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Ancon

Shearfix Punching Shear Reinforcement

EC2 Design Manual

Ancon Shearfix EC2 Design Manual

Contents

Document Version Notes (all latest modifications of document highlighted)

5.0	29 October 2018	First issued
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, β 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

List of Figures

List of equations

List of tables

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

f_{yk}	Characteristic tensile strength of reinforcement
f_{ywd}	Design strength of the punching shear reinforcement
$f_{ywd,ef}$	Effective design strength of the punching shear reinforcement
g_	Distance of slab edge from column (with suffices a, b, D, L, y, z) – see section 8.1
h	slab depth
h_1	where slab depth varies across top of column, slab depth 1
h_2	where slab depth varies across top of column, slab depth 2
k	(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))
k_1	According to NA to BS EN 1992-1-1, 6.4.4 (1)
l	effective length of wall resisting punching shear load
l_1	larger dimension of a rectangular slab opening
l_2	shorter dimension of a rectangular slab opening
l_3	the minimum distance between tangential lines defining the ineffective slab region due to an opening in the slab
l_y / l_z	location of opening centre relative to column centre
s_r	Radial spacing of shear studs
$s_{r,0}$	Radial distance to first shear stud from column face
s_t	maximum tangential spacing between outermost shear studs
t	wall thickness
u_0	Perimeter of loaded area at the column face
u_1	Basic control perimeter
u_1^*	Reduced basic control perimeter
u_{out}	The control perimeter at which shear reinforcement is not required
$u_{out,ef}$	The control perimeter a distance kd from the outermost perimeter of shear reinforcement for a cruciform rail layout
$v_{Ed,0}$	Design shear stress at the face of the column
$v_{Ed,1}$	Design value of the shear stress at the basic control perimeter
$v_{Rd,c}$	Design value of the punching shear resistance at the basic control perimeter of the slab without shear reinforcement
$v_{Rd,cs}$	Design value of the punching shear resistance at the basic control perimeter of the slab with shear reinforcement
$v_{Rd.0,max}$	Design value of the maximum punching shear resistance at the loaded face
$v_{Rd.c,max}$	The maximum limiting value of the punching shear capacity of the slab
y	column dimension parallel to y-axis
y_0	co-ordinate of the u_1 centroid relative to the column centroid in the y-direction
y’	dimension of rectangular slab opening parallel to y-axis
z	column dimension parallel to z-axis
z_0	co-ordinate of the u_1 centroid relative to the column centroid in the z-direction
z’	dimension of rectangular slab opening parallel to z-axis

1.3 Greek Lower Case

α	Angle between shear reinforcement and the slab
α_{cc}	Coefficient taking account of long term effects taken as 1.0
β	Eccentricity factor
γ_s	Partial safety factor for the steel
γ_c	Partial safety factor for concrete
v	Strength reduction factor for cracked concrete in shear
σ_{cp}	Compressive stress in the concrete due to the axial load
σ_{cy}	Concrete stress at the critical section in y direction
σ_{cz}	Concrete stress at the critical section in z direction
ρ_l	Reinforcement ratio
ρ_{ly}	Reinforcement ratio in the y direction
ρ_{lz}	Reinforcement ratio in the z direction

2 References

BS EN 1992-1-1:2004+A1:2014, Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings

NA+A2:2014 to BS EN 1992-1-1:2004+A1:2014, UK National Annex to Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings

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/mm^2. 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 β 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

Column location	Internal
Column shape	Rectangular
Dimension, y	500 mm
Dimension, z	300 mm
Dimension, D	500 mm
Slab depth, h	250 mm
Concrete grade	C20/25
Top cover, $c_{nom,t}$	25 mm
Top cover, $c_{nom,b}$	25 mm
Reinforcement	None
(add) → Bar diameter	8 mm
(add) → Spacing	150 mm
Eccentricity factor, β	Calculated
Shear load, V_{Ed}	500 kN
Moment, $M_{Ed,y}$	0 kNm
Moment, $M_{Ed,z}$	0 kNm

Openings	None
(add rectangular) → l_y	500 mm
(add rectangular) → l_z	500 mm
(add rectangular) → y’	400 mm
(add rectangular) → z’	600 mm
(add circular) → l_y	500 mm
(add circular) → l_z	500 mm
(add circular) → Ø	500 mm
Shearfix layout	Auto
Shearfix stud diameter	Auto
Large and elongated columns	Best Practice
Include distribution rails	Yes
Rail placing	Bottom-up
Distance to first stud	0.5d

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.)

