Upper	90	90	94
Full zone	Upper	220	220	

7. DEFINITION OF THE REINFORCEMENT IN LIGHTENED ZONES

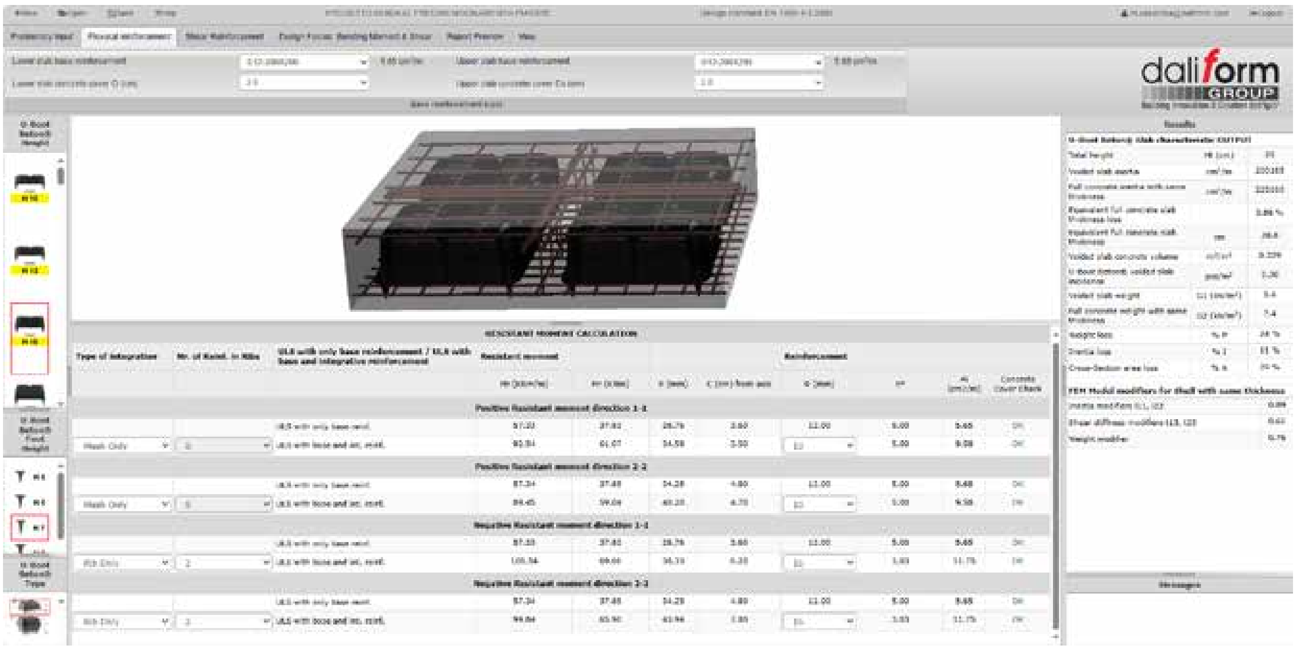
Once the maximum values of the design stresses have been defined, as with the design of any structural element, it is necessary to dimension the reinforcement in order to check the section. In this case too, you can use the **U-Boot® Beton Design Software**, which allows you to dimension the required reinforcement in a simple and intuitive way.

Proceed as follows in relation to the suggested example:

- Lower and upper diffuse reinforcement: Φ 12 mm spacing 20 cm;
- Lower integrations (if necessary): Φ 10 mm on 20 cm grid,
- Upper integrations (if required): 2 bars of Φ 16 mm per rib (reinforcement placed inside the beams);
- Shear reinforcement: single bent bars Φ10 mm at 20 cm spacing

Additional bending reinforcement, both top and bottom, should only be used in those areas of the slab where the strength of the base reinforcement alone is insufficient.

For shear reinforcement, bars should only be placed in areas where the strength is insufficient without specific reinforcement.



