Ancon Shearfix EC2 Design Manual

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5.7 7 January 2020 $u_0$ and $u_1*$ control perimeters modified (11.2; tables 3, 4 and 5; design examples 2, 3 and 4)

5.10 15 January 2021 $u_1*$ control perimeters reduce at openings, $\beta$ calc’s modified to suit (10; 12; equations 7, 8, 9)

6.0 6 April 2021 removal of references to version 5 where they may cause confusion
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1 Symbols

1.1 Latin Upper Case

- \( A_{cy} \): Concrete area in the \( y \) direction
- \( A_{cz} \): Concrete area in the \( z \) direction
- \( A_{sw} \): Area of one perimeter of shear reinforcement
- \( A_{sy} \): Area of slab reinforcement in \( y \)-direction per metre of slab (number suffix → layer number)
- \( A_{sz} \): Area of slab reinforcement in \( z \)-direction per metre of slab (number suffix → layer number)
- \( C_{rd,c} \): According to NA to BS EN 1992-1-1, 6.4.4 (1)
- \( D \): Diameter of circular column
- \( L \): Column dimension parallel to flat face of oval column
- \( L_1 \): Effective column dimension parallel to flat face of oval column
- \( M_{ed} \): Design moment about centroid of column (with \( y/z \) suffix → about \( y/z \) axis)
- \( M'_{ed} \): Design moment about centroid of basic control perimeter (with \( y/z \) suffix → about \( y/z \) axis)
- \( N_{ed,y} \): Longitudinal forces across the critical section in the \( y \) direction
- \( N_{ed,z} \): Longitudinal forces across the critical section in the \( z \) direction
- \( V_{ed} \): Design value of the applied shear force
- \( W_1 \): Integral of the basic control perimeter length by the distance from its centroidal axis (with \( y/z \) suffix → relative to \( y/z \) axis)

1.2 Latin Lower Case

- \( a \): Larger dimension of a rectangular column
- \( a_1 \): Effective dimension of a rectangular column corresponding to the actual dimension, \( a \)
- \( a_{e,y} \): Distance between the column face and the edge of the slab in the \( y \)-direction
- \( a_{e,z} \): Distance between the column face and the edge of the slab in the \( z \)-direction
- \( b \): Smaller dimension of a rectangular column
- \( b_1 \): Effective dimension of a rectangular column corresponding to the actual dimension, \( b \)
- \( b_y \): Dimension of the control perimeter in the \( y \) direction
- \( b_z \): Dimension of the control perimeter in the \( z \) direction
- \( c_1 \): Column dimension parallel to the eccentricity of the load
- \( c_2 \): Column dimension perpendicular to the eccentricity of the load
- \( c_3 \): Distance of radial setting out point from corner of column, parallel to column dimension \( z \)
- \( c_4 \): Distance of radial setting out point from corner of column, parallel to column dimension \( y \)
- \( c_{nom,t} \): Dimension of the concrete cover at the top of slab
- \( c_{nom,b} \): Dimension of the concrete cover at the bottom of slab
- \( d \): Mean effective depth of the slab
- \( d_y \): Effective depth of the reinforcement in the \( y \) direction (with number suffix → layer number)
- \( d_z \): Effective depth of the reinforcement in the \( z \) direction (with number suffix → layer number)
- \( e \): (1) Distance from the centroid of the basic control perimeter, \( u_1 \)
- (2) Eccentricity of the applied load
  - (a) \( y/z \) suffix → in the \( y/z \) direction (i.e. \( e_y = M_{ed,y} / V_{ed} \) )
  - (b) \( par \) suffix → eccentricity parallel to slab edge due to a moment about an axis perpendicular to slab edge
- \( f_{cd} \): Design compressive strength of concrete
- \( f_{ck} \): Cylinder strength of concrete
Characteristic tensile strength of reinforcement

Design strength of the punching shear reinforcement

Effective design strength of the punching shear reinforcement

Distance of slab edge from column (with suffices a, b, D, L, y, z) – see section 8.1

Slab depth

where slab depth varies across top of column, slab depth 1

where slab depth varies across top of column, slab depth 2

(1) Coefficient dependant on the ratio between the control dimensions \( c_1 \) and \( c_2 \) (Table 1) (with suffix y/z → relating to \( M_{Ed,y} \) and \( M_{Ed,z} \) respectively) NB. The \( k \) in (eq. 6.44) is determined by replacing \( c_1/c_2 \) in Table 1 with \( c_1/(2c_2) \).

(2) Coefficient depending on effective depth of slab (6.4.4(1))

(3) Coefficient determining distance between the outermost perimeter of shear reinforcement and the control perimeter at which shear reinforcement is no longer required, \( u_{out} \) (6.4.5(4))

According to NA to BS EN 1992-1-1, 6.4.4 (1)

effective length of wall resisting punching shear load

larger dimension of a rectangular slab opening

shorter dimension of a rectangular slab opening

the minimum distance between tangential lines defining the ineffective slab region due to an opening in the slab

location of opening centre relative to column centre

Radial spacing of shear studs

Radial distance to first shear stud from column face

maximum tangential spacing between outermost shear studs

wall thickness

Perimeter of loaded area at the column face

Basic control perimeter

Reduced basic control perimeter

The control perimeter at which shear reinforcement is not required

The control perimeter a distance \( kd \) from the outermost perimeter of shear reinforcement for a cruciform rail layout

Design shear stress at the face of the column

Design value of the shear stress at the basic control perimeter

Design value of the punching shear resistance at the basic control perimeter of the slab without shear reinforcement

Design value of the punching shear resistance at the basic control perimeter of the slab with shear reinforcement

Design value of the maximum punching shear resistance at the loaded face

The maximum limiting value of the punching shear capacity of the slab

column dimension parallel to y-axis

co-ordinate of the \( u_1 \) centroid relative to the column centroid in the y-direction

dimension of rectangular slab opening parallel to y-axis

column dimension parallel to z-axis

co-ordinate of the \( u_1 \) centroid relative to the column centroid in the z-direction

dimension of rectangular slab opening parallel to z-axis
1.3 Greek Lower Case

\( \alpha \)  
Angle between shear reinforcement and the slab

\( \alpha_{cc} \)  
Coefficient taking account of long term effects taken as 1.0

\( \beta \)  
Eccentricity factor

\( \gamma_s \)  
Partial safety factor for the steel

\( \gamma_c \)  
Partial safety factor for concrete

\( \nu \)  
Strength reduction factor for cracked concrete in shear

\( \sigma_{cp} \)  
Compressive stress in the concrete due to the axial load

\( \sigma_{cy} \)  
Concrete stress at the critical section in y direction

\( \sigma_{cz} \)  
Concrete stress at the critical section in z direction

\( \rho_l \)  
Reinforcement ratio

\( \rho_{ly} \)  
Reinforcement ratio in the y direction

\( \rho_{lz} \)  
Reinforcement ratio in the z direction

2 References


3 Introduction

Shear reinforcement is used within a slab or foundation around a column to prevent punching shear failure. Ancon Shearfix is the ideal solution to the design and construction problems associated with punching shear.

The Ancon Shearfix system comprises double-headed studs welded to a pair of flat rails. It is manufactured to suit the specific requirements of each application. The quantity of each component, the dimensions and spacing, and the layout pattern around the column are determined by calculation. Leviat provides free software to determine the optimum system design.

Studs are manufactured from high strength steel bar with a characteristic yield strength of 500 N/mm². In the UK, five diameters are available (10, 12, 16, 20 and 25mm); in Australia, four diameters are available (12, 16, 20 and 24mm). The heads are hot forged to three times the diameter of the bar. Studs are manufactured to virtually any length to suit the depth of the slab, but in the UK they are normally formed in increments of 5mm within the 100-1000mm range, and in Australia they are normally formed in increments of 10mm within the 100-500mm range.

The studs are welded to the rails at spacings determined by our software or design calculation. The rail performs no structural function but ensures stud alignment and positioning within the slab.

The rails are manufactured from strips of steel, typically 20mm wide, reducing to 16mm wide for 10, 12 and 16mm diameter studs in the UK. The gap between the strips allows for passage of concrete during pouring and also enables the rail to be nailed through spacers to formwork when fixed ‘bottom up’ i.e. prior to other reinforcement.

Ancon Shearfix is a proven system, which has undergone independent mechanical and structural testing. It has been approved by CARES for use in reinforced concrete slabs designed in accordance with EC2 design standard.

We are pleased to offer this Design Manual which demonstrates our expertise in the field of punching shear reinforcement to EC2.

The design method for Shearfix punching shear reinforcement is based on section 6.4 of BS EN 1992-1-1:2004, and is outlined within this Design Manual. The supporting Shearfix software reflects this method.

This Design Manual and the Shearfix program accommodate some column shapes and locations and some design options which are not specifically addressed by the Eurocode. BS EN 1992-1-1:2004 does not include oval columns or columns at re-entrant corners. Leviat has drawn upon the principles presented in the BS EN 1992-1-1:2004, the expert advice of Professor Regan and verification testing that was carried out by us at Cambridge University with Professor Regan in March 2012. Furthermore, BS EN 1992-1-1:2004 does not include dimensional limits for the spread of punching shear stresses around the control perimeters of large and elongated columns. We have drawn upon the principles presented in Model Code 2010 and recent research findings to develop a “Best Practice” design option when dealing with large and elongated columns, whilst an “EC2” design option (which adheres to the rules of BS EN 1992-1-1:2004) is also provided.
4 Design Information and Assumptions

4.1 Information required
The following information is required in order to design the punching shear reinforcement:

- Column shape (rectangular, circular, oval)
- Column location (interior, edge, corner, re-entrant corner, wall end, wall corner)
- Column dimensions
- Distances to slab edges
- Slab properties (thickness, concrete strength, cover to main reinforcement)
- Diameter and spacing of tension reinforcement in both directions within 3d from the column face; or mean effective depth of tension reinforcement and reinforcement ratios in both directions
- The ultimate design load, \( V_{Ed} \), and ultimate design moments, \( M_{Ed,y} \) and \( M_{Ed,z} \); or, the ultimate design load, \( V_{Ed} \), and the appropriate \( \beta \) factor to be applied (see section 10)
- Location and size of any opening(s) within 6d from the column face

4.2 Design Assumptions
The following assumptions have been made in line with guidance within EC2:

- The minimum slab thickness is 200mm
- The minimum column dimension is 155mm
- The loads and moments entered have been factored in accordance with the Eurocodes
- The loads do not include the loads from the column above
- The concrete slab is to be constructed from normal weight concrete
- The reinforcement is detailed and installed as set out in EC2

4.3 Software Defaults

<table>
<thead>
<tr>
<th>Column location</th>
<th>Internal</th>
<th>Openings</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column shape</td>
<td>Rectangular</td>
<td>(add rectangular) → ( l_y )</td>
<td>500 mm</td>
</tr>
<tr>
<td>Dimension, ( y )</td>
<td>500 mm</td>
<td>(add rectangular) → ( l_z )</td>
<td>500 mm</td>
</tr>
<tr>
<td>Dimension, ( z )</td>
<td>300 mm</td>
<td>(add rectangular) → ( y' )</td>
<td>400 mm</td>
</tr>
<tr>
<td>Dimension, ( D )</td>
<td>500 mm</td>
<td>(add rectangular) → ( z' )</td>
<td>600 mm</td>
</tr>
<tr>
<td>Slab depth, ( h )</td>
<td>250 mm</td>
<td>(add circular) → ( l_y )</td>
<td>500 mm</td>
</tr>
<tr>
<td>Concrete grade</td>
<td>C20/25</td>
<td>(add circular) → ( l_z )</td>
<td>500 mm</td>
</tr>
<tr>
<td>Top cover, ( c_{nom,t} )</td>
<td>25 mm</td>
<td>(add circular) → ( \varnothing )</td>
<td>500 mm</td>
</tr>
<tr>
<td>Top cover, ( c_{nom,b} )</td>
<td>25 mm</td>
<td>Shearfix layout</td>
<td>Auto</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>None</td>
<td>Shearfix stud diameter</td>
<td>Auto</td>
</tr>
<tr>
<td>(add) → Bar diameter</td>
<td>8 mm</td>
<td>Large and elongated columns</td>
<td>Best Practice</td>
</tr>
<tr>
<td>(add) → Spacing</td>
<td>150 mm</td>
<td>Include distribution rails</td>
<td>Yes</td>
</tr>
<tr>
<td>Eccentricity factor, ( \beta )</td>
<td>Calculated</td>
<td>Rail placing</td>
<td>Bottom-up</td>
</tr>
<tr>
<td>Shear load, ( V_{Ed} )</td>
<td>500 kN</td>
<td>Distance to first stud</td>
<td>0.5d</td>
</tr>
<tr>
<td>Moment, ( M_{Ed,y} )</td>
<td>0 kNm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moment, ( M_{Ed,z} )</td>
<td>0 kNm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5  **Slab depth, h**

The software can accommodate a step in slab depth. This step can be parallel to the y-axis or parallel to the z-axis and it can occur on the top or bottom surface of the slab. It may be located anywhere within the column width.

The smaller slab depth is applied to all shear capacity calculations. Both slab depths are applied to stud height calculations, such that some rails comprise of short studs for the thinner portion of slab and other rails comprise of tall studs for the thicker portion of slab. The shear studs in one rail are all the same height.