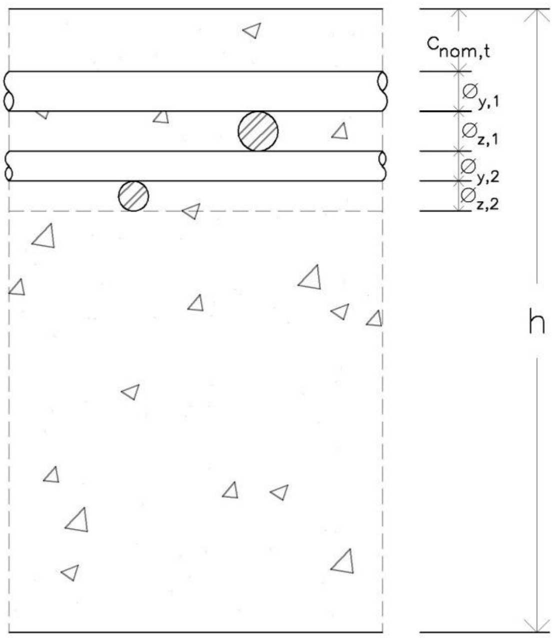


Figure 1 Reinforcement in the slab

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

where

$$d_{y,1} = h - c_{nom,t} - \frac{\emptyset_{y,1}}{2}$$

$$d_{z,1} = h - c_{nom,t} - \emptyset_{y,1} - \frac{\emptyset_{z,1}}{2}$$

$$d_{y,2} = h - c_{nom,t} - \emptyset_{y,1} - \emptyset_{z,1} - \frac{\emptyset_{y,2}}{2}$$

$$d_{z,2} = h - c_{nom,t} - \emptyset_{y,1} - \emptyset_{z,1} - \emptyset_{y,2} - \frac{\emptyset_{z,2}}{2}$$

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, ρ

The reinforcement ratio of the slab is calculated as follows:

$$\rho_l = \sqrt{\rho_{ly} \times \rho_{lz}} \leq 0.02$$

Where: $\rho_{ly} = \frac{A_{sy}}{A_c} = \frac{A_{sy,1}}{d_{y,1}} + \frac{A_{sy,2}}{d_{y,2}}$ and $\rho_{lz} = \frac{A_{sz}}{A_c} = \frac{A_{sz,1}}{d_{z,1}} + \frac{A_{sz,2}}{d_{z,2}}$

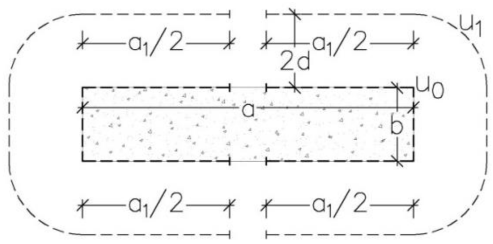
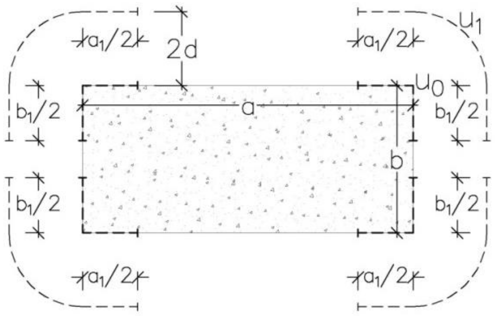
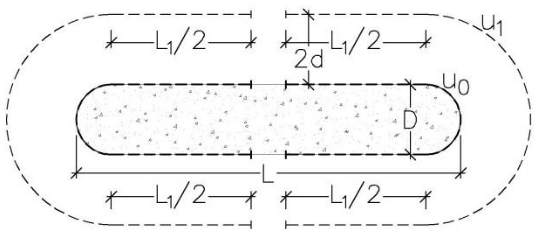
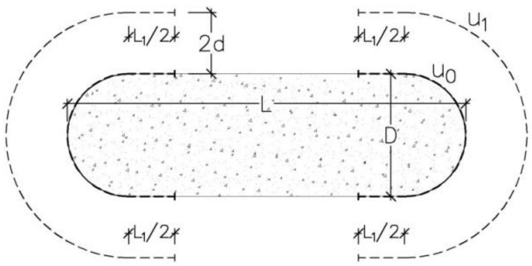
Equation 2 Calculation of the slab reinforcement ratio, based on BS EN 1992-1-1:2004, 6.4.4 (1)

For the purpose of this calculation, the units for the area of tensile slab reinforcement, A_s, are mm^2/mm width of slab. The area of concrete, A_c, mm^2/mm width of slab is equal to the effective depth of the reinforcement, d (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).

“EC2”	“Best Practice”
 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: $L_1 = \min(L\text{-}D,3D)$ $u_0 = 2L_1 + \pi D$ $u_1 = 2L_1 + \pi(D + 4d)$	 Where: $L_1 = \min(L\text{-}D,3D,3d)$ $u_0 = 2L_1 + \pi D$ $u_1 = 2L_1 + \pi(D + 4d)$

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.

