INDEX

1.- DESCRIPTION......................................................................................................................... 2

2.- CHECKS............................................................................................................................... 2
   2.1.- Perimeter of the support (P5).......................................................................................... 2
       2.1.1.- Zone adjacent to the support or load (non-seismic combinations)......................... 2
   2.2.- Critical perimeter (P5).................................................................................................... 4
       2.2.1.- Zone with punching shear reinforcement (non-seismic combinations)............... 4
   2.3.- Punching shear reinforcement perimeter (P5)............................................................... 6
       2.3.1.- External zone to the punching shear reinforcement (non-seismic combinations). 6
   2.4.- Additional reinf. (P5)....................................................................................................... 8
       2.4.1.- Punching shear reinforcement (EN 1992-1-1:2004/AC:2008, 9.4.3(2))
                (non-seismic combinations).................................................................................. 8
       2.4.2.- Clear distance between two isolated consecutive bars......................................... 8
       2.4.3.- Distance between the support's face and the first punching shear reinforcement.. 9
       2.4.4.- Distance between transverse consecutive reinforcement perimeters................... 9
       2.4.5.- Distance between two consecutive reinforcements in peripheral direction......... 9
1.- DESCRIPTION

Calculation of the punching shear perimeters

<table>
<thead>
<tr>
<th>Perimeter of the support (P5)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_0$</td>
<td>1200 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Critical perimeter</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>3899 mm</td>
</tr>
<tr>
<td>$x_0$</td>
<td>2000 mm</td>
</tr>
<tr>
<td>$y_0$</td>
<td>2000 mm</td>
</tr>
<tr>
<td>$W_{xx}$</td>
<td>15351.7 cm²</td>
</tr>
<tr>
<td>$W_{yy}$</td>
<td>15351.7 cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Punching shear reinforcement perimeter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{out,ef}$</td>
<td>3440 mm</td>
</tr>
<tr>
<td>$x_0$</td>
<td>2000 mm</td>
</tr>
<tr>
<td>$y_0$</td>
<td>2000 mm</td>
</tr>
<tr>
<td>$W_{out,ef,x}$</td>
<td>18960.1 cm²</td>
</tr>
<tr>
<td>$W_{out,ef,y}$</td>
<td>18960.1 cm²</td>
</tr>
</tbody>
</table>

2.- CHECKS

2.1.- Perimeter of the support (P5)

2.1.1.- Zone adjacent to the support or load (non-seismic combinations)

The worst case design forces occur for load combination 1.35·SW+1.35·DL+1.5·Qa.
The following criteria must be satisfied:

$$0.98 \text{ MPa} \leq v_{Ed} \leq 4.50 \text{ MPa}$$

Where:

- $v_{Ed}$: Design value of the sheer stress along the control section considered.
- $v_{Ed,max}$: Design value of the maximum punching shear resistance along the control section considered.

The design value of the shear stress along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.5):

$$v_{Ed} = \left| \frac{\beta \cdot V_{Ed}}{u_0 \cdot d} \right|$$

Where:

- $V_{Ed}$: Design value of the applied shear force.
- $\beta$: Coefficient which takes into account the effects of load eccentricity. (EN 1992-1-1:2004/AC:2008, 6.4.3).

$$\beta = 1 + k_x \cdot \frac{M_{xx}}{V_{Ed}} \cdot \frac{u_{xx}}{W_{xx}} + k_y \cdot \frac{M_{yy}}{V_{Ed}} \cdot \frac{u_{yy}}{W_{yy}}$$

<table>
<thead>
<tr>
<th>$v_{Ed}$</th>
<th>0.98 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{Ed,max}$</td>
<td>4.50 MPa</td>
</tr>
</tbody>
</table>

Verification of the ultimate punching shear resistance
Definition of the ultimate punching shear resistance

- $k_x$: Coefficient which depends on the relationship between the dimensions $c_y$ (dimension in direction of the y-axis) and $c_x$ (dimension in direction of the x-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).
- $k_y$: Coefficient which depends on the relationship between the dimensions $c_x$ (dimension in direction of the x-axis) and $c_y$ (dimension in direction of the y-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).

- $M_{Edx}$: Design moment around the x-axis, regarding the center of gravity of the critical perimeter $u_1$.
  \[ M_{Edx} = M_{EdOx} + V_{Ed} \cdot y_G \]

- $M_{Edy}$: Design moment around the y-axis, regarding the center of gravity of the critical perimeter $u_1$.
  \[ M_{Edy} = M_{EdOy} - V_{Ed} \cdot x_G \]

- $M_{EdOx}$: Design moment around the x-axis, regarding the center of gravity of the column.
- $M_{EdOy}$: Design moment around the y-axis, regarding the center of gravity of the column.