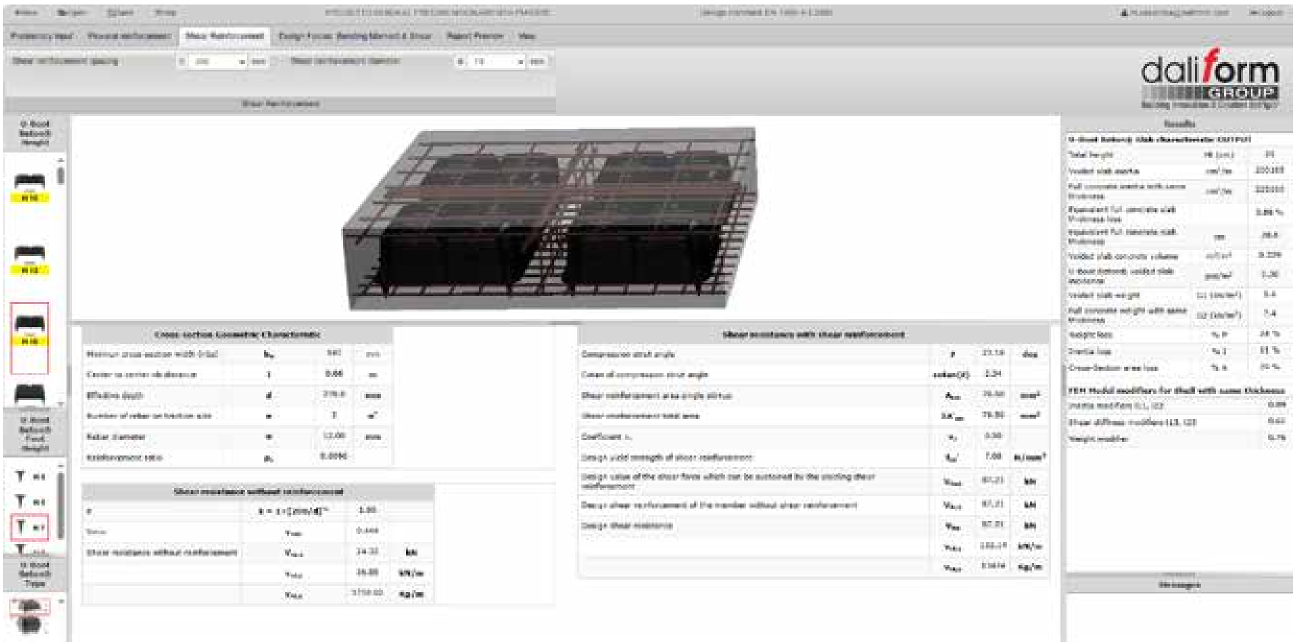
U-Boot® Concrete Design Software - Step 2: *Define the design bending reinforcement.*
In the Bending Reinforcement and Shear Reinforcement tabs, it is possible to provide all types of reinforcement to be provided, either distributed or additional.
The resisting moment value is automatically calculated for the main calculation directions 1-1 and 2-2, taking into account that the reinforcement can be inserted differently in the two directions.
At this stage, in addition to the diameter and pitch of the bars, it is also checked whether the reinforcement is superimposed and whether the concrete cover is respected.

Lower slab base reinforcement	Φ12-200X200	5.65 cm²/m	Upper slab base reinforcement	Φ12-200X200	5.65 cm²/m
Lower slab concrete cover Ci (cm)	3.0		Upper slab concrete cover Cs (cm)	3.0	
Base reinforcement input					

By setting the design concrete cover in the top bar, you can easily set the diffuse reinforcement in the bottom and top slabs.