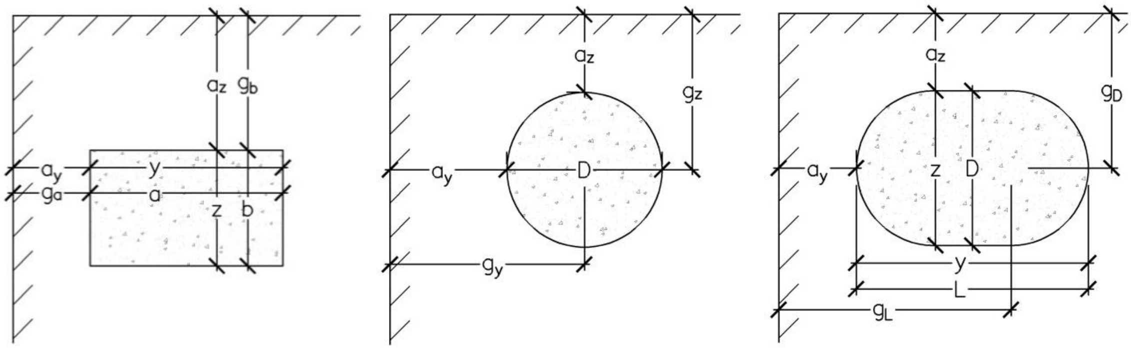
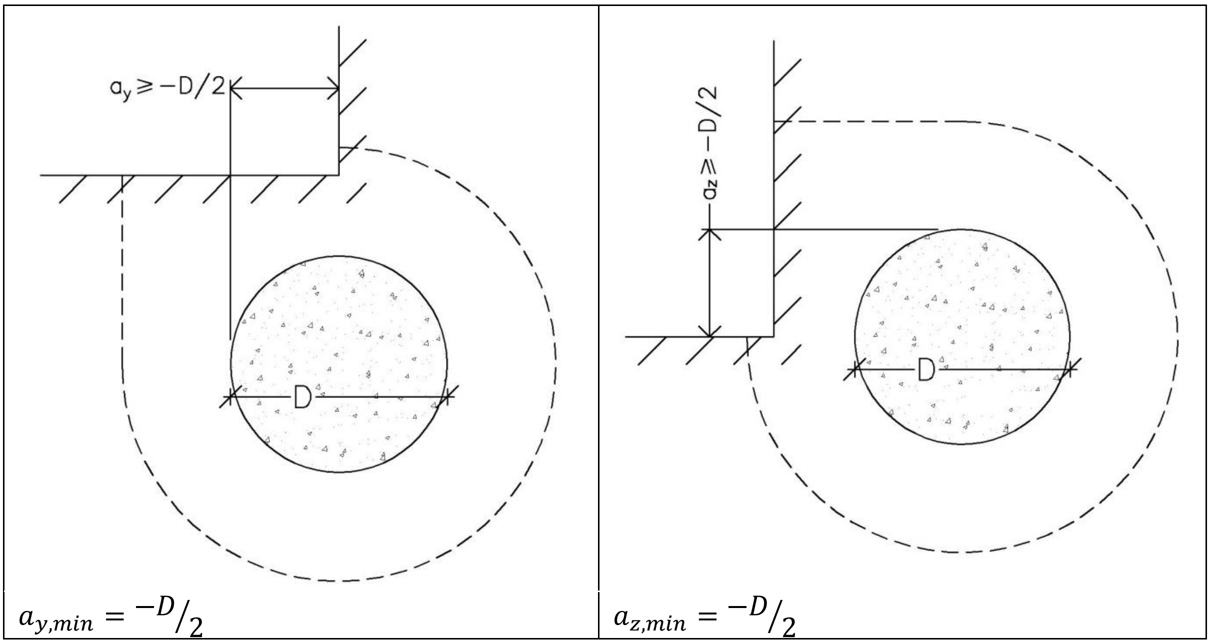


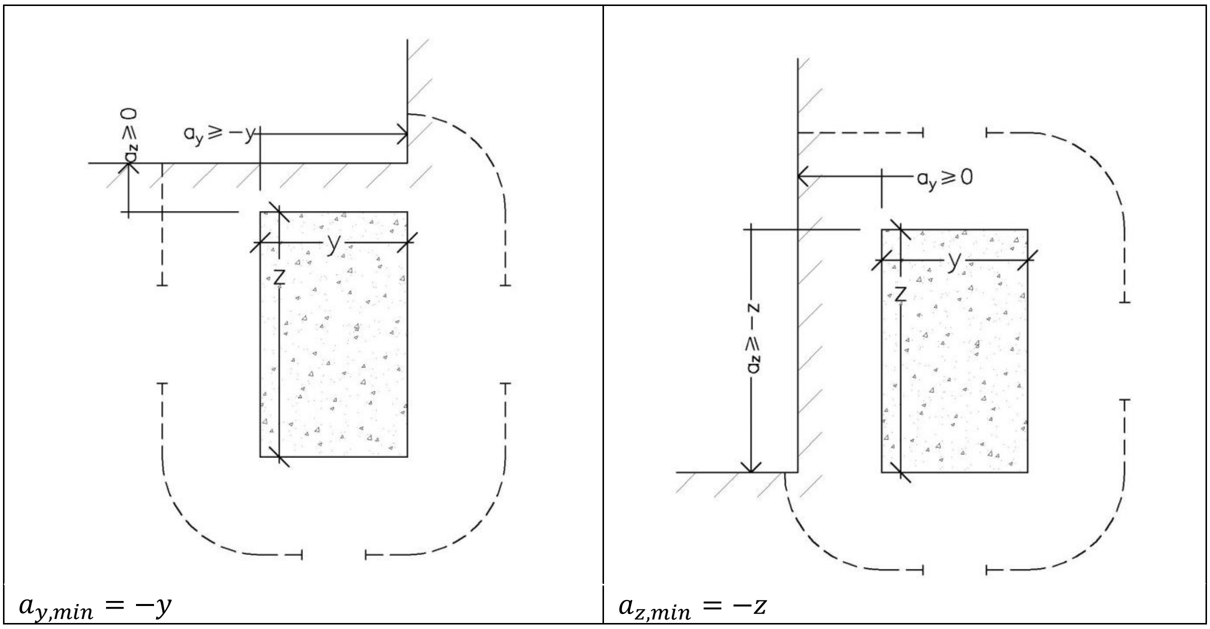
Figure 2 Edge dimensions

$a_{e,y}$	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.