6  **Effective depth, d**

The effective depth of the reinforcement is the mean effective depth of all layers of reinforcement present. The equations below assume there are two layers of reinforcement in each direction in the order illustrated. If this is not the case, the equations need to be adapted accordingly. (The Shearfix software can accommodate up to two layers of reinforcement in each direction.)

\[
d = 0.25\left( d_{y,1} + d_{z,1} + d_{y,2} + d_{z,2} \right)
\]

where

\[
d_{y,1} = h - c_{nom,t} - \frac{\phi_{y,1}}{2}
\]

\[
d_{z,1} = h - c_{nom,t} - \phi_{y,1} - \frac{\phi_{z,1}}{2}
\]

\[
d_{y,2} = h - c_{nom,t} - \phi_{y,1} - \phi_{z,1} - \frac{\phi_{y,2}}{2}
\]

\[
d_{z,2} = h - c_{nom,t} - \phi_{y,1} - \phi_{z,1} - \phi_{y,2} - \frac{\phi_{z,2}}{2}
\]

Equation 1 Calculation of the effective depth of the slab, d

Where there is a step in the slab depth, the lesser of the two depths is used in the above equations.

7  **Reinforcement ratio, \( \rho \)**

The reinforcement ratio of the slab is calculated as follows:

\[
\rho_t = \sqrt{\rho_{ty} \times \rho_{tz}} \leq 0.02
\]

Where:

\[
\rho_{ty} = \frac{A_{sy}}{A_c} = \frac{A_{sy,1}}{d_{y,1}} + \frac{A_{sy,2}}{d_{y,2}} \quad \text{and} \quad \rho_{tz} = \frac{A_{sz}}{A_c} = \frac{A_{sz,1}}{d_{z,1}} + \frac{A_{sz,2}}{d_{z,2}}
\]

Equation 2 Calculation of the slab reinforcement ratio, based on BS EN 1992-1-1:2004, 6.4.4 (1)

For the purpose of this calculation, the units for the area of tensile slab reinforcement, \( A_{sy} \), are \( \text{mm}^2/\text{mm width of slab} \). The area of concrete, \( A_c \), \( \text{mm}^2/\text{mm width of slab} \) is equal to the effective depth of the reinforcement, \( d \) (\( \text{mm}^2 \)), multiplied by a 1mm strip width of slab.
8 Column and edge dimensions

There are varying schools of thought regarding the column perimeter length effective in resisting punching shear. The only limit in the current Eurocode is the aspect ratio which differentiates a column from a wall, 1:4 (BS EN 1992-1-1:2004+A1:2014, 9.5.1). However, research suggests that punching shear stresses in the slab are focused at the corners of columns. The larger a column is the more significant this effect. To accommodate these two schools of thought, we have developed two design options for dealing with large and elongated columns: “EC2” and “Best Practice”.

For both approaches, the length to breadth ratio of rectangular and oval columns is limited to 4:1. There is no limit to the control perimeters of a circular column or to the curved faces of an oval column. In the Best Practice approach, an additional rule is imposed limiting the control perimeters to a distance of 1.5d from the corners of rectangular columns and from the point of transition between the straight and curved faces of an oval column. The Best Practice approach is in accordance with fib Model Code 2010 and the research paper, “Study on Influence of Column Size and Slab Slenderness on Punching Strength” (Einpaul, J., Bujnak, J., Fernandez Ruiz, M. and Muttoni, A. (2016), ACI Structural Journal, V. 113, No. 1, pp. 135-146).

<table>
<thead>
<tr>
<th>EC2</th>
<th>Best Practice</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Diagram EC2" /></td>
<td><img src="image2" alt="Diagram Best Practice" /></td>
</tr>
</tbody>
</table>

Where:
- \( a_1 = \min(a, 4b) \)
- \( u_0 = 2a_1 + 2b \)
- \( u_1 = 2a_1 + 2b + 4\pi d \)

Where:
- \( a_1 = \min(a, 4b, 3d) \)
- \( b_1 = \min(b, 3d) \)
- \( u_0 = 2a_1 + 2b_1 \)
- \( u_1 = 2a_1 + 2b_1 + 4\pi d \)

Where:
- \( L_1 = \min(L-D, 3D) \)
- \( u_0 = 2L_1 + \pi D \)
- \( u_1 = 2L_1 + \pi (D + 4d) \)

Where:
- \( L_1 = \min(L-D, 3D, 3d) \)
- \( u_0 = 2L_1 + \pi D \)
- \( u_1 = 2L_1 + \pi (D + 4d) \)

The Eurocode notation for column dimensions \((c_1, c_2)\) is dependent on the direction of the applied load. For design simplicity, the program input (and the notation of this design manual) relates to the directions of the y and z axes. EC2 notation is translated accordingly.
8.1 Edge dimensions

The Shearfix program requires entry of the distances between column faces and slab edges in the y- and z-directions, $a_{e,y}$ and $a_{e,z}$. For calculations, these are translated into edge distances $g_a$, $g_b$, $g_L$, $g_D$, $g_y$ or $g_z$ as appropriate. The relationships between these dimensions are illustrated in Figure 2.

![Figure 2 Edge dimensions](image)

- $a_{e,y}$: distance between column face and slab edge parallel to y-axis (labelled $a_y$ in diagrams)
- $a_{e,z}$: distance between column face and slab edge parallel to z-axis (labelled $a_z$ in diagrams)
- $g_a$: distance between column face and slab edge parallel to dimension a of column
- $g_b$: distance between column face and slab edge parallel to dimension b of column
- $g_y$: distance between column centre and slab edge parallel to y-axis
- $g_z$: distance between column centre and slab edge parallel to z-axis
- $g_L$: distance between slab edge and further radial centre of oval column parallel to dimension L
- $g_D$: distance between column centre and slab edge parallel to dimension D

8.2 Edge dimension limits

For re-entrant corners in the Shearfix software, the edge distances are limited. In the following sketches, the columns are drawn at the maximum permitted distance from the re-entrant corner.

- $a_y \geq -D/2$
- $a_z \geq -D/2$
- $a_{y,\text{min}} = -D/2$
- $a_{z,\text{min}} = -D/2$
9 Column locations and virtual slab openings

The design approach allows for the user-defined column location to be automatically overridden if another location is more appropriate. The shortest possible basic control perimeter determines the column location.

This approach follows from BS EN 1992-1-1:2004 6.4.2 (4), “For a loaded area situated near an edge or a corner, the control perimeter should be taken as shown in [Figure 3 below], if this gives a perimeter (excluding the unsupported edges) smaller than that obtained from [Figure 4 below].”

Figure 3 BS EN 1992-1-1:2004, Figure 6.15 Basic control perimeters for edge and corner columns

Figure 4 BS EN 1992-1-1:2004, Figure 6.13 Typical basic control perimeters around loaded areas
If a slab edge is located within a distance of 6d from the column face and is not accounted for in the determined column location, then it is considered as a virtual opening in the slab. The size of a virtual opening is determined as shown in the following example.

![Diagram showing user-defined edge column designed as internal column with virtual opening at slab edge.](image)

**10 Eccentricity factor β**

The recommended approach for determining the eccentricity factor β is to use equations in section 6.4.3 parts (3)-(5) in EC2, based on the geometry and applied moments, referred to as “calculated” in the software.

The Eurocode presents one equation (6.39) which is applicable to all columns types. The Eurocode also presents a series of other equations each of which is applicable to a specific scenario. Our approach is to calculate the β-value according to the general formula (Equation 3) and according to a specific scenario formula where applicable. The greater of these two values is then adopted as the β value. A minimum value of β = 1.0 is applied to all column shapes and locations.

In version 5.10 onwards, the software has been modified such that the $u_1^*$ parameter accounts for reductions due to slab openings. Accordingly, in the β calculation, the $u_1$ value also accounts for reductions due to slab openings where the $u_1$ value relates to the $u_1^*$ value; and, the $u_1$ value does not account for reductions due to slab openings where the $u_1$ value relates to the $W_1$ factor.

Alternatively to the calculated approach, the user may input a β value they have calculated independently or a β value provided in Figure 6. The latter are referred to as “recommended” values in EC2 and as “default” values in the Shearfix program. The values in Figure 6 must only be used for structures where the adjacent slabs do not differ in length by more than 25% and where the lateral stability does not depend on frame action between the slabs and the columns. (Please note there is no recommended / default value for a re-entrant corner location.)
10.1 General formula for $\beta$ values
The general formula for calculating the $\beta$-value is a re-arranged version of equation (6.39) from BS EN 1992-1-1:2004.

$$\beta = 1 + k \frac{M'_{Ed}}{V_{Ed}} \frac{u_1}{W_1}$$

Equation 3  General formula for beta-value adapted version of eq. (6.39)

Where,
- $k$ = coefficient relative to appropriate axes (See Table 1)
- $M'_{Ed}$ = design moment about centroid of basic control perimeter (See Section 11.1)
- $V_{Ed}$ = design shear force
- $u_1$ = basic control perimeter (See Table 3)
- $W_1$ = property of basic control perimeter relative to appropriate axes (See Section 11.3)

The $k$ value is taken from the following table. Linear interpolation is assumed between stated values.

For circular columns, $k = 0.6$

<table>
<thead>
<tr>
<th>$c_1/c_2$</th>
<th>$\leq 0.5$</th>
<th>1.0</th>
<th>2.0</th>
<th>$&gt; 3.0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>0.45</td>
<td>0.60</td>
<td>0.70</td>
<td>0.80</td>
</tr>
</tbody>
</table>

Table 1  BS EN 1992-1-1:2004, Table 6.1 Values of $k$ for rectangular loaded areas

10.2 Internal column with biaxial moments

$$\beta = 1 + 1.8 \sqrt{\left(\frac{e_y}{b_y}\right)^2 + \left(\frac{e_z}{b_z}\right)^2}$$

Equation 4  BS EN 1992-1-1:2004 (6.43), $\beta$ for internal rectangular column with biaxial moments

Where,
- $e_y$ and $e_z$ = eccentricities along y and z axes respectively
- $b_y$ and $b_z$ = dimensions of the control perimeter

Counter-intuitively,

$$e_y = \frac{M_{Ed,x}}{V_{Ed}} \quad \text{and} \quad e_z = \frac{M_{Ed,y}}{V_{Ed}}$$
Regardless of column size, \( b_y = y + 4d \) and \( b_z = z + 4d \)

10.3 Edge column with moment towards interior of slab
This case applies to both edge columns and wall ends when the translated moment (acting about the centroid of the basic control perimeter) is towards the interior of the slab (see Section 11.1).

\[
\beta = \frac{u_1}{u_1^*} + k \frac{u_1}{W_1} e_{par}
\]

Equation 5 BS EN 1992-1-1:2004 eq. (6.44) \( \beta \): edge column with loading towards interior of slab

Where, 
- \( u_1 \) = basic control perimeter (Table 3)
- \( u_1^* \) = reduced basic control perimeter (Table 3)
- \( k \) = coefficient given in Table 1 with the ratio \( c_1/c_2 \) replaced by \( c_1/2c_2 \)
- \( W_1 \) = property of basic control perimeter relative to axis perpendicular to slab edge (Section 11.3)
- \( e_{par} \) = eccentricity parallel to slab edge resulting from a moment about an axis perpendicular to slab edge

10.4 Corner column with moment towards interior of slab
This case applies to both corner columns and wall corners when the translated moment (acting about the centroid of the basic control perimeter) is towards the interior of the slab (see Section 11.1).

\[
\beta = \frac{u_1}{u_1^*}
\]

Equation 6 BS EN 1992-1-1:2004 eq. (6.46) \( \beta \): edge column where eccentricity is towards interior

Where, 
- \( u_1 \) = basic control perimeter (Table 3)
- \( u_1^* \) = reduced basic control perimeter (Table 3)
10.5 Default β-value
Where β cannot be calculated using the above formulae, the following values can be used. These values can only be used if the lateral stability of the structure does not depend on frame action between the slabs and the columns and if adjacent spans do not differ in length by more than 25%.

<table>
<thead>
<tr>
<th>Column location</th>
<th>Default β-value, Figure (6.21N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>1.15</td>
</tr>
<tr>
<td>Edge or wall end</td>
<td>1.4</td>
</tr>
<tr>
<td>Corner or wall corner</td>
<td>1.5</td>
</tr>
<tr>
<td>Re-entrant corner</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 2 BS EN 1992-1-1:2004 Figure 6.21N, Default (“Recommended”) values for β

11 Parameters for calculating β-values

11.1 Translation of moments
In order to calculate the β value, the designer needs to provide the design moments applied to the column. These values are entered relative to the centre of the column, wall end or wall centre. (The “centre of a wall corner” is located at the centre of a square column of side dimension, I, where I is the effective length of the wall corner.) For the calculation of β, these are translated relative to the centroid of the basic control perimeter, $u_1$. The Shearfix program calculates this automatically.

The notation used is as follows:
- $M_{Ed,y}$: Design moment about axis y through centroid of column
- $M_{Ed,z}$: Design moment about axis z through centroid of column
- $M'_{Ed,y}$: Design moment about axis y through centroid of basic control perimeter
- $M'_{Ed,z}$: Design moment about axis z through centroid of basic control perimeter

The sign convention is determined by the right-hand rule: a positive bending moment follows the direction of curled fingers on the right hand when the thumb is pointed in the positive axis direction.