- $x_G$: x-coordinate of the center of gravity of the $u_1$ critical perimeter regarding the center of the column.
- $y_G$: y-coordinate of the center of gravity of the $u_1$ critical perimeter regarding the center of the column.


\[ W_{lx} = \int_0^{u_1} |e_x| \cdot dl \]
\[ W_{ly} = \int_0^{u_1} |e_y| \cdot dl \]
\[ e_x \]: Distance from dl to the axis where the moment $M_{Edx}$ acts about.
\[ e_y \]: Distance from dl to the axis where the moment $M_{Edy}$ acts about.

- $u_0$: Verification critical punching shear perimeter of the area adjacent to the support or load (EN 1992-1-1:2004/AC:2008, 6.4.5).

The design value of the maximum punching shear resistance along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.5):

\[ v_{Rd,max} = 0.5 \cdot v \cdot f_{cd} \]
\[ v = 0.6 \left( 1 - \frac{f_{ck}}{250} \right) \]

Where:
- $f_{ck}$: Concrete compressive strength.
- $f_{cd}$: Design value of the concrete compression force in the direction of the longitudinal member axis.
2.2.- Critical perimeter (P5)

2.2.1.- Zone with punching shear reinforcement (non-seismic combinations)

The worst case design forces occur for load combination 1.35·SW+1.35·DL+1.5·Qa. The following criteria must be satisfied:

\[ V_{Ed} \leq V_{Rd,cs} \]

Where:

- \( V_{Ed} \): Design value of the shear stress along the control section considered.
- \( V_{Rd,cs} \): Design value of the punching shear resistance of a slab with punching shear reinforcement along the control section considered.

\[ 0.30 \text{ MPa} \leq 0.62 \text{ MPa} \]

The design value of the shear stress along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.3):

\[ V_{Ed} = \frac{\beta \cdot V_{Ed}}{u_i \cdot d} \]

Where:

- \( V_{Ed} \): Design value of the applied shear force.
- \( \beta \): Coefficient which takes into account the effects of load eccentricity. (EN 1992-1-1:2004/AC:2008, 6.4.3).

\[ \beta = 1 + k_x \cdot \frac{|M_{Edx}|}{V_{Ed}} \cdot \frac{u_i}{W_{Ix}} + k_y \cdot \frac{|M_{Edy}|}{V_{Ed}} \cdot \frac{u_i}{W_{Iy}} \]

- \( k_x \): Coefficient which depends on the relationship between the dimensions \( c_y \) (dimension in direction of the y-axis) and \( c_x \) (dimension in direction of the x-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).
- \( k_y \): Coefficient which depends on the relationship between the dimensions \( c_x \) (dimension in direction of the x-axis) and \( c_y \) (dimension in direction of the y-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).

\[ M_{Edx} \]: Design moment around the x-axis, regarding the center of gravity of the critical perimeter \( u_i \).

\[ M_{Edy} = M_{Edy} + V_{Ed} \cdot y_G \]

\[ M_{Edy} \]: Design moment around the y-axis, regarding the center of gravity of the critical perimeter \( u_i \).

\[ M_{Edx} = M_{Edx} - V_{Ed} \cdot x_G \]

\[ M_{Edy} \]: Design moment around the x-axis, regarding the center of gravity of the column.

\[ M_{Edy} \]: Design moment around the y-axis, regarding the center of gravity of the column.

\[ x_G \]: x-coordinate of the center of gravity of the \( u_i \) critical perimeter regarding the center of the column.

\[ y_G \]: y-coordinate of the center of gravity of the \( u_i \) critical perimeter regarding the center of the column.


\[ W_{Ix} = \int_0^{u_i} |e_x| \cdot dl \]

\( dr \): Differential element of the critical perimeter length.
Verification of the ultimate punching shear resistance

\( e_x \): Distance from dl to the axis where the moment \( M_{ex} \) acts about.

\[ W_{ex} = \int |e_x| \cdot dl \]

\( W_{ty} \): Distance from dl to the axis where the moment \( M_{ty} \) acts about.

\( d \): Nominal depth of the slab.