RESISTANT MOMENT CALCULATION										
Type of integration	Nr. of Reinf. in Ribs	ULS with only base reinforcement / ULS with base and integrative reinforcement	Resistant moment				Reinforcement			
			Mr (KNm/m)	Mr (KNm)	X (mm)	C (cm) from axis	Φ (mm)	n°	Ai (cm2/m)	Concrete Cover Check
Positive Resistant moment direction 1-1										
		ULS with only base reinf.	57.33	37.83	28.76	3.60	12.00	5.00	5.65	OK
Mesh Only	0	ULS with base and irt. reinf.	92.54	61.07	34.58	3.50	10	5.00	9.58	OK
Positive Resistant moment direction 2-2										
		ULS with only base reinf.	57.34	37.85	34.25	4.80	12.00	5.00	5.65	OK
Mesh Only	0	ULS with base and irt. reinf.	89.45	59.04	40.20	4.70	10	5.00	9.58	OK
Negative Resistant moment direction 1-1										
		ULS with only base reinf.	57.33	37.83	28.76	3.60	12.00	5.00	5.65	OK
Rib Only	2	ULS with base and irt. reinf.	105.54	69.66	38.33	6.20	16	3.03	11.75	OK
Negative Resistant moment direction 2-2										
		ULS with only base reinf.	57.34	37.85	34.25	4.80	12.00	5.00	5.65	OK
Rib Only	2	ULS with base and irt. reinf.	99.84	65.90	43.94	7.80	16	3.03	11.75	OK

The lower window is used to enter any additions to be inserted in the lightened area. The additions can be of two types: diffuse or in ribs. This depends on the required diameter of the bar and, so on the respect of the concrete cover and overlay. The software outputs the value of the positive and negative resisting moment, separated in the two main directions of the calculation.

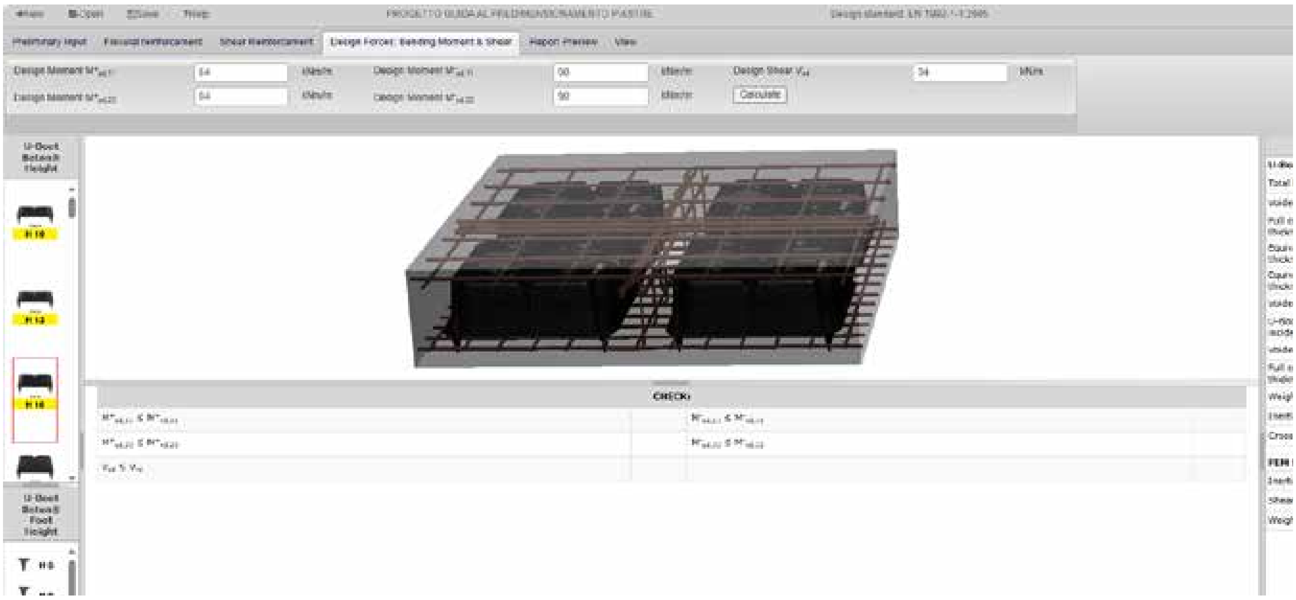


U-Boot Beton Design Software - Step 3: *Set the design shear reinforcement.*
In this window, as for bending reinforcement, the shear reinforcement can be defined. The software allows to set typical shear reinforcements, i.e. bent bars with hooks, for which the pitch and diameter can be defined. The shear resistance values without shear reinforcement (Vrd,c) and with specific reinforcement (Vrd,s) are output at the bottom of the table.