![Figure 8 Translation of moment about column to moment about basic control perimeter](image)

\[ M'_{Ed,y} = M_{Ed,y} - z_0 V_{Ed} \quad \text{and} \quad M'_{Ed,z} = M_{Ed,z} - y_0 V_{Ed} \]

Equation 7 Translation of moment

where $y_0$, $z_0$, $M_{Ed,y}$ and $M_{Ed,z}$ are positive as illustrated in Figure 8.
11.2 Control perimeters

The column face control perimeters ($u_0$) are presented in the Eurocode as follows:

<table>
<thead>
<tr>
<th>$u_0$</th>
<th>for an interior column</th>
<th>$u_0 = \text{enclosing minimum periphery [mm]}$ [5, 6]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>for an edge column</td>
<td>$u_0 = 2d + 3d \leq c_2 + 2c_1$ [mm]</td>
</tr>
<tr>
<td>$u_1$</td>
<td>for a corner column</td>
<td>$u_0 = 3d \leq c_1 + c_2$ [mm]</td>
</tr>
</tbody>
</table>

Figure 9 BS EN 1992-1-1:2004, 6.4.5(3) column face perimeters

The basic control perimeters ($u_1$) for internal columns, and for edge and corner columns are presented in the Eurocode as follows:

Figure 10 BS EN 1992-1-1:2004 Figure 6.13 Typical basic control perimeters around loaded areas

Figure 11 BS EN 1992-1-1:2004, Figure 6.15 Basic control perimeters for edge and corner columns

The reduced basic control perimeters ($u_1^*$) for edge and corner columns are presented in the Eurocode as follows:

Figure 12 BS EN 1992-1-1:2004 Figure 6.20 Reduced basic control perimeter $u_1^*$

The control perimeter definitions (Table 3) are based on these figures and the application of effective dimensions as described in section 8 above. These definitions have been revised for Shearfix 5.7 to incorporate the “1.5d” and “3d” limits to $u_0$ and $u_1^*$ values described above.
### Ancon Shearfix Punching Shear Reinforcement

<table>
<thead>
<tr>
<th>Column Location</th>
<th>Shape</th>
<th>Control perimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td>Rectangular</td>
<td>$u_0 = 2a_1 + 2b_1$</td>
</tr>
<tr>
<td></td>
<td>Circular</td>
<td>$u_0 = \pi D$</td>
</tr>
<tr>
<td></td>
<td>Oval</td>
<td>$u_0 = 2L_1 + \pi D$</td>
</tr>
<tr>
<td><strong>Edge</strong></td>
<td>Rectangular</td>
<td>$u_0 = 2a_{1w0} + b_1$</td>
</tr>
<tr>
<td></td>
<td>Wall end</td>
<td>$u_0 = 2l_{w0} + t$</td>
</tr>
<tr>
<td><strong>Corner</strong></td>
<td>Rectangular</td>
<td>$u_0 = a_{1w0} + b_{1w0}$</td>
</tr>
<tr>
<td></td>
<td>Wall corner</td>
<td>$u_0 = 2l_{w0}$</td>
</tr>
<tr>
<td></td>
<td>Circular</td>
<td>$u_0 = 2D_{w0}$</td>
</tr>
<tr>
<td></td>
<td>Oval</td>
<td>$u_0 = L_{1w0} + D_{w0} + 0.125\pi D$</td>
</tr>
<tr>
<td><strong>Re-entrant</strong></td>
<td>Rectangular</td>
<td>$u_0 = a_1 + b_1 + a_{1w0} + b_{1w0}$</td>
</tr>
<tr>
<td></td>
<td>$g_a \geq 0, g_b \geq 0$</td>
<td>$u_0 = a_1 + b_1 + a_{1w0} + b_{1w0}$</td>
</tr>
<tr>
<td></td>
<td>$g_a &lt; 0, g_b \geq 0$</td>
<td>$u_0 = a_1 + b_1 + a_{2w0} + b_{1w0}$</td>
</tr>
<tr>
<td></td>
<td>Circular</td>
<td>$u_0 = 0.5\pi D + 2D_{w0}$</td>
</tr>
</tbody>
</table>

Table 3 Control perimeters $u_0$, $u_1$ and $u_1^*$ (see Table 4 & Table 5 below for parameter definitions)
<table>
<thead>
<tr>
<th>Column shape</th>
<th>Parameter</th>
<th>Best Practice</th>
<th>EC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>rectangular</td>
<td>a</td>
<td>Max (y, z)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>Min (y, z)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a₁</td>
<td>Min (a, 4b, 3d)</td>
<td>Min (a, 4b)</td>
</tr>
<tr>
<td></td>
<td>a₁₁u₀</td>
<td>Min (a, 4b, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a₁₁us</td>
<td>Min (a, 4b, 3d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b₁</td>
<td>Min (b, 3d)</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>b₁₁u₀</td>
<td>Min (b, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b₁₁us</td>
<td>Min (b, 3d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a₂</td>
<td>Min (a+gₐ, 2b, 1.5d)</td>
<td>Min (a+gₐ, 2b)</td>
</tr>
<tr>
<td></td>
<td>a₂₁u₀</td>
<td>Min (a+gₐ, 2b, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b₂</td>
<td>Min (b+gₐ, 1.5d)</td>
<td>Min (b+gₐ, 1.5d)</td>
</tr>
<tr>
<td></td>
<td>b₂₁u₀</td>
<td>Min (b+gₐ, 1.5d)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column shape</th>
<th>Parameter</th>
<th>Best Practice</th>
<th>EC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>oval &amp; circular</td>
<td>L</td>
<td>Max (y, z)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>Min (y, z)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L₁</td>
<td>Min (L-D, 3D, 3d)</td>
<td>Min (L-D, 3D)</td>
</tr>
<tr>
<td></td>
<td>L₁₁u₀</td>
<td>Min (L-D, 3D, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>L₁₁us</td>
<td>Min (L-D, 3D, 3d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D₁₀</td>
<td>Min (0.25πD, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D₁₁₀</td>
<td>Min (0.25π(D+4d), 3d)</td>
<td></td>
</tr>
<tr>
<td>walls</td>
<td>l₁</td>
<td>l₁auto or l₁user (whichever is selected)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>l₁user</td>
<td>User input value</td>
<td></td>
</tr>
<tr>
<td></td>
<td>l₁auto</td>
<td>Min (2t, 1.5d)</td>
<td>2t</td>
</tr>
<tr>
<td></td>
<td>l₁₀</td>
<td>Min (2t, 1.5d)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>l₁us</td>
<td>Min (2t, 3d)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 Control perimeter parameters

<table>
<thead>
<tr>
<th>Distance parallel to...</th>
<th>Distance parallel to...</th>
</tr>
</thead>
<tbody>
<tr>
<td>gₐ</td>
<td>gₐ</td>
</tr>
<tr>
<td>dimension a from column face to slab edge</td>
<td>dimension b from column face to slab edge</td>
</tr>
<tr>
<td>g₀</td>
<td>g₀</td>
</tr>
<tr>
<td>dimension D from centre of column to slab edge</td>
<td>dimension L from the further radial centre of column to slab edge</td>
</tr>
<tr>
<td>gᵧ</td>
<td>gₙ</td>
</tr>
<tr>
<td>y-axis from centre of column to slab edge</td>
<td>z-axis from centre of column to slab edge</td>
</tr>
</tbody>
</table>

g = gₓ or gᵧ, as appropriate

For accompanying diagrams, see 8.1 Edge dimensions on page 11

Table 5 Edge distance parameters
11.3 \( W_1 \) values

The \( W_1 \) value is a shear distribution factor. It is a function of the basic control perimeter. It is the integral of the length of the basic control perimeter by its distance from the centroidal axis.

\[
W_i = \int_0^{u_i} |e| \, dl
\]

Equation 8 BS EN 1992-1-1:2004 eq. (6.40) Definition of \( W_i \) as a function of a control perimeter

Where, 
\( dl \) = length increment of the perimeter
\( e \) = distance of \( dl \) from the axis about which the translated moment \( M'_{ed} \) acts

This integral has been calculated for two column scenarios which are both presented in the Eurocode. The first scenario is a “small” rectangular internal column. “Small” means that the effective column dimensions are equal to the actual column dimensions, i.e. \( a_1 = a \) and \( b_1 = b \).

\[
W_1 = 0.5c_1^2 + c_1c_2 + 4c_2d + 16d^2 + 2\pi dc_1
\]

Equation 9 BS EN 1992-1-1:2004 eq. (6.41), \( W_1 \) formula for internal rectangular column

The second applies to a “small” rectangular column at a slab edge where the load eccentricity parallel to the slab edge is zero.

\[
W_1 = 0.25c_2^2 + c_1c_2 + 4c_1d + 8d^2 + \pi dc_2
\]

Equation 10 BS EN 1992-1-1:2004 eq. (6.45), \( W_1 \) formula when \( a_1 = a, b_1 = b \) and edge distance = 0

For all scenarios, the \( W_1 \) value is automatically calculated by the Shearfix software.

12 Slab openings

For columns situated near openings, if the shortest distance from the column face to the edge of the opening does not exceed 6d, that part of the control perimeter contained between two tangents drawn to the outline of the opening from the column centre is considered ineffective. (BS EN 1992-1-1:2004 6.4.2 (3)). This leads to reduced effective control perimeters (\( u_0, u_1, u_1^* \) and \( u_{out} \)) which are applied to the \( \beta \) calculations, shear stress calculations and the layout of punching shear reinforcement.

For rectangular openings, the two tangential lines must be a minimum distance apart. This minimum distance is measured at the corner of the opening which sets out the position of a tangential line and is closest to the column. This minimum distance is: \( l_3 \geq \sqrt{l_1^2 \times l_2^2} \) where \( l_1 \) is the larger slab opening dimension and \( l_2 \) is the lesser slab opening dimension. (See Figure 13.) There is no equivalent minimum distance for circular openings.
Figure 13 Control perimeter near openings, developed from BS EN 1992-1-1:2004 Figure 6.14
13 Shear stress calculations
The design procedure is described in the following flowchart:

For the purpose of these calculations,
- $u_0$ [mm] the column face control perimeter accounting for reductions due to slab openings
- $u_1$ [mm] the basic control perimeter accounting for reductions due to slab openings

The shear stresses are calculated as follows. (All references relate to BS EN 1992-1-1 or its national annex.)

The applied design shear stress at the column face,

$$v_{Ed,0} = \frac{\beta V_{Ed}}{u_0 \times d} \leq v_{Rd,0,\text{max}} \text{ [MPa]}$$  eq. (6.53)

where
- $\beta$ = the eccentricity factor (Section 10)
- $V_{Ed}$ = the applied design shear force [N]
- $u_0$ = the column face control perimeter accounting for reductions due to slab openings (Table 3 and Section 12) [mm]
- $d$ = slab effective depth (Section 5) [mm]
The maximum shear capacity at the column face, \( v_{Rd, max} = 0.5v f_{cd} \) [MPa] (NA 6.4.5 (3))

where  
- strength reduction factor, \( \nu = 0.6 \left(1 - \frac{f_{ck}}{250}\right) \) NA 6.2.2 (6)  
- cylinder strength of concrete (MPa) \( f_{ck} \) 
- design compressive strength, \( f_{cd} = \alpha_{cc} f_{ck} / \gamma_c \) [MPa] eq. (3.15) 
- coefficient taking account of long term effects, \( \alpha_{cc} = 1 \) NA 3.1.6 (1) 
- partial safety factor for concrete, \( \gamma_c = 1.5 \) Table 2.1N (NA 2.4.2.4(1))

The applied design shear stress at the basic control perimeter, \( v_{Ed,1} = \frac{\beta v \cdot E_d}{u_1 \times d} \) (MPa) eq. (6.38)

where  
- \( u_1 \) = the basic control perimeter accounting for reductions due to slab openings (determined using Table 3 and section 12) [mm]

The shear capacity without punching shear reinforcement, 
\[
v_{Rd,c} = C_{Rd,c} k (100 \rho_l f_{ck})^{1/3} + k_1 \sigma_{cp} \geq (v_{min} + k_1 \sigma_{cp}) \quad \text{eq. (6.47)}
\]

where  
- \( C_{Rd,c} = 0.18 / \gamma_c \) NA 6.4.4 (1) 
- partial safety factor for concrete, \( \gamma_c = 1.5 \) Table 2.1N (NA 2.4.2.4(1)) 
- \( k = 1 + \left( \frac{200}{\sqrt{d}} \right) \leq 2.0 \) 6.4.4 (1) 
- \( \rho_l \) = reinforcement ratio (Section 7) 
- \( k_1 = 0.1 \) NA 6.4.4 (1) 
- \( \sigma_{cp} = (\sigma_{cy} + \sigma_{cz}) / 2 \) 6.4.4 (1) 
- normal concrete stresses in the critical section in y- and z-directions (MPa, positive in compression), \( \sigma_{cy} = \frac{N_{Ed,y}}{A_{cy}} \) and \( \sigma_{cz} = \frac{N_{Ed,z}}{A_{cz}} \) 6.4.4 (1) 
- \( N_{Ed,y}, N_{Ed,z} = \) longitudinal forces across the critical section from a load or prestressing action. 
- \( A_c = \) area of concrete according to the definition of \( N_{Ed} \) [mm²] 6.4.4 (1) 
- \( v_{min} = 0.035 k^{3/2} f_{ck}^{1/2} \) NA 6.4.4 (1)

The maximum limiting value of punching shear capacity, \( v_{Rd,c, max} = 2 \times v_{Rd,c} \) NA 6.4.5(1)

If it is determined that punching shear reinforcement is required. The layout of that reinforcement is determined using Section 15.