The design value of the punching shear resistance of a slab with punching shear reinforcement along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.5):

\[ v_{Rd,cs} = 0.75 \cdot v_{Rd,c} + 1.5 \cdot \sum \left( \frac{A_{pm} \cdot f_{yd,ef} \cdot \sin \alpha}{u_i} \right) \]

where:

\[ v_{Rd,c} = \frac{0.18 \cdot k \cdot (100 \cdot \rho_i \cdot f_{ck})^{1/3}}{\gamma_c} + 0.1 \cdot \sigma_{cp} \]

with a minimum value of:

\[ v_{Rd,c,min} = 0.035 \cdot k^{3/2} \cdot f_{ck}^{1/2} + 0.1 \cdot \sigma_{cp} \]

where:

\( \gamma_c \): Concrete resistance reduction coefficient.

\( k \): Coefficient which depends on the nominal depth of 'd'.

\[ k = \left(1 + \frac{200}{d} \right) \leq 2 \]

\( f_{ck} \): Concrete compressive strength.

\( \rho_i \): Geometric steel area of the main tensile longitudinal reinforcement.

\[ \rho_i = \sqrt{\rho_{lx} \cdot \rho_{ly}} \leq 0.02 \]

where:

\( \rho_{lx} \): Ratio in X-direction.

\( \rho_{ly} \): Ratio in Y-direction.

\( \sigma_{cp} \): Average axial stress on the critical verification surface (positive compression), with a maximum value of \( \sigma_{cp,max} \).

\[ \sigma_{cp,max} = 0.20 \cdot f_{cd} \]

\( f_{cd} \): Design value of the concrete compression force in the direction of the longitudinal member axis.

The design value of the punching shear resistance of a slab with punching shear reinforcement along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.5):

\[ v_{Rd,cs} = 0.62 \text{ MPa} \]

<table>
<thead>
<tr>
<th>Reference</th>
<th>( A_{sw} ) (mm(^2))</th>
<th>( s_r ) (mm)</th>
<th>( \alpha ) (degrees)</th>
<th>( A_{sw}/s_r ) (cm(^2)/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 2</td>
<td>113</td>
<td>100</td>
<td>90.0</td>
<td>11.3</td>
</tr>
<tr>
<td>Beam 2</td>
<td>113</td>
<td>100</td>
<td>90.0</td>
<td>11.3</td>
</tr>
</tbody>
</table>
Verification of the ultimate punching shear resistance

\( f_{ywd,ef} \): Effective design strength of the punching shear reinforcement.
\( f_{ywd,ef} = 250 + 0.25 \cdot d \leq f_{ywd} \)

\( f_{ywd} \): Design yield strength of the shear reinforcement.
\( f_{ywd} = 0.8 \cdot f_{ywk} \)

(EN 1992-1-1:2004/AC:2008, 6.2.3(3))


\( f_{ywd,ef} \): 304.00 MPa
\( f_{ywd} \): 320.00 MPa
\( f_{ywk} \): 400.00 MPa

2.3.- Punching shear reinforcement perimeter (P5)

2.3.1.- External zone to the punching shear reinforcement (non-seismic combinations)

The worst case design forces occur for load combination 1.35·SW+1.35·DL+1.5·Qa.

The following criteria must be satisfied:

\[ 0.34 \text{ MPa} \leq 0.48 \text{ MPa} \]

Where:

- \( v_{Ed} \): Design value of the sheer stress along the control section considered.
- \( v_{Rd,c} \): Design value of the punching shear resistance of a slab without punching shear reinforcement along the control section considered.

The design value of the sheer stress along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.5):

\[ v_{Ed} = \frac{\beta \cdot V_{Ed}}{u_{out,ef} \cdot d} \]

Where:

- \( V_{Ed} \): Design value of the applied shear force.
- \( \beta \): Coefficient which takes into account the effects of load eccentricity. (EN 1992-1-1:2004/AC:2008, 6.4.3).

\[ \beta = 1 + k_x \cdot \frac{M_{Edx}}{V_{Ed}} \cdot \frac{u_{out,x}}{W_{out,x}} + k_y \cdot \frac{M_{Edy}}{V_{Ed}} \cdot \frac{u_{out,y}}{W_{out,y}} \]

- \( k_x \): Coefficient which depends on the relationship between the dimensions \( c_y \) (dimension in direction of the \( y \)-axis) and \( c_x \) (dimension in direction of the \( x \)-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).

- \( k_y \): Coefficient which depends on the relationship between the dimensions \( c_y \) (dimension in direction of the \( y \)-axis) and \( c_y \) (dimension in direction of the \( x \)-axis) of the column (EN 1992-1-1:2004/AC:2008, Table 6.1).