Shear reinforcement spacing	S	200	mm	Shear reinforcement diameter	Φ	10	mm
Shear Reinforcement							

The top bar defines the reinforcement spacing, i.e. the distance between two consecutive bars and their diameter.

Once the bending and shear reinforcements for the lightened zones have been defined, the stresses obtained from modelling the plate are entered and the cross-section is set to be verified:

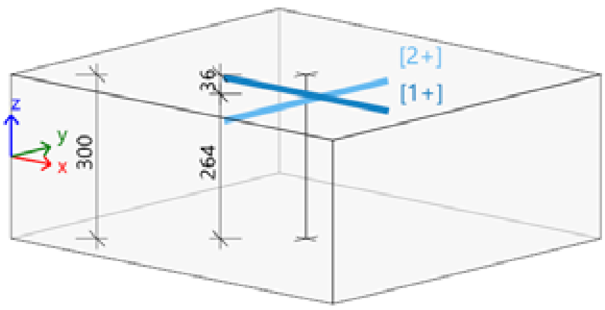


U-Boot® Beton Design Software - step 4: *Section verification.*
In the fourth tab, after setting the reinforcement in the previous steps, the stressing actions are compared with the resistance values in order to check whether the planned reinforcement is sufficient or not. The stress values to be considered in this case will be the maximum values for the lightened zones only.

8. FULL CONCRETE ZONES CHECK

As far as maximum negative deflection and punching are concerned, being within the solid zone, the same applies as for a solid plate.

Plate S1	**h=300 mm**
EC EN 1992-1-1:2004/AC:2008	Node 1492/1491 [X= 25,318, Y=1,452, Z=0,000 m]



Design width: b = 1.0 m

Concrete: C25/30(EN1992-2)
Bi-linear stress-strain diagram
Exposure class: XC3
Cover: 30 mm

Reinforcement: B 450C
Bi-linear with an inclined top branch
[1+] ϕ12,0/200 + ϕ18,0/100
[2+] ϕ12,0/200 + ϕ18,0/100

Longitudinal reinforcement

Designed reinforcement layers (in direction from the member local x axis):

	Basic	Additional		α	$A_{s,min}$	$A_{s,ult}$	$\Delta A_{s,serv}$	$A_{s,req}$	$A_{s,prov}$	$A_{s,max}$	$s_{min(cl)}$	s_{max}	Status
		User	Auto	[°]	[mm²]	[mm²]	[mm²]	[mm²]	[mm²]	[mm²]	[mm]	[mm]	
[1+]	ϕ12,0/200	ϕ18,0/100	---	0,0	397	2686	---	**2686**	**3110**	12000	57	67	**OK**
								0,90%	1,04%		≥37	≤400	
[2+]	ϕ12,0/200	ϕ18,0/100	---	90,0	379	2847	---	**2847**	**3110**	12000	57	67	**OK**
								0,95%	1,04%		≥37	≤400	

Ultimate limit state (ULS)

Bending with/without axial force (in direction of the reinforcement layers)

	Case	α_s [°]	$d_{s,ref}$ [mm]	m_{Ed} [kNm]	n_{Ed} [kN]	d [mm]	x [mm]	z [mm]	F_{cd} [kN]	F_{sd} [kN]	$A_{s,ult}$ [mm²]
[1+]	ULS-Set B (auto)/2	0,0	ϕ12	**-219,85**	**251,48**	264,0	64,0	239,1	-799,5	1051,0	**2686**
[2+]	ULS-Set B (auto)/2	90,0	ϕ12	**-219,85**	**251,48**	252,0	69,0	225,2	-862,5	1113,9	**2847**

ULS-Set B (auto)/2	1.30*LC1+1.30*LC2+1.50*LC3

Figure 8 Bending check on full concrete zone

Punching check:

Punching case	Punching shape	$UC_{vRd,max}$ [-]	$UC_{vRd,c}$ [-]	Shear reinforcement perimeters	$UC_{vRd,cs}$ [-]	$UC_{Asw,det}$ [-]	UC [-] Check
Internal column	Rectangle (400;400)	**0,75**	**1,27**	3x 11Ø10(radial) 120+2x140=400	**0,85**	**0,93**	0,93 OK, BUT

Concrete:

Punching case β [-]	Punching shape	V_{Ed} [kN] ΔV_{Ed} [kN]	Plate h [mm]	Material f_{cd} [MPa]	d_{eff} [mm] ρ_l [%]	u_0 [m] u_1 [m]	$V_{Ed,u0}$ [MPa] $V_{Ed,u1}$ [MPa]	$V_{Rd,max}$ [MPa] $V_{Rd,c}$ [MPa]	$UC_{vRd,max}$ [-] $UC_{vRd,c}$ [-]
Internal column 1,15	Rectangle (400;400)	**971,32** 0,00	Ceiling 300,00	C25/30(EN1992-2) 16,67	258,00 1,21	1,600 4,842	2,71 0,89	3,60 0,70	**0,75** **1,27**

With Reinforcement:

Shear reinforcement perimeters	u_{out} [m] a_{out} [mm]	$s_{t,u1}$ [mm] $s_{t,out}$ [mm]	Control perimeters (distance/capacity)	Material $f_{ywd,ef}$ [MPa]	$A_{sw,req}$ [mm²] $A_{sw1,min}$ [mm²]	A_{sw} [mm²] $A_{sw,tot}$ [mm²]	$V_{Rd,cs}$ [MPa] $k_{max}V_{Rd,c}$ [MPa]	$UC_{vRd,cs}$ [-] $UC_{Asw,det}$ [-]
3x 11Ø10(radial) 120+2x140=400	6,165 728	374 374	516/85%	B 450C 314,5	528 31	864 **2592**	1,13 1,05	**0,85** **0,93**

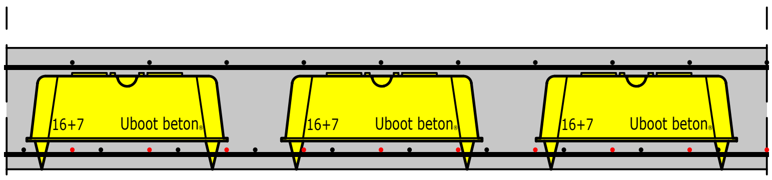
The proposed solution for lightening the load is therefore verified.

9. TYPICAL DETAILS OF FITTINGS

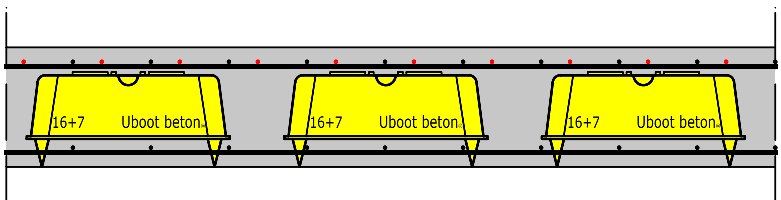
Once the structural analysis has been completed and the reinforcements required to satisfy the bending, shear and punching checks have been defined, the execution details for the construction on site must be provided.

The presence of plastic formwork must be taken into account when defining the reinforcement details of the lightened zones, and therefore some typical tips and tricks to be applied at this stage are given below.

Bending reinforcement

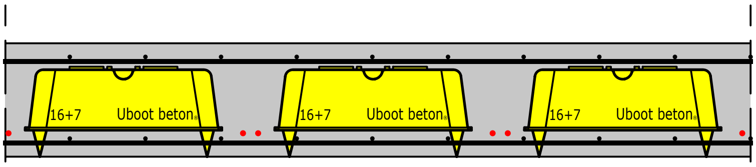


Detail 1 - Flexural reinforcement with integrations of equal diameter in the lower slab