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]."

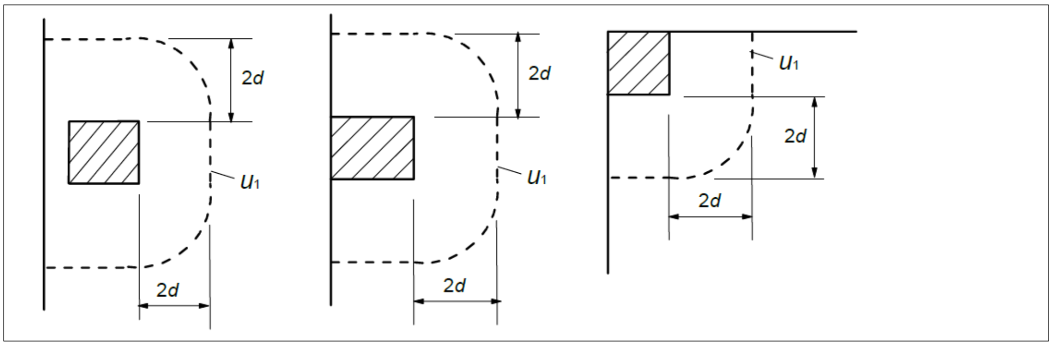


Figure 3 BS EN 1992-1-1:2004, Figure 6.15 Basic control perimeters for edge and corner columns

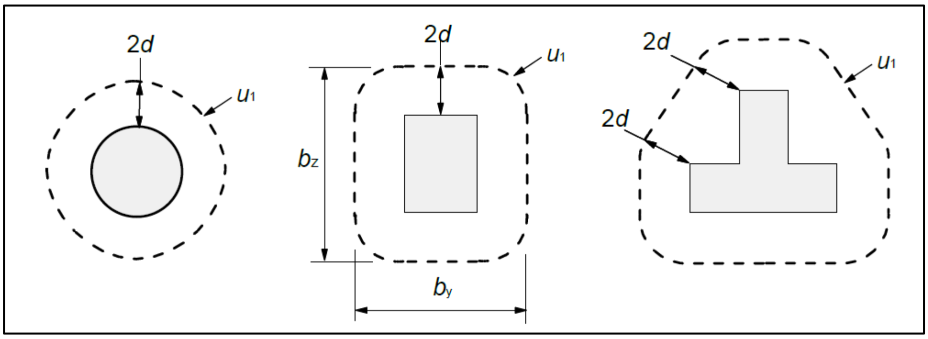


Figure 4 BS EN 1992-1-1:2004, Figure 6.13 Typical basic control perimeters around loaded areas

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.

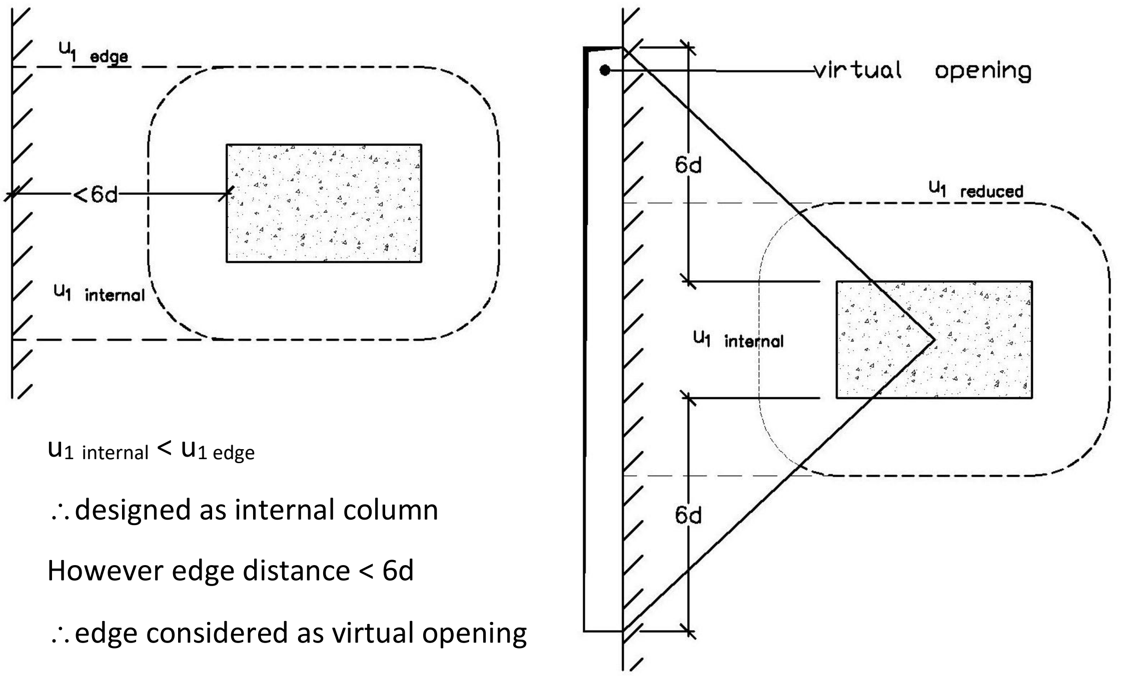


Figure 5 User-defined edge column designed as internal column with virtual opening at slab edge

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 $\beta = 1.0$ 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.)