- \( M_{Edx} \): Design moment around the \( x \)-axis, regarding the center of gravity of the critical perimeter \( u_{out,ef} \).

\[ M_{Edx} = M_{Edx} + V_{Ed} \cdot y_G \]

- \( M_{Edy} \): Design moment around the \( y \)-axis, regarding the center of gravity of the critical perimeter \( u_{out,ef} \).

\[ M_{Edy} = 0.00 \text{ kN-m} \]

---

Produced by a version for internal use of CYPE
Verification of the ultimate punching shear resistance

\[ M_{Ed,y} = M_{Ed,y} - V_{ed} \cdot x_G \]

\( M_{Ed,y} \): Design moment around the x-axis, regarding the center of gravity of the column.

\[ M_{Ed,x} = M_{Ed,x} - V_{ed} \cdot y_G \]

\( M_{Ed,x} \): Design moment around the y-axis, regarding the center of gravity of the column.

\( x_G \): x-coordinate of the center of gravity of the \( u_{out,ef} \) critical perimeter regarding the center of the column.

\( y_G \): y-coordinate of the center of gravity of the \( u_{out,ef} \) critical perimeter regarding the center of the column.

\( u_{out,ef} \): Critical punching shear perimeter outside the reinforced zone (EN 1992-1-1:2004/AC:2008, 6.4.5).

\[ W_{out,ef,x} = \int_0^{u_{out,ef}} |e_x| \cdot dl \]

\( dl \): Differential element of the critical perimeter length.

\( e_x \): Distance from \( dl \) to the axis where the moment \( M_{Ed,x} \) acts about.

\[ W_{out,ef,y} = \int_0^{u_{out,ef}} |e_y| \cdot dl \]

\( e_y \): Distance from \( dl \) to the axis where the moment \( M_{Ed,y} \) acts about.

\( d \): Nominal depth of the slab.

The design value of the punching shear resistance of a slab without punching shear reinforcement along the control section considered is obtained from the following expression (EN 1992-1-1:2004/AC:2008, 6.4.4):

\[ v_{Rd,c} = \frac{0.18}{\gamma_c} \cdot k \cdot (100 \cdot \rho_i \cdot f_{ck})^{1/3} + 0.1 \cdot \sigma_{cp} \]

with a minimum value of:

\[ v_{Rd,c,\text{min}} = 0.035 \cdot k^{3/2} \cdot f_{ck}^{1/2} + 0.1 \cdot \sigma_{cp} \]

Where:

\( \gamma_c \): Concrete resistance reduction coefficient.

\( k \): Coefficient which depends on the nominal depth of 'd'.

\[ k = \left( 1 + \sqrt{\frac{200}{d}} \right) \leq 2 \]

\( f_{ck} \): Concrete compressive strength.

\( \rho_i \): Geometric steel area of the main tensile longitudinal reinforcement.

\[ \rho_i = \sqrt{\rho_{ix} \cdot \rho_{iy}} \leq 0.02 \]

Where:

\( \rho_{ix} \): Ratio in X-direction.

\( \rho_{iy} \): Ratio in Y-direction.

\( \sigma_{cp} \): Average axial stress on the critical verification surface (positive compression), with a maximum value of \( \sigma_{cp,\text{max}} \).

\[ \sigma_{cp,\text{max}} = 0.20 \cdot f_{cd} \]

\( f_{cd} \): Design value of the concrete compression force in the direction of the longitudinal member axis.

\[ f_{cd} = 16.67 \text{ MPa} \]

\[ v_{Rd,c} = 0.48 \text{ MPa} \]

\[ v_{Rd,c,\text{min}} = 0.48 \text{ MPa} \]

\[ f_{ck} = 25.00 \text{ MPa} \]

\[ \rho_i = 0.0021 \]

\[ \rho_{ix} = 0.0021 \]

\[ \rho_{iy} = 0.0021 \]

\[ \sigma_{cp} = 0.00 \text{ MPa} \]

\[ \sigma_{cp,\text{max}} = 3.33 \text{ MPa} \]
Verification of the ultimate punching shear resistance

2.4.- Additional reinf. (P5)

2.4.1.- Punching shear reinforcement (EN 1992-1-1:2004/AC:2008, 9.4.3(2)) (non-seismic combinations)

Where shear reinforcement is required the area of a link leg (or equivalent), \( A_{sw,min} \), is given by Expression (9.11).