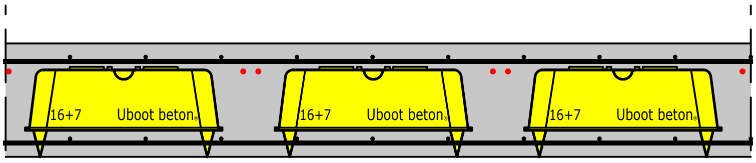


Detail 2 - Bending reinforcement with integrations of equal diameter in the upper slab

When defining the flexural reinforcement in the U-boot formwork areas, particular attention must be paid to the bar diameters in order to maintain the minimum concrete cover and bar overlap.
Where the base reinforcement is insufficient to ensure that the checks are satisfied, it will be necessary to position the reinforcements, which, depending on the diameter of the bars, can be positioned either in the lower and upper slabs (details 1 and 2) or inside the beams (details 2 and 3).

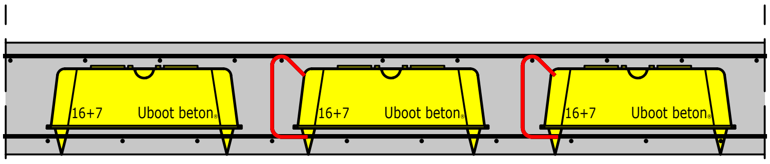


Detail 3 - Flexural reinforcement with rib additions

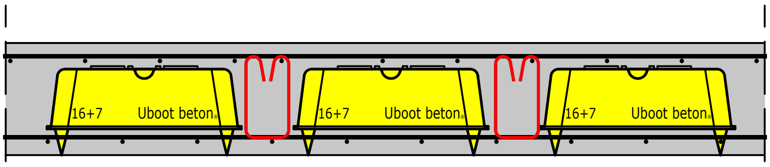


Detail 4 - Flexural reinforcement with rib additions

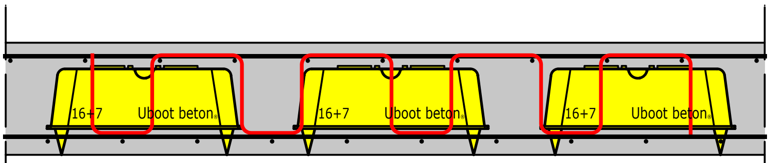
Shear reinforcement



Detail 5 - Shear reinforcement with bent bars



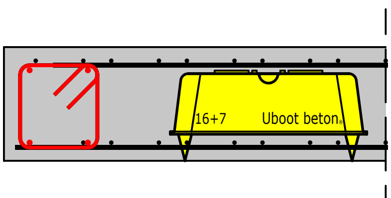
Detail 6 - Shear reinforcement with stirrups



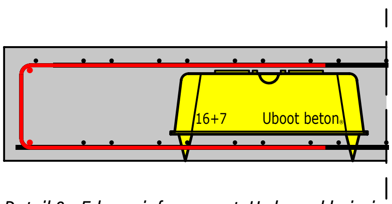
Detail 6 - Shear reinforcement with corrugated bars

In lightened zones where it is necessary to add specific reinforcement for shear stresses, there are basically 3 ways to proceed. The first (detail 5) is to insert "pins" in the ribs, i.e. 1 arm reinforcements at a distance defined by calculation. Alternatively, typical stirrups can be placed (detail 6), connected to the base reinforcement. A third option is to use pre-fabricated reinforcement that can be attached to the upper base reinforcement, making this step very quick on site.