The extent of that reinforcement is determined by calculating the length of the control perimeter at which punching shear reinforcement is no longer required:

\[
\nu_{out} = \frac{\beta v \cdot E_d}{v_{Rd,c} \times d} \quad \text{eq. (6.54)}
\]

The outer perimeter of shear studs must be within a distance of 1.5d from that perimeter. The shape of the outer control perimeter \( \nu_{out} \) is dependent on the arrangement of shear reinforcement, effective column dimensions and ineffective regions due to slab openings.
The shear capacity with punching shear reinforcement, $v_{Rd,cs} = 0.75v_{Rd,c} + 1.5\left(\frac{d}{S_r}\right)A_{sw}f_{ywd,ef} \left(\frac{1}{u_1d}\right)\sin \alpha$  \hspace{1cm} \text{eq. (6.52)}

This equation is rearranged to determine the area of punching shear reinforcement required per perimeter around the column, $A_{sw} = (v_{Ed,1} - 0.75v_{Rd,c})s_r u_1 / 1.5f_{ywd,ef}$

where $s_r = \text{radial spacing of perimeters of shear reinforcement [mm]}$

effective design strength of punching shear reinforcement, $f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$ [MPa]  \hspace{1cm} \text{6.4.5(1)}$

design yield strength of punching shear reinforcement, $f_{ywd} = \frac{f_{yk}}{\gamma_s}$ [MPa]  \hspace{1cm} \text{3.2.7(2)}$

characteristic yield strength of punching shear reinforcement, $f_{yk} = 500$ MPa

partial safety factor for reinforcing steel, $\gamma_s = 1.15$ \hspace{1cm} \text{Table 2.1N (NA 2.4.2.4(1))}$

Also, the minimum area of a single shear stud can be determined from: $A_{sw,min} (1.5 \sin \alpha + \cos \alpha) s_t / s_r s_t \geq 0.08\sqrt{f_{ck}} / f_{yk}$ \hspace{1cm} \text{eq. (9.11)}

where $\alpha = \text{the angle between the shear reinforcement and the main steel}$.

For Shearfix, $\alpha = 90^\circ$ therefore $\sin \alpha = 1, \cos \alpha = 0$.

Therefore equation (9.11) can be rearranged and simplified: $A_{sw,min} \geq 0.08s_r s_t \sqrt{f_{ck}} / 1.5f_{yk}$

where $s_t = \text{maximum tangential spacing of outermost studs [mm]}$

Typically, the number of shear studs per perimeter, or number of shear rails installed, is driven by the minimum spacing rules as described in Section 15. The area of punching shear reinforcement required per perimeter then dictates the size of each shear stud.
14 National Annex parameter values
The primary focus of our design approach is the Eurocode and its UK National Annex. However, to accommodate designs to other European National Annexes, the software allows the user to manually alter parameter values which are specified in the UK National Annex.

The values in grey font below can be altered. The value stated is the value in the UK National Annex and is set as default in the software.

<table>
<thead>
<tr>
<th>National Annex parameters</th>
<th>Clauses</th>
<th>Purpose of parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Rd,c} = 0.18/\gamma_C$</td>
<td>6.4.4(1)</td>
<td>To calculate the design punching shear resistance of slabs without shear reinforcement, $\nu_{Rd,c}$</td>
</tr>
<tr>
<td>$\nu_{\min} = 0.035k^{3/2}f_{ck}^{1/2}$</td>
<td>6.4.5(3)</td>
<td>The maximum limiting punching shear resistance at the column face</td>
</tr>
<tr>
<td>$k_1 = 1.0$</td>
<td>6.4.5(1)</td>
<td>The maximum limiting punching shear resistance of the slab with shear reinforcement</td>
</tr>
<tr>
<td>$\nu_{Rd,max} = 0.5\nu_{fcd}$</td>
<td>6.4.5(4)</td>
<td>The outermost perimeter of shear reinforcement should be placed at a distance not greater than $kd$ within $u_{out}$ or $u_{out,ef}$.</td>
</tr>
</tbody>
</table>

15 Layout of punching shear reinforcement
We have developed a procedure to determine the layout of Shearfix. This procedure is designed to accommodate the following detailing rules:

- Punching shear reinforcement should be detailed in accordance with BS EN 1992-1-1:2004 and its associated National Annex.
- The first stud is to be placed between 0.3d and 0.5d from the column face. (BS EN 1992-1-1:2004, Figure 9.10 a) and 9.4.3 (4).) (The default value is 0.5d.)
- Radial spacing of studs should not exceed 0.75d. (BS EN 1992-1-1:2004, 9.4.3 (1).)
- The maximum tangential spacing of studs inside the basic control perimeter is 1.5d. (BS EN 1992-1-1:2004, 9.4.3 (1).)
- The maximum tangential spacing of studs outside the basic control perimeter is 2d. (BS EN 1992-1-1:2004, 9.4.3 (1).)
- The minimum distance between a stud and a slab edge is 0.75d.
- The minimum tangential spacing between shear studs is 0.75d.
- The outermost perimeter of studs should be at a distance no greater than 1.5d within $u_{out}$. (NA to BS EN 1992-1-1:2004, 6.4.5 (4).)
- The shape of the outer control perimeter $u_{out}$ is dependent on the arrangement of shear reinforcement, the effective column dimensions and the ineffective regions due to slab openings. (See later in this section for more details.)
- There must be a minimum of two perimeters of punching shear reinforcement (according to the Eurocode). (BS EN 1992-1-1:2004, 9.4.3 (1).) See the next point.
If the outer control perimeter $u_{out}$ is situated within a distance of 3d from the column face, the shear studs should be placed between 0.3d and 1.5d from the column face. (NA to BS EN 1992-1-1:2004, 6.4.5 (4).) This is a UK National Annex criterion which effectively sets a minimum of three perimeters of punching shear reinforcement, overriding the Eurocode minimum of two perimeters.

- Two radial layouts and a cruciform layout are available.
- Radial layouts are permitted with any column shape. Cruciform layouts are only permitted with rectangular columns.
- With both radial layouts additional secondary reinforcement may be required to achieve the minimum tangential spacing between studs.
- With cruciform layouts secondary reinforcement is required at column corners.
- With cruciform layouts, increasing the number of studs per rail to more than three does not increase the length of the outer control perimeter, $u_{out}$. Therefore, three studs per rail is treated as both the minimum and the maximum number of shear studs per rail for a cruciform layout (when designing to suit the UK National Annex.)

The general procedures for radial and cruciform layouts are presented below.

### 15.1 Radial layout general procedure

Figure 14 illustrates the setting out points for radial layouts. For rectangular columns, the four setting out points are a distance $c_3$ and $c_4$ from each corner. For circular columns, the setting out point is at the column centre. For oval columns, the two setting out points are at the radial centres of the circular column ends.

$$c_3 = c_4 = \min \left( \frac{y}{2}, \frac{z}{2}, 0.75d \right)$$

**Figure 14 Radial layout setting out points**

Secondary rails are placed between radial main rails where the tangential distance between studs exceeds the maximum limit. Inside the basic control perimeter, this limit is 1.5d. Outside the basic control perimeter, this limit is 2d.
15.2 Cruciform layout general procedure

Cruciform layouts are only permitted for rectangular columns. Figure 16 illustrates the setting out points for cruciform layouts which are at a distance of $s_{0}$ from each column corner. On two faces these columns are full length main rails; on the other two faces these are secondary rails (shorter by one stud).

Further main rails are placed along the column faces as necessary to suit a maximum spacing of 1.5d. If the minimum distance between the outermost studs at each corner is greater than 2d, a further secondary rail is placed parallel to, and a distance of 0.75d from, the first secondary rail.
15.3 Rails near slab openings and distribution rails

Any rails which pass through an opening in the slab are deleted. Any rail with at least one shear stud in an ineffective area becomes a distribution rail. An area of slab becomes ineffective due to: (a) an opening; or, (b) its distance from the corner of a large or elongated column (according to the design approach selected: Best Practice or EC2). Any rails which have all studs in an ineffective opening zone are deleted.

An example rail layout is illustrated in Figure 18. All rails illustrated are main rails unless indicated otherwise. In this example, there are fifteen main rails, six distribution rails and no secondary rails. This is an example of a “large” column adhering to the “Best Practice” design approach. It also illustrates a reduction in the basic and outer control perimeters due to the slab opening.

If the designer selects the Best Practice approach, they can chose to include or exclude distribution rails. If distribution rails are excluded, it is recommended that the designer independently checks the shear capacity in the ineffective zone and designs shear reinforcement accordingly. Also, the designer may deduct the beam shear (one-way shear) resisted by the ineffective zones from the design punching shear resisted by the effective zones. (ie. The design shear load entered in the software may be reduced.)
16 Design Examples

<table>
<thead>
<tr>
<th>Example</th>
<th>Location</th>
<th>Shape</th>
<th>Layout</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interior</td>
<td>Rectangular</td>
<td>Cruciform</td>
<td>Change in slab depth</td>
</tr>
<tr>
<td>2</td>
<td>Edge</td>
<td>Oval</td>
<td>Radial</td>
<td>Edge → internal + virtual opening</td>
</tr>
<tr>
<td>3</td>
<td>Corner</td>
<td>Rectangular</td>
<td>Optimum</td>
<td>“Elongated” column</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rectangular opening</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Two layers of reinforcement</td>
</tr>
<tr>
<td>4</td>
<td>Re-entrant corner</td>
<td>Circular</td>
<td>Radial</td>
<td>Circular opening</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Two layers of reinforcement</td>
</tr>
</tbody>
</table>
16.1 Internal rectangular column

16.1.1 Inputs

Internal rectangular column

<table>
<thead>
<tr>
<th>Dimensions,</th>
<th>y = 600 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>z = 400 mm</td>
<td></td>
</tr>
<tr>
<td>Slab depth,</td>
<td>h₁ = 290 mm</td>
</tr>
<tr>
<td></td>
<td>h₂ = 250 mm</td>
</tr>
<tr>
<td>Change in slab depth: bottom surface</td>
<td>@ y = 0 mm</td>
</tr>
<tr>
<td>Concrete grade,</td>
<td>C30/37</td>
</tr>
<tr>
<td>fₜₜ = 30 N/mm²</td>
<td></td>
</tr>
<tr>
<td>Top cover,</td>
<td>cₜₒₜₜ = 30 mm</td>
</tr>
<tr>
<td>Bottom cover,</td>
<td>cₜₒₜₜ,ᵦ = 30 mm</td>
</tr>
<tr>
<td>Pre-compression,</td>
<td>σₒₜ = 0 N/mm²</td>
</tr>
<tr>
<td>Reinforcement, Layer 1,</td>
<td>y·y H16 @200 mm c/c</td>
</tr>
<tr>
<td></td>
<td>z·z H16 @200 mm c/c</td>
</tr>
<tr>
<td>Loading Design shear</td>
<td>Vₑᵈ = 600 kN</td>
</tr>
<tr>
<td>β</td>
<td>To be calculated</td>
</tr>
<tr>
<td>Design moments</td>
<td>Mₑᵈ,ₓ = 20 kNm</td>
</tr>
<tr>
<td></td>
<td>Mₑᵈ,ᵧ = 40 kNm</td>
</tr>
<tr>
<td>Distance to first stud</td>
<td>Sᵣ₀ = 0.5 d</td>
</tr>
</tbody>
</table>

Shearfix Layout Cruciform

Stud ø Automatic optimal

Rail placing Bottom-up

Large and elongated columns Best Practice

Include distribution rails Yes

![Diagram of internal rectangular column]

16.1.2 Design

Design parameters

Effective depth, based on minimum slab depth, \( h = \min(h₁, h₂) = h₂ \)

\[
d_{y₁} = h - cₜₒₜₜ,ᵦ - \varnothing y₁/2 = 212 \text{ mm}
\]

\[
d_{z₁} = h - cₜₒₜₜ,ᵦ - \varnothing y₁ - \varnothing z₁/2 = 196 \text{ mm}
\]

\[
d = (d_{y₁} + d_{z₁})/2 = 204 \text{ mm}
\]

Control perimeters,

\( a = \max(y, z) = 600 \text{ mm} \quad b = \min(y, z) = 400 \text{ mm} \)

\[
a₁ = \min(a, 4b, 3d) = \min(600, 1600, 612) = 600 \text{ mm}
\]

\[
b₁ = \min(b, 3d) = \min(400, 612) = 400 \text{ mm}
\]
Ancon Shearfix Punching Shear Reinforcement

\[ u_0 = 2a_1 + 2b_1 \]
\[ u_1 = 2a_1 + 2b_1 + 4\pi d \]
\[ = 2000\text{mm} \]
\[ = 4564\text{mm} \]

Reinforcement ratio,
\[ \rho_y = \frac{A_{sy1}}{A_{cy1}} = 0.00474 \]
\[ \rho_z = \frac{A_{sz1}}{A_{cz1}} = 0.00513 \]
\[ \rho_i = \sqrt{\rho_y \times \rho_z} = 0.00493 \quad (\equiv 0.493\%) \]

Load increase factor,

Internal column with biaxial moments: greatest value of
\[ \beta = 1 + k \frac{M'_{Ed} u_1}{V_{Ed} W_1} \quad \text{and} \quad \beta = 1 + 1.8 \sqrt{\left(\frac{\varepsilon_x}{b_x}\right)^2 + \left(\frac{\varepsilon_z}{b_y}\right)^2} \]

\[ \text{internal column:} \quad M'_{Ed,y} = M_{Ed,y} \quad \text{and} \quad M'_{Ed,z} = M_{Ed,z} \]
\[ \beta = 1 + k \frac{M'_{Ed} u_1}{V_{Ed} W_1} \]
\[ \beta = 1 + 1.8 \sqrt{\left(\frac{\varepsilon_y}{b_y}\right)^2 + \left(\frac{\varepsilon_z}{b_y}\right)^2} \]
\[ \beta = 1.098 \]
\[ \beta = 1.098 \]
\[ 1.107 > 1.098 \quad \therefore \beta = 1.107 \]