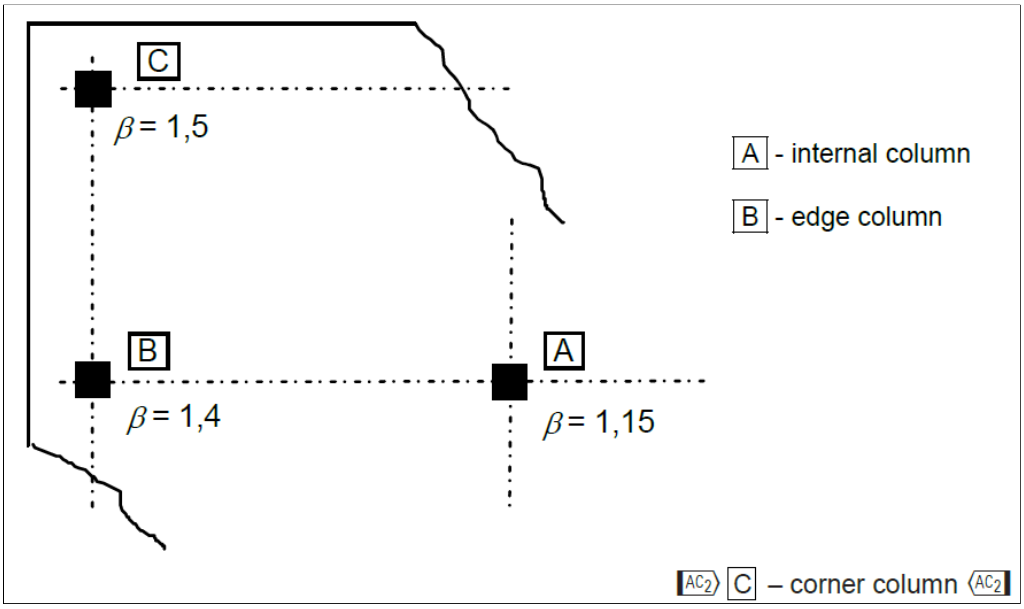


Figure 6 BS EN 1992-1-1:2004, Figure 6.21N Recommended values for β

10.1 General formula for β values

The general formula for calculating the β-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

c_1/c_2	≤ 0,5	1,0	2,0	≥ 3,0
k	0,45	0,60	0,70	0,80

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

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

Equation 4 BS EN 1992-1-1:2004 (6.43), β 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, $e_y = \frac{M_{Ed,z}}{V_{Ed}}$ and $e_z = \frac{M_{Ed,y}}{V_{Ed}}$

Regardless of column size, $b_y = y + 4d$ and $b_z = z + 4d$

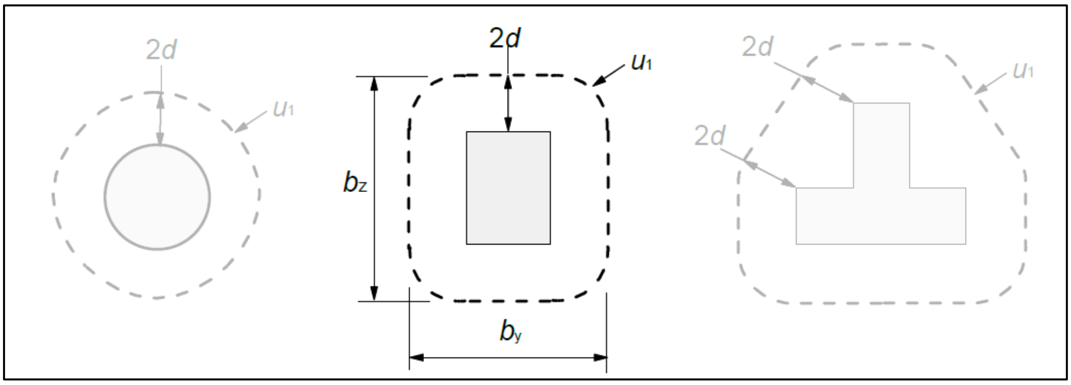


Figure 7 BS EN 1992-1-1:2004, Figure 6.13 Definition of b_y and b_z values

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) β: 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) β: 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%.

Column location	Default β-value, Figure (6.21N)
Internal	1.15
Edge or wall end	1.4
Corner or wall corner	1.5
Re-entrant corner	N/A

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, l, where l 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.