Curbs and forometries



Detail 7 – Edge reinforcement: stirrups



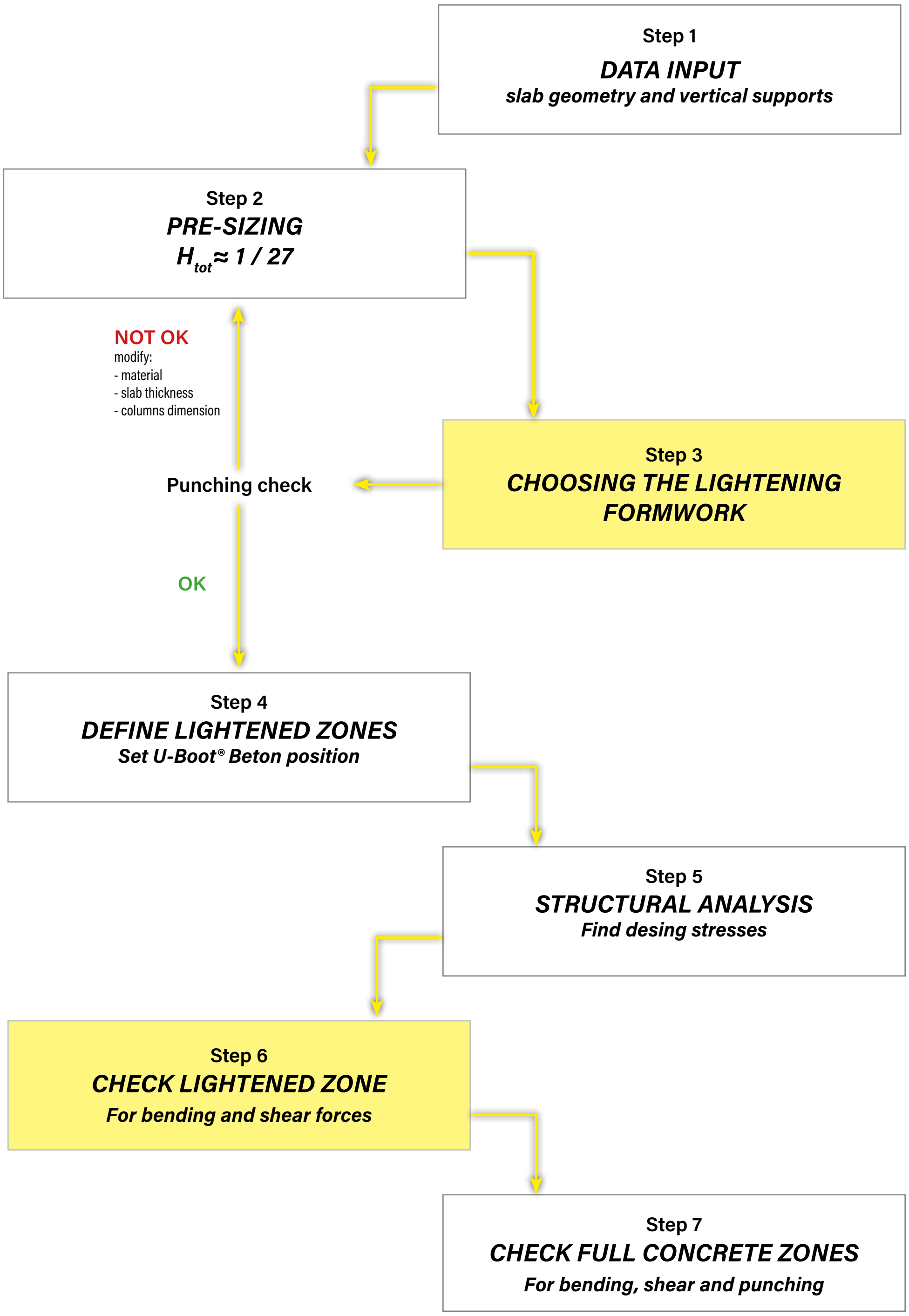
Detail 8 - Edge reinforcement: U shaped hairpin

An important aspect in the design and construction of slabs, whether solid or lightweight, is the reinforcement for openings and edges. Typical and commonly used details are those relating to stirrups with stirrups or U shaped hairpins

CONCLUSIONS

The use of lightweight slabs with U-Boot® Beton not only improves structural performance, but also contributes to more sustainable and cost-effective construction, meeting today's demands for efficiency and environmental friendliness.
With this guide, we want to give back to the wide audience of designers who want to take advantage of this construction method, by defining the main steps of the pre-sizing and design process.

To summarize the whole process, the following flow chart is suggested:



*yellow boxes provide for the use of U-Boot® Beton Design Software www.daliform.com

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