Results so far

| Effective depth | \(d\) | 204 mm |
| Control perimeters | \(u_0\) | 2000 mm |
| \(u_1\) | 4564 mm |
| Reinforcement ratios | \(\rho_i\) | 0.00493 |
| Load increase factor | \(\beta\) | 1.107 |

Shear at column face

Applied design shear at column face, \( (6.53) \)
\[ v_{Ed,0} = \frac{BV_{Ed}}{u_0 d} \]
\[ v_{Ed,0} = 1.63 \text{MPa} \]

Design shear capacity without reinforcement,
\[ v_{Ed,\text{max}} = 0.5vf_{cd} \]
where, \(NA \, 6.2.2 \, (6)\)
\[ v = 0.6 \left[ 1 - \frac{f_{ck}}{250} \right] = 0.528 \]
\[ (3.15) \quad f_{cd} = \frac{f_{ck}}{\gamma_c} \]

Table 2.1N \( \gamma_c = 1.5 \) “persistent and transient”
Ancon Shearfix Punching Shear Reinforcement

NA 3.1.6 (1) \( \alpha_{cc} = 1.0 \) “all other phenomena” 
\( f_{cd} = 20.0 \text{ MPa} \)
\( v_{Rd,max} = 5.28 \text{ MPa} \)

CHECK: \( v_{Ed,0} \leq v_{Rd,max} \) → OK to proceed with design

Shear at basic control perimeter without reinforcement

Applied design shear at basic control perimeter, (6.38) 
\[ v_{Ed,1} = \frac{\beta v_{Ed}}{u_1 d} \quad v_{Ed,1} = 0.71 \text{ MPa} \]

Design shear capacity without reinforcement, 
\[ (6.47) \quad v_{Rd,c} = \left[ C_{Rd,c} k \left( 100 \rho_l f_{ck} \right)^{1/3} + k_1 \sigma_{cp} \right] \geq \left( v_{\min} + k_1 \sigma_{cp} \right) \]
where, 
\[ C_{Rd,c} = 0.18 / \gamma_c = 0.12 \]
\[ k = 1 + \sqrt{200/d} \leq 2.0 \quad \rightarrow k = 1.99 \]
\[ \rho_l = \sqrt{\rho_iz \rho_{iy}} \leq 0.02 \quad \rightarrow \rho_l = 0.00493 \]
(NA6.4.4) \( k_1 = 0.1 \)
(NA6.4.4) \( v_{\min} = 0.035 k^{3/2} f_{ck}^{1/2} = 0.538 \)
\[ v_{Rd,c} = 0.586 \geq 0.538 \quad v_{Rd,c} = 0.59 \text{ MPa} \]

Limiting value of punching shear capacity, 
\[ v_{Rd,c,max} = 2 \times v_{Rd,c} \quad v_{Rd,c,max} = 1.17 \text{ MPa} \]

CHECK: 
\( v_{Ed,1} > v_{Rd,c} \) → punching shear reinforcement required
\( v_{Ed,1} \leq v_{Rd,c,max} \) → OK to proceed with design

Extent of punching shear reinforcement required

Control perimeter at which reinforcement is no longer required, 
\[ u_{out,req} = \frac{\beta v_{Ed}}{v_{Rd,c} d} \quad u_{out,req} = 5554 \text{ mm} \]

Cruciform layout

Cruciform layouts limited to shear rails with 3 studs. (Increasing the number of studs does not increase \( u_{out,ef} \).)

Distance to first stud, 
\[ s_{r0} = 0.5 d = 102 \text{ mm} \]
rounded down to nearest 1mm \( \rightarrow s_{r0} = 102 \text{ mm} \)

Radial spacing of studs, 
\[ s_r = 0.75 d = 153 \text{ mm} \]
rounded down to nearest 1mm \( \rightarrow s_r = 153 \text{ mm} \)
\[ u_{out,ef} = 2 \times (y_{sr0} + 2d + 0.75\pi d + z_{sr0} + 2d + 0.75\pi d) \]

where

\[ y_{sr0} = y + 2 \times s_{r0} = 804 \text{ mm} \]
\[ z_{sr0} = z + 2 \times s_{r0} = 604 \text{ mm} \]

\[ u_{out,ef} = 6371 \text{ mm} \geq u_{out,req} = 5554 \text{ mm} \]

Therefore, a cruciform layout is possible for this case.

**Number of main rails**

\[ y_{sr0} > 1.5d \rightarrow \frac{y_{sr0}}{1.5d} = \frac{804}{306} = 2.63 \rightarrow 4 \text{ rails perpendicular to y-face} \]
\[ z_{sr0} > 1.5d \rightarrow \frac{z_{sr0}}{1.5d} = \frac{604}{306} = 1.97 \rightarrow 3 \text{ rails perpendicular to z-face} \]

\[ \rightarrow 10 \text{ main rails} + 4 \text{ secondary rails as illustrated.} \]
Length of main rails
There must be three studs per main rail.

Secondary rails
Maximum permitted tangential spacing of studs, \(2d = 408\) mm
Actual tangential spacing of outermost studs, \(\sqrt{8s_r^2} = 432.75 > 408\)
Therefore, another 4 secondary rails required with two shear studs per rail.

Shear stud size
\[
A_{sw} = \left( v_{Ed,1} - 0.75v_{Rd,c} \right) s_r u_1 / 1.5f_{yw,ef} \quad \text{and} \quad A_{sw,\text{min}} \geq 0.08s_r s_t \sqrt{f_{ck}} / 1.5f_{yk}
\]
where
- \(f_{yk} = 500\) MPa
- \(f_{yw,ef} = 250 + 0.25d \leq f_{yw}\)
- \(f_{yw} = \frac{f_{yk}}{1.15} = 435\) MPa
- \(s_r = 153\) mm
- \(s_t = 433\) mm

\(A_{sw} = 424\) mm\(^2\) per perimeter
\(A_{sw,\text{min}} = 39\) mm\(^2\) per stud
Minimum number of main rail shear studs per perimeter = 10
\[
A_{\text{stud}} = \frac{A_{sw}}{n_{mr}} \geq A_{sw,\text{min}}
\]
\(A_{\text{stud}} = 42.4 \geq 39\)
\(A_{\text{stud,required}} = 42.4\)
10mm ø stud:
\(A_{\text{stud,provided}} = 78.5\) mm\(^2\) > \(A_{\text{stud,required}}\)
Therefore, optimal stud diameter for a cruciform layout is 10mm ø.

Stud height
\[
h_{\text{stud},h1} = h_1 - c_{nom,t} - c_{nom,b}
\]
\(h_{\text{stud},h1} = 290 - 30 - 30 = 230\) mm
\[
h_{\text{stud},h2} = h_2 - c_{nom,t} - c_{nom,b}
\]
\(h_{\text{stud},h2} = 250 - 30 - 30 = 190\) mm
Therefore, studs are either 230mm high or 190mm high.

Shear capacity with punching shear reinforcement
Shear capacity with reinforcement,
\[
(6.52) \quad v_{rd,cs} = 0.75v_{Rd,c} + 1.5 \left( \frac{d}{s_r} \right) A_{sw} f_{yw,ef} \left( \frac{1}{u_1 d} \right) \sin \alpha
\]
where,
- \(A_{sw} = 10 \times 78.5 = 785\) mm\(^2\)
- \(\alpha = 90° \rightarrow \sin \alpha = 1\)
\(\rightarrow v_{rd,cs} = 0.95\) MPa
16.1.3 Design solution

**Cruciform layout**

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 no. main rails (3 x 10mm ø studs @ 153mm c/c, 510mm long, 190mm high)</td>
<td>3 no. main rails (3 x 10mm ø studs @ 153mm c/c, 510mm long, 230mm high)</td>
</tr>
<tr>
<td>4 no. secondary rails (2 x 10mm ø studs @ 153mm c/c, 357mm long, 190mm high)</td>
<td>4 no. secondary rails (2 x 10mm ø studs @ 153mm c/c, 357mm long, 230mm high)</td>
</tr>
</tbody>
</table>
16.2 Edge oval column

16.2.1 Inputs

<table>
<thead>
<tr>
<th>Edge oval column</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions,</td>
<td>y = 600 mm</td>
</tr>
<tr>
<td></td>
<td>z = 400 mm</td>
</tr>
<tr>
<td>Edge @ right</td>
<td>a_{e,y} = 750 mm</td>
</tr>
<tr>
<td>Slab depth,</td>
<td>h = 230 mm</td>
</tr>
<tr>
<td>Concrete grade,</td>
<td>C28/35</td>
</tr>
<tr>
<td></td>
<td>f_{ck} = 28 N/mm²</td>
</tr>
<tr>
<td>Top cover,</td>
<td>c_{nom,t} = 25 mm</td>
</tr>
<tr>
<td>Bottom cover,</td>
<td>c_{nom,b} = 25 mm</td>
</tr>
<tr>
<td>Pre-compression,</td>
<td>σ_{cp} = 0 N/mm²</td>
</tr>
<tr>
<td>Reinforcement,</td>
<td>Layer 1,</td>
</tr>
<tr>
<td></td>
<td>y-y H16 @200 mm c/c</td>
</tr>
<tr>
<td></td>
<td>z-z H16 @200 mm c/c</td>
</tr>
<tr>
<td>Loading</td>
<td>Design shear</td>
</tr>
<tr>
<td></td>
<td>V_{Ed} = 300 kN</td>
</tr>
<tr>
<td>β</td>
<td>To be calculated</td>
</tr>
</tbody>
</table>

Design moments

M_{Ed,y} = 1 kNm
M_{Ed,z} = -15 kNm

Distance to first stud 

S_{r0} = 0.5 d

Shearfix

Layout 45° Radial
Stud Ø Automatic optimal
Rail placing Bottom-up

Large and elongated columns

Best Practice

Include distribution rails

Yes

16.2.2 Design

**Design parameters**

Effective depth,

\[ d_{y1} = h - c_{nom,t} - \phi_{y1}/2 \quad = 197\text{mm} \]
\[ d_{z1} = h - c_{nom,t} - \phi_{y1} - \phi_{z1}/2 \quad = 181\text{mm} \]
\[ d = (d_{y1} + d_{z1})/2 \quad = 189\text{mm} \]

Control perimeters,

\[ L = \max(y, z) = 600\text{mm} \quad D = \min(y, z) = 400\text{mm} \]
\[ L_1 = \min(L - D, 3D, 3d) = \min(200, 1200, 567) = 200\text{mm} \]
\[ L_{1u0} = \min(L - D, 3D, 1.5d) = \min(200, 1200, 283.5) = 200\text{mm} \]
Ancon Shearfix Punching Shear Reinforcement

\[ g_L = L + a_L - \frac{D}{2} = 1150 \text{mm} \quad \text{where} \quad a_L = a_{e,y} = 750 \text{mm} \]

\[ u_{0,\text{edge}} = 2L_{u0} + \frac{\pi}{2}D = 1028 \text{mm} \]

\[ u_{1,\text{edge}} = 2L_1 + \frac{\pi}{2}(D + 4d) + 2(g_L - L + D) = 4116 \text{mm} \]

\[ u_{0,\text{int}} = 2L_1 + \pi D = 1657 \text{mm} \]

\[ u_{1,\text{int}} = 2L_1 + \pi(D + 4d) = 4032 \text{mm} \]

\[ u_{1,\text{int}} < u_{1,\text{edge}} \quad \rightarrow \quad \text{design as internal column} \]

\[ a_y < 6d \quad \rightarrow \quad \text{treat edge as virtual opening} \]

opening:

\[ l_y = \frac{y}{2} + a_{e,y} + \frac{y'}{2} = 1100 \text{mm}, l_z = 0 \text{mm} , \]

\[ y' = 100 \text{mm}, z' = z + 12d = 2668 \text{mm} \]

... with opening reduction,

\[ u_0 = 1134 \text{mm} \]

\[ u_1 = 2829 \text{mm} \]

Reinforcement ratio,

\[ \rho_{ly} = \frac{A_{sy1}}{A_{cy1}} = 0.00510 \quad \rho_{lz} = \frac{A_{sz1}}{A_{cz1}} = 0.00555 \]

\[ \rho_l = \sqrt{\rho_{ly} \times \rho_{lz}} = 0.00532 (\equiv 0.532\%) \]

Load increase factor,

Internal column with biaxial moments: greatest value of

\[ \beta = 1 + k \frac{M'_{Ed,y}}{V_{Ed}/W_1} \quad \text{and} \quad \beta = 1 + 1.8 \sqrt{\left(\frac{e_y}{b_y}\right)^2 + \left(\frac{e_z}{b_z}\right)^2} \]

internal column: \[ M'_{Ed,y} = M_{Ed,y} \quad \text{and} \quad M'_{Ed,x} = M_{Ed,x} \]

\[ u_1 = 4032 \text{ mm} \quad \text{(without opening reduction)} \]

\[ \beta = 1 + k \frac{M'_{Ed,y}}{V_{Ed}/W_1} \quad \rightarrow \beta = 1.076 \]

\[ \beta = 1 + 1.8 \sqrt{\left(\frac{e_y}{b_y}\right)^2 + \left(\frac{e_z}{b_z}\right)^2} \quad \rightarrow \beta = 1.078 \]

\[ 1.078 > 1.076 \quad \therefore \beta = 1.078 \]