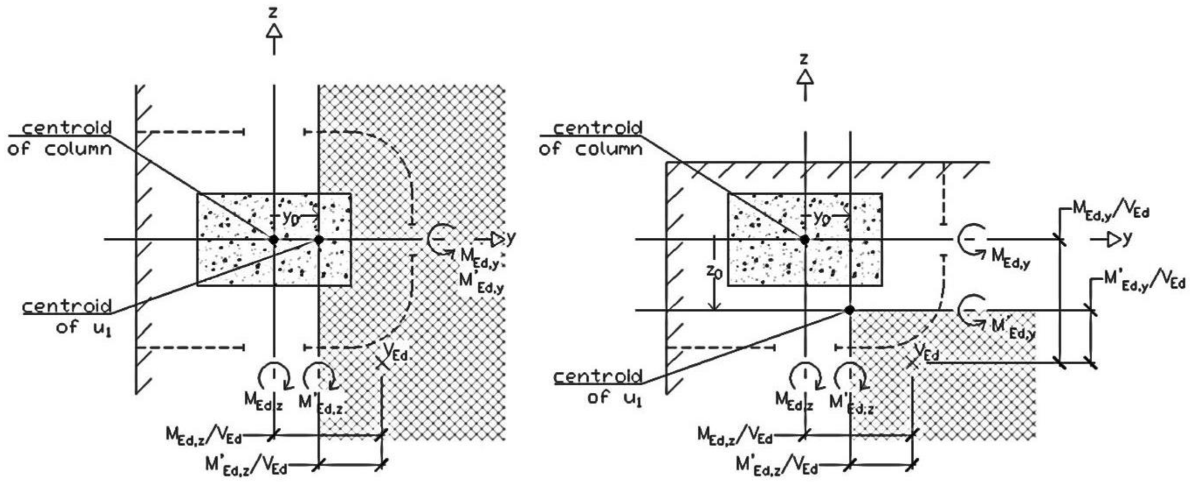


Figure 8 Translation of moment about column to moment about basic control perimeter

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

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:

u_0	for an interior column	AC2 u_0 = enclosing minimum periphery [mm] AC2
	for an edge column	$u_0 = c_2 + 3d \leq c_2 + 2c_1$ [mm]
	for a corner column	$u_0 = 3d \leq c_1 + c_2$ [mm]

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:

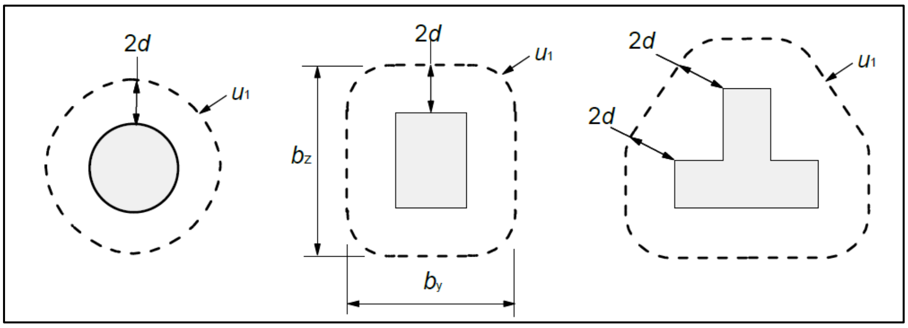


Figure 10 BS EN 1992-1-1:2004 Figure 6.13 Typical basic control perimeters around loaded areas

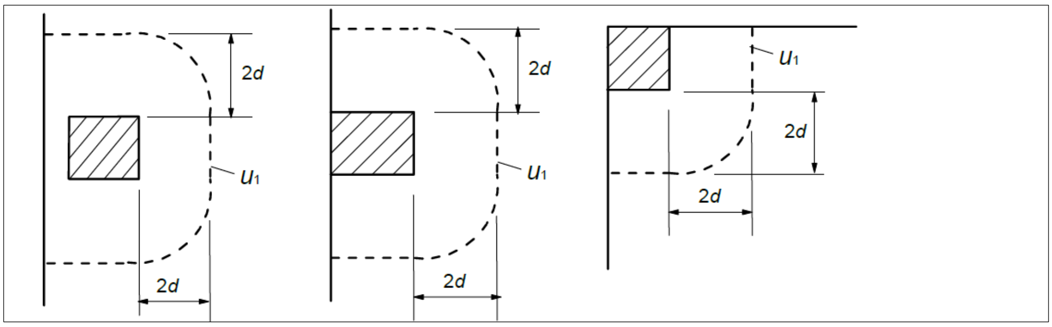


Figure 11 BS EN 1992-1-1:2004, Figure 6.15 Basic control perimeters for edge and corner columns

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

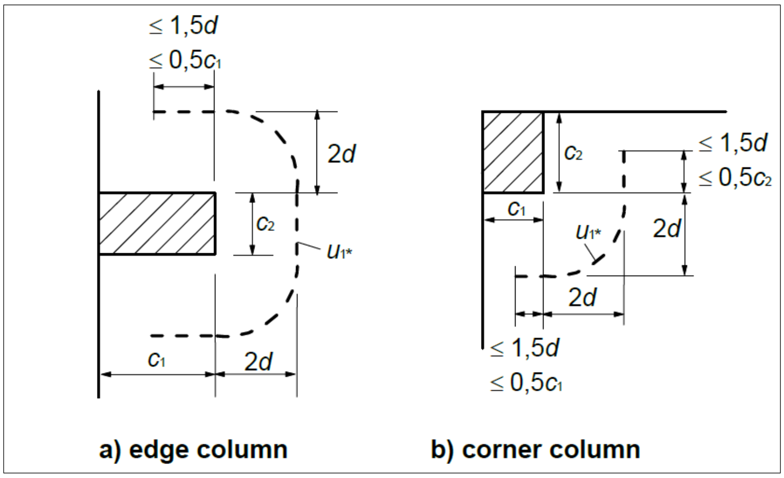


Figure 12 BS EN 1992-1-1:2004 Figure 6.20 Reduced basic control perimeter u_1*

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.