\[
A_{sw,min} \cdot \left( 1.5 \cdot \sin \alpha + \cos \alpha \right) / (s_r \cdot s_t) \geq 0.08 \cdot \sqrt{f_{ck}} / f_{sk}
\]  
(9.11)

\[
\rho_a = A_{sw,min} \cdot \left( 1.5 \cdot \sin \alpha + \cos \alpha \right) / (s_r \cdot s_t)
\]

\[
\rho_{a,min} = 0.08 \cdot \sqrt{f_{ck}} / f_{sk}
\]

<table>
<thead>
<tr>
<th>Reference</th>
<th>( A_{sw} ) (mm²)</th>
<th>( s_r ) (mm)</th>
<th>( s_t ) (mm)</th>
<th>( \alpha ) (degrees)</th>
<th>( \rho_a )</th>
<th>( \rho_{a,min} )</th>
<th>( \rho_a \geq \rho_{a,min} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 2</td>
<td>28</td>
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<td>214</td>
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<td>0.0020</td>
<td>0.0010</td>
<td>✓</td>
</tr>
<tr>
<td>Beam 2</td>
<td>28</td>
<td>100</td>
<td>214</td>
<td>90.0</td>
<td>0.0020</td>
<td>0.0010</td>
<td>✓</td>
</tr>
</tbody>
</table>

where:
- \( A_{sw} \): the area of a link leg (or equivalent).
- \( \alpha \): is the angle between the shear reinforcement and the main steel (i.e. for vertical links \( \alpha = 90^\circ \) and \( \sin \alpha = 1 \)).
- \( s_r \): is the spacing of shear links in the radial direction.
- \( s_t \): is the spacing of shear links in the tangential direction.
- \( f_{ck} \): is in MPa

\( f_{ck} = 25.00 \) MPa

2.4.2.- Clear distance between two isolated consecutive bars

The horizontal and vertical clear spacing \( d_l \) between two consecutive bars should be greater than or equal to \( s_{min} \) (8.2(2), \( d_l \)):

\[
d_l \geq s_{min}
\]

Where:
- \( s_{min} \): Maximum value of \( s_1, s_2, s_3 \).

\[
s_1 = \varnothing_{max}
\]

\[
s_2 = 5 + d_l
\]

\[
s_3 = 20 \text{mm}
\]

Where:
- \( \varnothing_{max} \): Diameter of the thickest bar of the transverse reinforcement.
- \( \varnothing_{max} \): Diameter of the thickest bar of the transverse reinforcement.

\( \varnothing_{max} = 6 \text{ mm} \)


<table>
<thead>
<tr>
<th>Reference</th>
<th>( d_l ) (mm)</th>
<th>( s_{min} ) (mm)</th>
<th>( \varnothing_{max} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 2</td>
<td>94</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Beam 2</td>
<td>94</td>
<td>20</td>
<td>6</td>
</tr>
</tbody>
</table>
2.4.3.- Distance between the support’s face and the first punching shear reinforcement

The distance between the face of the support or loaded area and the first punching shear reinforcement should not be greater than $s_{\text{max}}$ (EN 1992-1-1:2004/AC:2008, 9.4.3):

$$d \leq s_{\text{max}}$$

Where:

$$s_{\text{max}} = 0.5 \cdot d$$

$d$: Nominal depth of the slab.

20 mm $\leq$ 108 mm

Where:

$s_{\text{max}}$ = 108 mm

$d$ = 215 mm

2.4.4.- Distance between transverse consecutive reinforcement perimeters

The distance $d_l$ between consecutive transverse reinforcement perimeters should be, at most, equal to $s_{\text{max}}$ (EN 1992-1-1:2004/AC:2008, 9.4.3):

$$d_l \leq s_{\text{max}}$$

Where:

$$s_{\text{max}} = 0.75 \cdot d$$

$d$: Nominal depth of the slab.

100 mm $\leq$ 161 mm

Where:

$s_{\text{max}}$ = 161 mm

$d$ = 215 mm

2.4.5.- Distance between two consecutive reinforcements in peripheral direction

The distance $d_l$ between two consecutive perimeter reinforcements should not be greater than $s_{\text{max}}$ (EN 1992-1-1:2004/AC:2008, 9.4.3):

$$d_l \leq s_{\text{max}}$$

Where:

$$s_{\text{max}} = 1.5 \cdot d$$

$d$: Nominal depth of the slab.

214 mm $\leq$ 323 mm

Where:

$s_{\text{max}}$ = 323 mm

$d$ = 215 mm