Results so far

<table>
<thead>
<tr>
<th>Effective depth</th>
<th>d = 189 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control perimeters</td>
<td>( u_0 = 1134 \text{ mm} )</td>
</tr>
<tr>
<td>( u_1 = 2829 \text{ mm} )</td>
<td></td>
</tr>
<tr>
<td>Reinforcement ratios</td>
<td>( \rho_l = 0.00532 )</td>
</tr>
<tr>
<td>Load increase factor</td>
<td>( \beta = 1.078 )</td>
</tr>
</tbody>
</table>
Shear at column face

Applied design shear at column face, \[ v_{Ed,0} = \frac{Bv_{Ed}}{u_0d} \]

where, \( u_0 = 1134 \text{ mm} \) (with opening reduction)

Design shear capacity without reinforcement, \[ v_{Rd,max} = 0.5vf_{cd} \]

Design shear at column face, \[ v_{Ed,0} = 1.51 \text{ MPa} \]

Design shear capacity without reinforcement, \[ v_{Rd,max} = 4.97 \text{ MPa} \]

CHECK: \[ v_{Ed,0} \leq v_{Rd,max} \rightarrow \text{OK to proceed with design} \]

Table 2.1N

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>( \gamma_c )</th>
<th>( f_{cd} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent and transient</td>
<td>1.5</td>
<td>18.67 MPa</td>
</tr>
<tr>
<td>All other phenomena</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

\( f_{cd} = \frac{a_{cc}f_{ck}}{\gamma_c} \)

Design Manual 6 April 2021
Shear at basic control perimeter without reinforcement

Applied design shear at basic control perimeter, (6.38) \( v_{Ed,1} = \frac{\beta V_{Ed}}{u_1d} \)

where, \( u_1 = 2829 \text{ mm} \) (with opening reduction)

\[ v_{Ed,1} = 0.60 \text{ MPa} \]

Design shear capacity without reinforcement,

(6.47) \( v_{Rd,c} = \left[ C_{Rd,c} k \left( 100 \rho_0 f_{ck} \right)^{1/3} + k_1 \sigma_{cp} \right] \geq \left( v_{min} + k_1 \sigma_{cp} \right) \)

where,

\[ C_{Rd,c} = 0.18 / y_c = 0.12 \]

\[ k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad \Rightarrow k = 2.0 \]

\[ \rho_l = \sqrt{\rho_x \rho_y} \leq 0.02 \quad \Rightarrow \rho_l = 0.00532 \]

(NA6.4.4) \[ k_1 = 0.1 \]

(NA6.4.4) \[ v_{min} = 0.035 k^{3/2} f_{ck}^{1/2} = 0.524 \]

\[ v_{Rd,c} = 0.591 \geq 0.524 \quad v_{Rd,c} = 0.59 \text{ MPa} \]

Limiting value of punching shear capacity,

\[ v_{Rd,c,\text{max}} = 2 \times v_{Rd,c} = 1.18 \text{ MPa} \]

CHECK:

\[ v_{Ed,1} > v_{Rd,c} \quad \Rightarrow \text{punching shear reinforcement required} \]

\[ v_{Ed,1} \leq v_{Rd,c,\text{max}} \quad \Rightarrow \text{OK to proceed with design} \]

Extent of punching shear reinforcement required

Control perimeter at which reinforcement is no longer required,

\[ u_{out,\text{req}} = \frac{\beta V_{Ed}}{v_{Rd,c,d}} \]

\[ u_{out,\text{req}} = 2897 \text{ mm} \]

45° Radial layout

Number of main rails

\( D/2 = 200 \text{ mm} \)

\[ s_2 = L - D = 200 \text{ mm} \geq 0.75d \leq 1.5d \quad \Rightarrow 2 \text{ rails perpendicular to } y \text{-face} \]

potentially 10 main rails, depending on location of opening(s).

Three rails located entirely within ineffective opening zone, therefore, 7 main rails required.
Ancon Shearfix Punching Shear Reinforcement

Length of main rails
Distance to first stud, \( s_{r0} = 0.5d = 94.5\, \text{mm} \)
rounded down to nearest 1mm \( \rightarrow s_{r0} = 94\, \text{mm} \)
Radial spacing of studs, \( s_r = 0.75d = 141.75\, \text{mm} \)
rounded down to nearest 1mm \( \rightarrow s_r = 141\, \text{mm} \)

By trial and error, using CAD, length of outer perimeter for different numbers of studs on main rails:

<table>
<thead>
<tr>
<th>Number of studs per main rail</th>
<th>Length of outer perimeter</th>
<th>Sufficient?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4054 mm</td>
<td>≥ 2829 sufficient</td>
</tr>
</tbody>
</table>

Therefore, three studs per main rail required.

Secondary rails
Maximum tangential spacing inside basic control perimeter, \( 1.5d = 283.5\, \text{mm} \)

<table>
<thead>
<tr>
<th>Stud number</th>
<th>Maximum tangential spacing</th>
<th>Secondary rail required?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>441 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>2</td>
<td>333 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>1</td>
<td>225 mm</td>
<td>&lt; 1.5d secondary rail not required</td>
</tr>
</tbody>
</table>

Therefore, six secondary rails required with two shear studs per rail.

Shear stud size
\[
A_{sw} = \left( v_{Ed,1} - 0.75v_{Rd,c} \right) s_r u_1 / 1.5 \frac{f_y w_d, \text{ef}}{} \quad \text{and} \quad A_{sw, \text{min}} \geq 0.08s_r s_t \sqrt{f_{ck}} / 1.5f_y k
\]

where
\[
f_y k = 500 \, \text{MPa} \\
\frac{f_y w_d, \text{ef}}{} = 250 + 0.25d \leq f_y w_d \\
\frac{f_y w_d}{1.15} = 435 \, \text{MPa} \\
\frac{f_y w_d, \text{ef}}{} = 297 \leq 435 \\
s_r = 141 \, \text{mm} \\
s_t = 441 \, \text{mm}
\]

\( A_{sw} = 145.0 \, \text{mm}^2 \, \text{per perimeter} \)
\( A_{sw, \text{min}} = 35.1 \, \text{mm}^2 \, \text{per stud} \)

Minimum number of effective main rail shear studs per perimeter = 7
\[
A_{\text{stud}} = \frac{A_{sw}}{n_{mr}} \geq A_{sw, \text{min}} \\
A_{\text{stud}} = 20.7 < 35.1 \\
A_{\text{stud,required}} = 35.1
\]

10mm Ø stud:
\( A_{\text{stud,provided}} = 78.5 \, \text{mm}^2 \geq A_{\text{stud,required}} \)
Therefore, optimal stud diameter for a 45° radial layout is 10mm Ø

Stud height
\[
h_{\text{stud}} = h - c_{\text{nom,t}} - c_{\text{nom,b}} \\
h_{\text{stud}} = 230 - 25 - 25 = 180 \, \text{mm}
\]
Therefore, studs are 180mm high.

Shear capacity with punching shear reinforcement
Shear capacity with reinforcement,
\[
(6.52) \quad v_{Rd,cs} = 0.75v_{Rd,c} + 1.5 \left( \frac{d}{s_r} \right) A_{sw} f_y w_d, \text{ef} \left( \frac{1}{u_1 d} \right) \sin \alpha
\]
where,
\[
A_{sw} = 7 \times 78.5 = 550 \, \text{mm}^2 \\
\alpha = 90° \quad \rightarrow \sin \alpha = 1 \quad \rightarrow v_{Rd,cs} = 1.06 \, \text{MPa}
\]
16.2.3 Design solution

45° radial layout

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 no. main rails (3 x 10mm ø studs @ 141mm c/c, 470mm long, 180mm high)</td>
<td></td>
</tr>
<tr>
<td>6 no. secondary rails (2 x 10mm ø studs @ 141mm c/c, 329mm long, 180mm high)</td>
<td></td>
</tr>
</tbody>
</table>
16.3 Corner rectangular column

16.3.1 Inputs

<table>
<thead>
<tr>
<th>Corner rectangular column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions, ( y = 300 ) mm</td>
</tr>
<tr>
<td>( z = 900 ) mm</td>
</tr>
<tr>
<td>Edge @ right ( a_{e,y} = 400 ) mm</td>
</tr>
<tr>
<td>Edge @ top ( a_{e,z} = 250 ) mm</td>
</tr>
<tr>
<td>Slab depth, ( h = 250 ) mm</td>
</tr>
<tr>
<td>Concrete grade, C35/45 ( f_{ck} = 35 ) N/mm²</td>
</tr>
<tr>
<td>Top cover, ( c_{nom,t} = 25 ) mm</td>
</tr>
<tr>
<td>Bottom cover, ( c_{nom,b} = 25 ) mm</td>
</tr>
<tr>
<td>Pre-compression, ( \sigma_{cp} = 0 ) N/mm²</td>
</tr>
<tr>
<td>Reinforcement, Layer 1, ( y )-( y ) H12 @150 mm c/c</td>
</tr>
<tr>
<td>( z )-( z ) H12 @150 mm c/c</td>
</tr>
<tr>
<td>Layer 2, ( y )-( y ) H16 @150 mm c/c</td>
</tr>
<tr>
<td>( z )-( z ) H16 @150 mm c/c</td>
</tr>
<tr>
<td>Loading Design shear ( V_{Ed} = 210 ) kN</td>
</tr>
<tr>
<td>( \beta ) To be calculated</td>
</tr>
<tr>
<td>Design moments ( M_{Ed,y} = 12 ) kNm</td>
</tr>
<tr>
<td>( M_{Ed,z} = -10 ) kNm</td>
</tr>
<tr>
<td>Opening Rectangular ( l_y = -800 ) mm</td>
</tr>
<tr>
<td>( l_z = 450 ) mm</td>
</tr>
<tr>
<td>( y' = 100 ) mm</td>
</tr>
<tr>
<td>( z' = 200 ) mm</td>
</tr>
<tr>
<td>Distance to first stud ( S_{r0} = 0.5 ) d</td>
</tr>
<tr>
<td>Shearfix Layout Automatic optimal</td>
</tr>
<tr>
<td>Stud ø Automatic optimal</td>
</tr>
<tr>
<td>Rail placing Bottom-up</td>
</tr>
<tr>
<td>Large and elongated columns Best Practice</td>
</tr>
<tr>
<td>Include distribution rails Yes</td>
</tr>
</tbody>
</table>

![Diagram of corner rectangular column](image)
Ancon Shearfix Punching Shear Reinforcement

16.3.2 Design

Design parameters

Effective depth,
\[ \begin{align*}
  d_{y1} &= h - c_{nom,t} - \phi_{y1}/2 = 219\text{mm} \\
  d_{z1} &= h - c_{nom,t} - \phi_{y1} - \phi_{z1}/2 = 207\text{mm} \\
  d_{y2} &= h - c_{nom,t} - \phi_{y1} - \phi_{z1} - \phi_{y2}/2 = 193\text{mm} \\
  d_{z2} &= h - c_{nom,t} - \phi_{y1} - \phi_{z1} - \phi_{y2} - \phi_{z2}/2 = 177\text{mm} \\
  d &= (d_{y1} + d_{z1} + d_{y2} + d_{z2})/4 = 199\text{mm}
\end{align*} \]

Opening,
\[ l_1 = 100\text{mm}, \quad l_2 = 200\text{mm}, \quad \sqrt{l_1 \times l_2} = 141.42\text{mm} \]
where \( l_3 \) found using CAD: \( l_3 = 222.04\text{mm} \geq \sqrt{l_1 l_2} \quad \therefore \ l_3 = 222\text{mm} \)

Control perimeters,
\[ \begin{align*}
  a &= \max(y, z) = 900\text{mm} \quad b = \min(y, z) = 300\text{mm} \\
  g_a &= a_{e,x} = 250\text{mm} \quad g_b &= a_{e,y} = 400\text{mm} \\
  a_1 &= \min(a, 4b, 3d) = \min(900, 1200, 597) = 597\text{mm} \\
  a_{1u0} &= \min(a, 4b, 1.5d) = \min(900, 1200, 298.5) = 298.5\text{mm} \\
  b_1 &= \min(b, 3d) = \min(300, 597) = 300\text{mm} \\
  b_{1u0} &= \min(b, 1.5d) = \min(300, 298.5) = 298.5\text{mm}
\end{align*} \]

without opening,
\[ \begin{align*}
  u_0 &= a_{1u0} + b_{1u0} = 597\text{mm} \\
  u_1 &= a_1 + b_1 + g_a + g_b + \pi d = 2172\text{mm}
\end{align*} \]

with opening,
\[ \begin{align*}
  u_0 &= a_{1u0} + b_{1u0} = 597\text{mm} \\
  u_1 &= a_1 + b_1 + g_a + g_b + \pi d = 1996\text{mm}
\end{align*} \]

Reinforcement ratio,
\[ \rho_{y} = \frac{A_{y1}}{A_{cy1}} + \frac{A_{y2}}{A_{cy2}} = 0.0104 \quad \rho_{z} = \frac{A_{z1}}{A_{cz1}} + \frac{A_{z2}}{A_{cz2}} = 0.0112 \]
\[ \rho_{t} = \sqrt{\rho_{y} \times \rho_{z}} = 0.01079 \ (\equiv 1.079\%) \]