Column		Control perimeter		
Location	**Shape**	**Column face, u_0**	**Basic, u_1**	**Reduced basic, u_1***
Internal	Rectangular	$u_0 = 2a_1 + 2b_1$	$u_1 = 2a_1 + 2b_1 + 4\pi d$	N/A
	Circular	$u_0 = \pi D$	$u_1 = \pi(D + 4d)$	N/A
	Oval	$u_0 = 2L_1 + \pi D$	$u_1 = 2L_1 + \pi(D + 4d)$	N/A
Edge (equations depend on column orientation)	Rectangular	$u_0 = 2a_{1u0} + b_1$ $u_0 = a_1 + 2b_{1u0}$	$u_1 = 2a_1 + b_1 + 2g_a + 2\pi d$ $u_1 = a_1 + 2b_1 + 2g_b + 2\pi d$	$u_1{}^* = a_{1us} + b_1 + 2\pi d$ $u_1{}^* = a_1 + b_{1us} + 2\pi d$
	Wall end	$u_0 = 2l_{u0} + t$	$u_1 = 2l + t + 2\pi d$	$u_1{}^* = l_{us} + t + 2\pi d$
	Circular	$u_0 = 0.25\pi D + 2D_{u0}$	$u_1 = 0.5\pi(D + 4d) + 2g$	$u_1{}^* = 0.25\pi(D + 4d) + D_{us}$
	Oval	$u_0 = 2L_{1u0} + 0.5\pi D$ $u_0 = L_1 + 0.25\pi D + 2D_{u0}$	$u_1 = 2L_1 + 0.5\pi(D + 4d) + 2(g_L - L + D)$ $u_1 = L_1 + 0.5\pi(D + 4d) + 2g_D$	$u_1{}^* = 0.5\pi(D + 4d) + L_{1us}$ $u_1{}^* = 0.25\pi(D + 4d) + L_1 + D_{us}$
Corner	Rectangular	$u_0 = a_{1u0} + b_{1u0}$	$u_1 = a_1 + b_1 + g_a + g_b + \pi d$	$u_1{}^* = 0.5a_{1us} + 0.5b_{1us} + \pi d$
	Wall corner	$u_0 = 2l_{u0}$	$u_1 = 2l + \pi d$	$u_1{}^* = l_{us} + \pi d$
	Circular	$u_0 = 2D_{u0}$	$u_1 = 0.25\pi(D + 4d) + g_y + g_z$	$u_1{}^* = D_{us}$
	Oval	$u_0 = L_{1u0} + D_{u0} + 0.125\pi D$	$u_1 = L_1 + 0.25\pi(D + 4d) + g_L - L + D + g_D$	$u_1{}^* = 0.5L_{1us} + 0.5D_{us} + 0.125\pi(D + 4d)$
Re-entrant corner	Rectangular $g_a \geq 0, g_b \geq 0$	$u_0 = a_1 + b_1 + a_{1u0} + b_{1u0}$	$u_1 = 2a_1 + 2b_1 + g_a + g_b + 3\pi d$	N/A
	$g_a \geq 0, g_b < 0$	$u_0 = a_1 + b_1 + a_{1u0} + b_{2u0}$	$u_1 = 2a_1 + b_1 + b_2 + g_a + 3\pi d$	N/A
	$g_a < 0, g_b \geq 0$	$u_0 = a_1 + b_1 + a_{2u0} + b_{1u0}$	$u_1 = a_1 + 2b_1 + a_2 + g_b + 3\pi d$	N/A
	Circular	$u_0 = 0.5\pi D + 2D_{u0}$	$u_1 = 0.75\pi(D + 4d) + g_y + g_z$	N/A

Table 3 Control perimeters u_0, u_1 and u_1* (see Table 4 & Table 5 below for parameter definitions)

<table>
<tr><th>Column shape</th><th>Parameter</th><th>Best Practice</th><th>EC2</th></tr>
<tr><td rowspan="12">rectangular</td><td>a</td><td colspan="2">Max (y, z)</td></tr>
<tr><td>b</td><td colspan="2">Min (y, z)</td></tr>
<tr><td>a_1</td><td>Min (a, 4b, 3d)</td><td>Min (a, 4b)</td></tr>
<tr><td>a_{1u0}</td><td colspan="2">Min (a, 4b, 1.5d)</td></tr>
<tr><td>a_{1us}</td><td colspan="2">Min (a, 4b, 3d)</td></tr>
<tr><td>b_1</td><td>Min (b, 3d)</td><td>b</td></tr>
<tr><td>b_{1u0}</td><td colspan="2">Min (b, 1.5d)</td></tr>
<tr><td>b_{1us}</td><td colspan="2">Min (b, 3d)</td></tr>
<tr><td>a_2</td><td rowspan="2">Min (a+g_a, 2b, 1.5d)</td><td>Min (a+g_a, 2b)</td></tr>
<tr><td>a_{2u0}</td><td>Min (a+g_a, 2b, 1.5d)</td></tr>
<tr><td>b_2</td><td rowspan="2">Min (b+g_b, 1.5d)</td><td>b+g_b</td></tr>
<tr><td>b_{2u0}</td><td>Min (b+g_b, 1.5d)</td></tr>
</table>