Load increase factor,

Corner column: Is moment towards interior or exterior of slab? centroid of control perimeter (ignoring opening reduction), where a positive \( y_0 \) or \( z_0 \) value is in negative \( y \)- or \( z \)-direction.
\[ \begin{align*}
  y_0 &= 265.3\text{mm} \\
  z_0 &= 409.6\text{mm}
\end{align*} \]
where \( u_1 = 2172\text{mm} \) (without opening reduction)

moment about centroid of basic control perimeter,
\[ \begin{align*}
  M'_{Ed,y} &= M_{Ed,y} - z_0 V_{Ed} = -74.02\text{ kNm} \leq 0 \quad \therefore \text{towards exterior} \\
  M'_{Ed,x} &= M_{Ed,x} - y_0 V_{Ed} = -45.71\text{ kNm} \leq 0 \quad \therefore \text{towards exterior}
\end{align*} \]

Therefore, load increase factor:
\[ \beta = 1 + k \frac{M'_{Ed}}{V_{Ed} u_1} \quad \rightarrow \beta = 1.700 \]

Results so far

<table>
<thead>
<tr>
<th>Effective depth</th>
<th>( d ) = 199 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control perimeters</td>
<td>( u_0 ) = 597 mm</td>
</tr>
<tr>
<td>( u_1 ) = 1996 mm</td>
<td></td>
</tr>
</tbody>
</table>
Ancon Shearfix Punching Shear Reinforcement

<table>
<thead>
<tr>
<th>Reinforcement ratios</th>
<th>$\rho_1 = 0.01079$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load increase factor</td>
<td>$\beta = 1.700$</td>
</tr>
</tbody>
</table>

Shear at column face

Applied design shear at column face,  
(6.53)  
$$v_{Ed,0} = \frac{\beta V_{Ed}}{u_0 d}$$  
$$v_{Ed,0} = 3.00 \text{ MPa}$$

Design shear capacity without reinforcement,  
$$v_{Rd,max} = 0.5 f_{cd}$$

where, (6.6N)  
$$v = 0.6 \left[ 1 - \frac{f_{ck}}{250} \right] = 0.516$$  
(3.15)  
$$f_{cd} = \frac{a_{cc}f_{ck}}{\gamma_c}$$

Table 2.1N  
$$\gamma_c = 1.5 \quad \text{“persistent and transient”}$$  
(3.1.6)  
$$\alpha_{cc} = 1.0 \quad \text{“all other phenomena”}$$  
$$f_{cd} = 23.33 \text{ MPa}$$  

CHECK:  
$$v_{Ed,0} \leq v_{Rd,max} \quad \rightarrow \text{OK to proceed with design}$$

Shear at basic control perimeter without reinforcement

Applied design shear at basic control perimeter, (6.38)  
$$v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 d}$$  
$$v_{Ed,1} = 0.90 \text{ MPa}$$

Design shear capacity without reinforcement,  
(6.47)  
$$v_{Rd,c} = \left[ C_{Rd,c} k(100\rho_l f_{ck})^{1/3} + k_1 \sigma_{cp} \right] \geq (v_{min} + k_1 \sigma_{cp})$$

where,  
$$C_{Rd,c} = 0.18/\gamma_c = 0.12$$  
$$k = 1 + \sqrt{200/d} \leq 2.0 \quad \rightarrow k = 2.0$$  
$$\rho_l = \sqrt{\rho_{iz} \rho_{iy}} \leq 0.02 \quad \rightarrow \rho_l = 0.01079$$
Ancon Shearfix Punching Shear Reinforcement

\[(NA6.4.4) \quad k_1 = 0.1\]
\[(NA6.4.4) \quad v_{\text{min}} = 0.035k^3/2f_{ck}^{1/2} = 0.586\]
\[v_{Rd,c} = 0.805 \geq 0.586 \quad v_{Rd,c} = 0.81 \, MPa\]

Limiting value of punching shear capacity,
\[v_{Rd,c,\text{max}} = 2 \times v_{Rd,c} \quad v_{Rd,c,\text{max}} = 1.61 \, MPa\]

CHECK:
\[v_{Ed,1} > v_{Rd,c} \quad \rightarrow \text{punching shear reinforcement required}\]
\[v_{Ed,1} \leq v_{Rd,c,\text{max}} \quad \rightarrow \text{OK to proceed with design}\]

**Extent of punching shear reinforcement required**
Control perimeter at which reinforcement is no longer required,
\[u_{out,req} = \frac{\beta v_{Ed}}{v_{Rd,c}}d\]
\[u_{out,req} = 2228 \, mm\]

**30° Radial layout**

**Number of main rails**
\[c_3 = c_4 = \min \left(\frac{y}{z}, \frac{z}{y}, 0.75d\right) = 149.25 \, mm\]
\[s_1 = z + g_z - c_3 - 0.75d = 851.5 \quad \geq 1.5d \quad \frac{s_1}{1.5d} = \frac{851.5}{149.25} = 5.68 \quad \rightarrow 3 \text{ additional rails}\]
\[s_2 = y + g_y - c_4 - 0.75d = 401.5 \quad \geq 1.5d \quad \frac{s_2}{1.5d} = \frac{401.5}{149.25} = 2.68 \quad \rightarrow 2 \text{ additional rails}\]

\[\rightarrow \text{potentially 9 main rails, depending on location of opening(s).}\]

**No rails pass through cover zone of opening and no rails are located entirely within ineffective opening zone, therefore, 9 main rails required.**
Length of main rails
Distance to first stud, \( s_{r0} = 0.5d = 99.5\mm \)
rounded down to nearest 1mm \( \rightarrow s_{r0} = 99\mm \)
Radial spacing of studs, \( s_r = 0.75d = 149.25\mm \)
rounded down to nearest 1mm \( \rightarrow s_r = 149\mm \)

By trial and error, using CAD, length of outer perimeter for different numbers of studs on main rails:

<table>
<thead>
<tr>
<th>Number of studs per main rail</th>
<th>Length of outer perimeter</th>
<th>Sufficient?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2331 mm</td>
<td>( \geq 2228 ) sufficient</td>
</tr>
</tbody>
</table>

Therefore, three studs per main rail required.

Secondary rails
Maximum tangential spacing inside basic control perimeter, \( 1.5d = 298.5\mm \)

<table>
<thead>
<tr>
<th>Stud number</th>
<th>Maximum tangential spacing</th>
<th>Secondary rail required?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>295 mm</td>
<td>( \leq 1.5d ) secondary rail not required</td>
</tr>
</tbody>
</table>

Therefore, secondary rails not required.

Shear stud size

\[
A_{sw} = \left(v_{Ed,1} - 0.75v_{Rd,c}\right) s_r u_r / 1.5f_{ywd,ef}\quad \text{and} \quad A_{sw,min} \geq 0.08s_r s_t \sqrt{f_{ck}} / 1.5f_{yk}
\]

where

\[
f_{yk} = 500 \MPa
\]
\[
f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}
\]
\[
f_{ywd} = \frac{f_{yk}}{1.15} = 435 \MPa
\]
\[
f_{ywd,ef} = 300 \leq 435
\]
\[
s_r = 149 \mm
\]
\[
s_t = 295 \mm
\]

\(A_{sw} = 195.1 \mm^2\) per perimeter
\(A_{sw,min} = 27.7 \mm^2\) per stud

Minimum number of effective main rail shear studs per perimeter = 7
(not including distribution rails indicated in figure below)

\[
A_{stud} = A_{sw} / n_{mr} \geq A_{sw,min}
\]
\(A_{stud} = 27.9 \geq 27.7\)
\(A_{stud,required} = 27.9\)

10mm \( \phi \) stud:

\(A_{stud,provided} = 78.5 \mm^2 > A_{stud,required}\)

Therefore, optimal stud diameter for a 30° radial layout is 10mm \( \phi \)

Stud height

\[
h_{stud} = h - c_{nom,t} - c_{nom,b}
\]
\[
h_{stud} = 250 - 25 - 25 = 200 \mm
\]

Therefore, studs are 200mm high.

30° radial solution:
7 no. main rails (3 x 10mm \( \phi \) studs @ 149mm c/c, 496mm long, 200mm high)
2 no. distribution rails (3 x 10mm \( \phi \) studs @ 149mm c/c, 496mm long, 200mm high)
45° Radial layout

Number of main rails

As for 30° radial layout, \( c_3 = c_4 = 149.25 \text{ mm} \)

\( s_1 = 852, \frac{s_1}{1.5d} = 2.85 \) → 3 additional rails  \( s_2 = 401, \frac{s_2}{1.5d} = 1.34 \) → 2 additional rails

\( \rightarrow \) potentially 8 main rails, depending on location of opening(s).

No rails pass through cover zone of opening and no rails are located entirely within ineffective opening zone, therefore, 8 main rails required.
Length of main rails
As for 30° radial layout, \( s_{r0} = 99\text{mm} \quad s_r = 149\text{mm} \)

By trial and error, using CAD, length of outer perimeter for different numbers of studs on main rails:

<table>
<thead>
<tr>
<th>Number of studs per main rail</th>
<th>Length of outer perimeter</th>
<th>Sufficient?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2369 mm</td>
<td>≥ 2228 sufficient</td>
</tr>
</tbody>
</table>

Therefore, three studs per main rail required.

Secondary rails
Maximum tangential spacing inside basic control perimeter, \( 1.5d = 298.5 \text{ mm} \)

<table>
<thead>
<tr>
<th>Stud number</th>
<th>Maximum tangential spacing</th>
<th>Secondary rail required?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>445 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>2</td>
<td>333 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>1</td>
<td>221 mm</td>
<td>≤ 1.5d secondary rail not required</td>
</tr>
</tbody>
</table>

Minimum rail length = 2 studs
Therefore, 2 secondary rails required with two shear studs per rail.

Shear stud size
\[
A_{sw} = \frac{(v_{Ed,1} - 0.75v_{Rd,c})s_t u_f}{1.5f_{ywde}f_{ck}} \quad \text{and} \quad A_{sw,min} \geq 0.08s_t \sqrt{f_{ck}}/1.5f_{yk}
\]

As for 30° radial layout, \( A_{sw} = 195.1 \text{ mm}^2 \text{ per perimeter} \)
\[
s_r = 149 \text{ mm} \\
s_t = 445 \text{ mm} \\
A_{sw,min} = 41.9 \text{ mm}^2 \text{ per stud}
\]

Minimum number of effective main rail shear studs per perimeter = 6
\[
A_{stud} = \frac{A_{sw}}{n_{mr}} \geq A_{sw,min} \\
A_{stud,required} = 32.5 < 41.9 \\
A_{stud,required} = 41.9
\]

10mm ø stud: \( A_{stud,provided} = 78.5 \text{ mm}^2 > A_{stud,required} \)
Therefore, optimal stud diameter for a 45° radial layout is 10mm ø

Stud height
As for 30° radial layout, studs are 200mm high.

45° radial solution:
6 no. main rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)
2 no. distribution rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)
2 no. secondary rails (2 x 10mm ø studs @ 149mm c/c, 347mm long, 200mm high)
**Cruciform layout**

Cruciform layouts limited to shear rails with 3 studs. (Increasing the number of studs does not increase $u_{\text{out,ef}}$.)
Ancon Shearfix Punching Shear Reinforcement

\[ u_{out,ef} = 2340 \, mm \geq u_{out,req} = 2228 \, mm \]
Therefore, a cruciform layout is possible for this case.

Number of main rails
\[ y + s_r + g_y - 0.75d > 0.75d \rightarrow \frac{y+s_r+g_y-0.75d}{15d} = \frac{650.0}{298.5} = 2.18 \rightarrow 4 \text{ rails perpendicular to } y\text{-face} \]
\[ z + s_r + g_z - 0.75d > 0.75d \rightarrow \frac{z+s_r+g_z-0.75d}{15d} = \frac{1100.0}{298.5} = 3.68 \rightarrow 5 \text{ rails perpendicular to } z\text{-face} \]

Secondary rails
Maximum permitted tangential spacing of studs, \(2d = 398 \, mm\)
Actual tangential spacing of outermost studs, \(\sqrt{8s_r z} = 421 > 398\)
Therefore, a further secondary rail at the corner is required.

\[ \rightarrow 6 \text{ main rails} + 2 \text{ distribution rails} + 2 \text{ secondary rails} \text{ as illustrated.} \]

Length of main rails
Cruciform layout \(\rightarrow\) There must be three studs per main rail.

Shear stud size
\[ A_{sw} = \left( v_{Ed,1} - 0.75v_{Rd,c} \right)s_r u_1 / 1.5f_{yw,def} \quad \text{and} \quad A_{sw,\text{min}} \geq 0.08s_r s_t \sqrt{f_{ck}} / 1.5f_{yk} \]
As for 30° radial layout, \(A_{sw} = 195.1 \, mm^2 \text{ per perimeter}\)
\[ s_r = 149 \, mm \]
$s_t = 421 \text{ mm}$

$A_{sw, \text{min}} = 39.6 \text{ mm}^2 \text{ per stud}$

Minimum number of main rail shear studs per perimeter = 6

$A_{\text{stud}} = \frac{A_{sw}}{n_{mr}} \geq A_{sw, \text{min}}$

$A_{\text{stud}} = 32.5 < 39.6$

$A_{\text{stud, required}} = 39.6$

10mm ø stud: $A_{\text{stud, provided}} = 78.5 \text{ mm}^2 > A_{\text{stud, required}}$

Therefore, optimal stud diameter for a cruciform layout is 10mm ø

**Stud height**

As for 30° radial layout, studs are 200mm high.

---

**Cruciform solution:**

6 no. main rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)

2 no. distribution rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)

2 no. secondary rails (2 x 10mm ø studs @ 149mm c/c, 347mm long, 200mm high)

**Optimal layout solution**

<table>
<thead>
<tr>
<th>Layout</th>
<th>Total number of shear studs</th>
<th>Total number of rails</th>
</tr>
</thead>
<tbody>
<tr>
<td>30° radial</td>
<td>27</td>
<td>9</td>
</tr>
<tr>
<td>45° radial</td>
<td>28</td>
<td>10</td>
</tr>
<tr>
<td>Cruciform</td>
<td>28</td>
<td>10</td>
</tr>
</tbody>
</table>
Optimal solution determined by total number of shear studs and then by total number of rails. The 30° radial layout requires the smallest number of shear studs, therefore that is the optimal solution.

**Shear capacity with punching shear reinforcement**

Shear capacity with reinforcement,

\[
(6.52) \quad v_{Rd,cs} = 0.75v_{Rd,c} + 1.5\left(\frac{d}{s_r}\right)A_{sw}f_{yw,ef} \left(\frac{1}{u_1 d}\right) \sin \alpha
\]

where,

\[
A_{sw} = 6 \times 78.5 = 471 \ mm^2 \\
\alpha = 90° \quad \rightarrow \sin \alpha = 1
\]

\[
\rightarrow v_{Rd,cs} = 1.32 \ MPa
\]

### 16.3.3 Design solution

**30° radial layout**

- 7 no. main rails (3 x 10mm Ø studs @ 149mm c/c, 496mm long, 200mm high)
- 2 no. distribution rails (3 x 10mm Ø studs @ 149mm c/c, 496mm long, 200mm high)
### 16.4 Re-entrant corner circular column

#### 16.4.1 Inputs

**Re-entrant corner circular column**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>D = 400 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge @ left</td>
<td>( a_{e,y} = 200 \text{ mm} )</td>
</tr>
<tr>
<td>Edge @ top</td>
<td>( a_{e,z} = 200 \text{ mm} )</td>
</tr>
<tr>
<td>Slab depth,</td>
<td>( h = 240 \text{ mm} )</td>
</tr>
<tr>
<td>Concrete grade,</td>
<td>C40/50</td>
</tr>
<tr>
<td>( f_{ck} )</td>
<td>40 N/mm(^2)</td>
</tr>
<tr>
<td>Top cover,</td>
<td>( c_{nom,t} = 30 \text{ mm} )</td>
</tr>
<tr>
<td>Bottom cover,</td>
<td>( c_{nom,b} = 30 \text{ mm} )</td>
</tr>
<tr>
<td>Pre-compression,</td>
<td>( \sigma_{cp} = 0 \text{ N/mm}^2 )</td>
</tr>
<tr>
<td>Reinforcement,</td>
<td>Layer 1, ( y-y ) H12 @150 mm c/c</td>
</tr>
<tr>
<td></td>
<td>( z-z ) H12 @150 mm c/c</td>
</tr>
<tr>
<td></td>
<td>Layer 2, ( y-y ) H12 @200 mm c/c</td>
</tr>
<tr>
<td></td>
<td>( z-z ) H12 @200 mm c/c</td>
</tr>
</tbody>
</table>

| Loading | Design shear | \( V_{Ed} = 500 \text{ kN} \) |
| To be calculated | |
| Design moments | \( M_{Ed,y} = 5 \text{ kNm} \) |
|               | \( M_{Ed,z} = 5 \text{ kNm} \) |
| Opening 1 | Circular |
| \( l_y \) | 700 mm |
| \( l_z \) | 150 mm |
| \( \phi \) | 150 mm |

| Distance to first stud | \( S_{r0} = 0.5 \text{ d} \) |
| Shearfix | Layout | 45° Radial |
| Stud \( \phi \) | Automatic optimal |

#### 16.4.2 Design

**Design parameters**

- Effective depth,
  - \( d_{y1} = h - c_{nom,t} - \phi_{y1}/2 \) = 204 mm
  - \( d_{z1} = h - c_{nom,t} - \phi_{y1} - \phi_{z1}/2 \) = 192 mm
Ancon Shearfix Punching Shear Reinforcement

\[
d_{y2} = h - c_{nom,t} - \phi_{y1} - \phi_{z1} - \phi_{y2}/2 = 180\text{mm}
\]
\[
d_{z2} = h - c_{nom,t} - \phi_{y1} - \phi_{z1} - \phi_{y2}/2 = 168\text{mm}
\]
\[
d = (d_{y1} + d_{z1} + d_{y2} + d_{z2})/4 = 186\text{mm}
\]

Control perimeters,
\[
D_{u0} = \min(0.25\pi D, 1.5d) = \min(314, 279) = 279\text{mm}
\]
\[
g_y = a_{e,y} + \frac{d}{2} = 400\text{mm}
\]
\[
g_z = a_{e,z} + \frac{d}{2} = 400\text{mm}
\]

without opening,
\[
u_0 = 0.5\pi D + 2D_{u0} = 1186\text{mm}
\]
\[
u_1 = \frac{3\pi}{4}(D + 4d) + g_y + g_z = 3495\text{mm}
\]

with opening,
\[
u_0 = 1144\text{mm}
\]
\[
u_1 = 3375\text{mm}
\]

Reinforcement ratio,
\[
\rho_Y = \frac{A_{sy1}}{A_{cy1}} + \frac{A_{sy2}}{A_{cy2}} = 0.00683
\]
\[
\rho_z = \frac{A_{sz1}}{A_{cz1}} + \frac{A_{sz2}}{A_{cz2}} = 0.00729
\]
\[
\rho_l = \sqrt{\rho_Y \times \rho_z} = 0.00706 (\equiv 0.706\%)
\]

Load increase factor,
\[
\beta = 1 + k \frac{M_{Ed,y} u_1}{V_{Ed} W_t}
\]
\[
y_0 = 5.3\text{ mm} \quad z_0 = 5.3\text{ mm}
\]
(\text{where: } +y_0 \text{ is in } +y \text{ direction; } +z_0 \text{ is in } -z \text{ direction})
\]
\[
M_{Ed,y} = M_{Ed,y} - z_0 V_{Ed} = 2.35 \text{ kNm}
\]
\[
M_{Ed,z} = M_{Ed,z} - y_0 V_{Ed} = 2.35 \text{ kNm}
\]
\[
\beta = 1 + k \frac{M_{Ed,y} u_1}{V_{Ed} W_t} \rightarrow \beta = 1.011
\]

Results so far

<table>
<thead>
<tr>
<th>Effective depth</th>
<th>d = 186 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control perimeters</td>
<td>(u_0 = 1144\text{ mm})</td>
</tr>
<tr>
<td>(u_1 = 3375\text{ mm})</td>
<td></td>
</tr>
<tr>
<td>Reinforcement ratios</td>
<td>(\rho_l = 0.00706)</td>
</tr>
<tr>
<td>Load increase factor</td>
<td>(\beta = 1.011)</td>
</tr>
</tbody>
</table>
Shear at column face

Applied design shear at column face, \( v_{Ed,0} = \frac{\beta V_{Ed}}{u_0d} \) \( v_{Ed,0} = 2.38 \text{ MPa} \)

Design shear capacity without reinforcement, \( v_{Rd,max} = 0.5vf_{cd} \)

where, \( v = 0.6 \left[ 1 - \frac{f_{ck}}{250} \right] = 0.504 \)

\[ f_{cd} = \frac{accf_{ck}}{\gamma_c} \]

Table 2.1N \( \gamma_c = 1.5 \) “persistent and transient”

\[ f_{cd} = 26.67 \text{ MPa} \]

\( v_{Rd,max} = 6.72 \text{ MPa} \)

CHECK: \( v_{Ed,0} \leq v_{Rd,max} \) \( \rightarrow \) OK to proceed with design

Shear at basic control perimeter without reinforcement

Applied design shear at basic control perimeter, \( v_{Ed,1} = \frac{\beta V_{Ed}}{u_1d} \) \( v_{Ed,1} = 0.81 \text{ MPa} \)

Design shear capacity without reinforcement,

\( v_{Rd,c} = \left[ C_{Rd,c}k(100\rho_lf_{ck})^{1/3} + k_1\sigma_{cp} \right] \geq (v_{min} + k_1\sigma_{cp}) \)

where,

\[ C_{Rd,c} = 0.18/\gamma_c = 0.12 \]

\[ k = 1 + \sqrt{200/d} \leq 2.0 \rightarrow k = 2.0 \]

\[ \rho_l = \sqrt{\rho_x\rho_y} \leq 0.02 \rightarrow \rho_l = 0.00706 \]

(NA6.4.4) \( k_1 = 0.1 \)

(NA6.4.4) \( v_{min} = 0.035k^{3/2}f_{ck}^{1/2} = 0.626 \)

\[ v_{Rd,c} = 0.731 \geq 0.626 \]

\( v_{Rd,c} = 0.73 \text{ MPa} \)

Limiting value of punching shear capacity,

\( v_{Rd,c, max} = 2 \times v_{Rd,c} \) \( v_{Rd,c, max} = 1.46 \text{ MPa} \)

CHECK: \( v_{Ed,1} > v_{Rd,c} \) \( \rightarrow \) punching shear reinforcement required

\( v_{Ed,1} \leq v_{Rd,c, max} \) \( \rightarrow \) OK to proceed with design

Extent of punching shear reinforcement required

Control perimeter at which reinforcement is no longer required,

\[ u_{out,req} = \frac{\beta V_{Ed}}{v_{Rd,c,d}} \]

\( u_{out,req} = 3718 \text{ mm} \)

45° Radial layout

Number of main rails

\[ s_2 = g_y - 0.75d = 260 > 0.75d \rightarrow \text{ main rail parallel to edge} \]

\[ \frac{s_2}{1.5d} = \frac{260}{279} = 0.93 \rightarrow \text{ no additional rails} \]

\[ s_1 = g_z - 0.75d = 260 > 0.75d \rightarrow \text{ secondary rail parallel to edge} \]

\[ \frac{s_1}{1.5d} = \frac{260}{279} = 0.93 \rightarrow \text{ no additional rails} \]

\( \rightarrow 8 \text{ main rails and 1 secondary rail}, \) as illustrated. (Location of opening means no rails deleted.)
Length of main rails
Distance to first stud, $s_{r0} = 0.5d = 93\, mm$
rounded down to nearest 1mm $\rightarrow s_{r0} = 93\, mm$
Radial spacing of studs, $s_r = 0.75d = 139.5\, mm$
rounded down to nearest 1mm $\rightarrow s_r = 139\, mm$

By trial and error, using CAD, length of outer perimeter for different numbers of studs on main rails:

<table>
<thead>
<tr>
<th>Number of studs per main rail</th>
<th>Length of outer perimeter</th>
<th>Sufficient?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4624 mm</td>
<td>≥ 3718 sufficient</td>
</tr>
</tbody>
</table>

Therefore, three studs per main rail required.

Secondary rails
Maximum tangential spacing inside basic control perimeter, $1.5d = 279\, mm$

<table>
<thead>
<tr>
<th>Stud number</th>
<th>Maximum tangential spacing</th>
<th>Secondary rail required?</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>437 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>2</td>
<td>331 mm</td>
<td>&gt; 1.5d secondary rail required</td>
</tr>
<tr>
<td>1</td>
<td>224 mm</td>
<td>≤ 1.5d secondary rail not required</td>
</tr>
</tbody>
</table>

Therefore, six secondary rails required with two shear studs per rail. (Location of opening means no rails deleted.)

Shear stud size

$$A_{sw} = \left( v_{Ed,1} - 0.75 v_{Rd,c} \right) s_r u_1 / 1.5 f_{ywd,ef}$$
and

$$A_{sw,\min} \geq 0.08 s_r s_t \sqrt{f_{ck}} / 1.5 f_{yk}$$

where

- $f_{yk} = 500\, MPa$
- $f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$
- $f_{ywd} = f_{yk}^{\frac{1}{1.15}} = 435\, MPa$
- $f_{ywd,ef} = 297 \leq 435$
- $s_r = 139\, mm$
- $s_t = 437\, mm$
\[ A_{sw} = 270.4 \text{ mm}^2 \text{ per perimeter} \]
\[ A_{sw,\min} = 41.0 \text{ mm}^2 \text{ per stud} \]

Minimum number of effective main rail shear studs per perimeter = 8

\[ A_{\text{studs}} = \frac{A_{sw}}{n_{mr}} \geq A_{sw,\min} \]
\[ A_{\text{studs}} = 33.8 < 41.0 \]
\[ A_{\text{studs,required}} = 41.0 \]

10mm ø stud:

\[ A_{\text{studs,provided}} = 78.5 \text{ mm}^2 > A_{\text{studs,required}} \]

Therefore, optimal stud diameter for a 45° radial layout is 10mm ø.

**Stud height**

\[ h_{\text{studs}} = h - c_{\text{nom,t}} - c_{\text{nom,b}} \]
\[ h_{\text{studs}} = 240 - 30 - 30 = 180 \text{ mm} \]

Therefore, studs are 180mm high.

### 16.4.3 Design solution

**45° radial layout**

8 no. main rails (3 x 10mm ø studs @ 139mm c/c, 464mm long, 180mm high)
7 no. secondary rails (2 x 10mm ø studs @ 139mm c/c, 325mm long, 180mm high)