<table>
<tr><th>Column shape</th><th>Parameter</th><th>Best Practice</th><th>EC2</th></tr>
<tr><td rowspan="7">oval & circular</td><td>L</td><td colspan="2">Max (y, z)</td></tr>
<tr><td>D</td><td colspan="2">Min (y, z)</td></tr>
<tr><td>L_1</td><td>Min (L-D, 3D, 3d)</td><td>Min (L-D, 3D)</td></tr>
<tr><td>L_{1u0}</td><td colspan="2">Min (L-D, 3D, 1.5d)</td></tr>
<tr><td>L_{1us}</td><td colspan="2">Min (L-D, 3D, 3d)</td></tr>
<tr><td>D_{u0}</td><td colspan="2">Min (0.25πD, 1.5d)</td></tr>
<tr><td>D_{us}</td><td colspan="2">Min (0.25π(D+4d), 3d)</td></tr>
<tr><td rowspan="5">walls</td><td>l</td><td colspan="2">l_{auto} or l_{user} (whichever is selected)</td></tr>
<tr><td>l_{user}</td><td colspan="2">User input value</td></tr>
<tr><td>l_{auto}</td><td>Min (2t, 1.5d)</td><td>2t</td></tr>
<tr><td>l_{u0}</td><td colspan="2">Min (2t, 1.5d)</td></tr>
<tr><td>l_{us}</td><td colspan="2">Min (2t, 3d)</td></tr>
</table>

Table 4 Control perimeter parameters

<table>
<tr><td></td><td>Distance parallel to…</td><td></td><td>Distance parallel to…</td></tr>
<tr><td>g_a</td><td>dimension a from column face to slab edge</td><td>g_b</td><td>dimension b from column face to slab edge</td></tr>
<tr><td>g_D</td><td>dimension D from centre of column to slab edge</td><td>g_L</td><td>dimension L from the further radial centre of column to slab edge</td></tr>
<tr><td>g_y</td><td>y-axis from centre of column to slab edge</td><td>g_z</td><td>z-axis from centre of column to slab edge</td></tr>
<tr><td colspan="4">g = g_y or g_z, as appropriate</td></tr>
<tr><td colspan="4">For accompanying diagrams, see 8.1 Edge dimensions on page 11</td></tr>
</table>

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.

$$W_1 = 0.5{c_1}^2 + c_1 c_2 + 4c_2 d + 16d^2 + 2\pi d c_1$$

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.

$$W_1 = 0.25{c_2}^2 + c_1 c_2 + 4c_1 d + 8d^2 + \pi d c_2$$

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 β 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: $l_3 \geq \sqrt{l_1 \times l_2}$ 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.

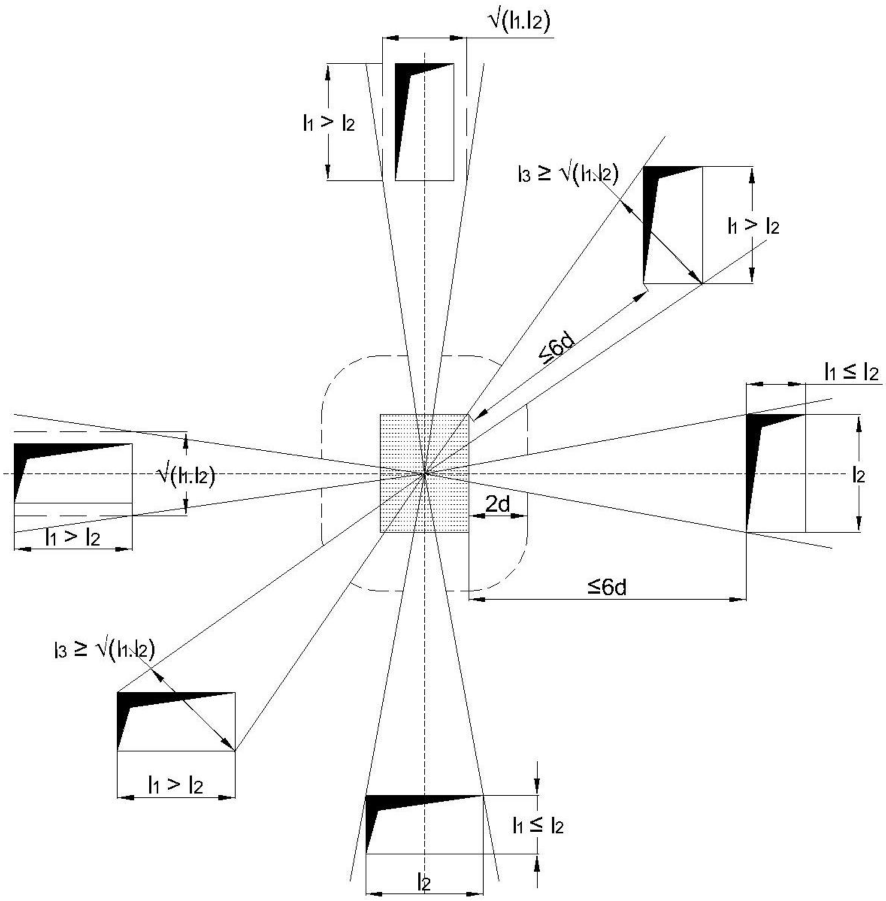
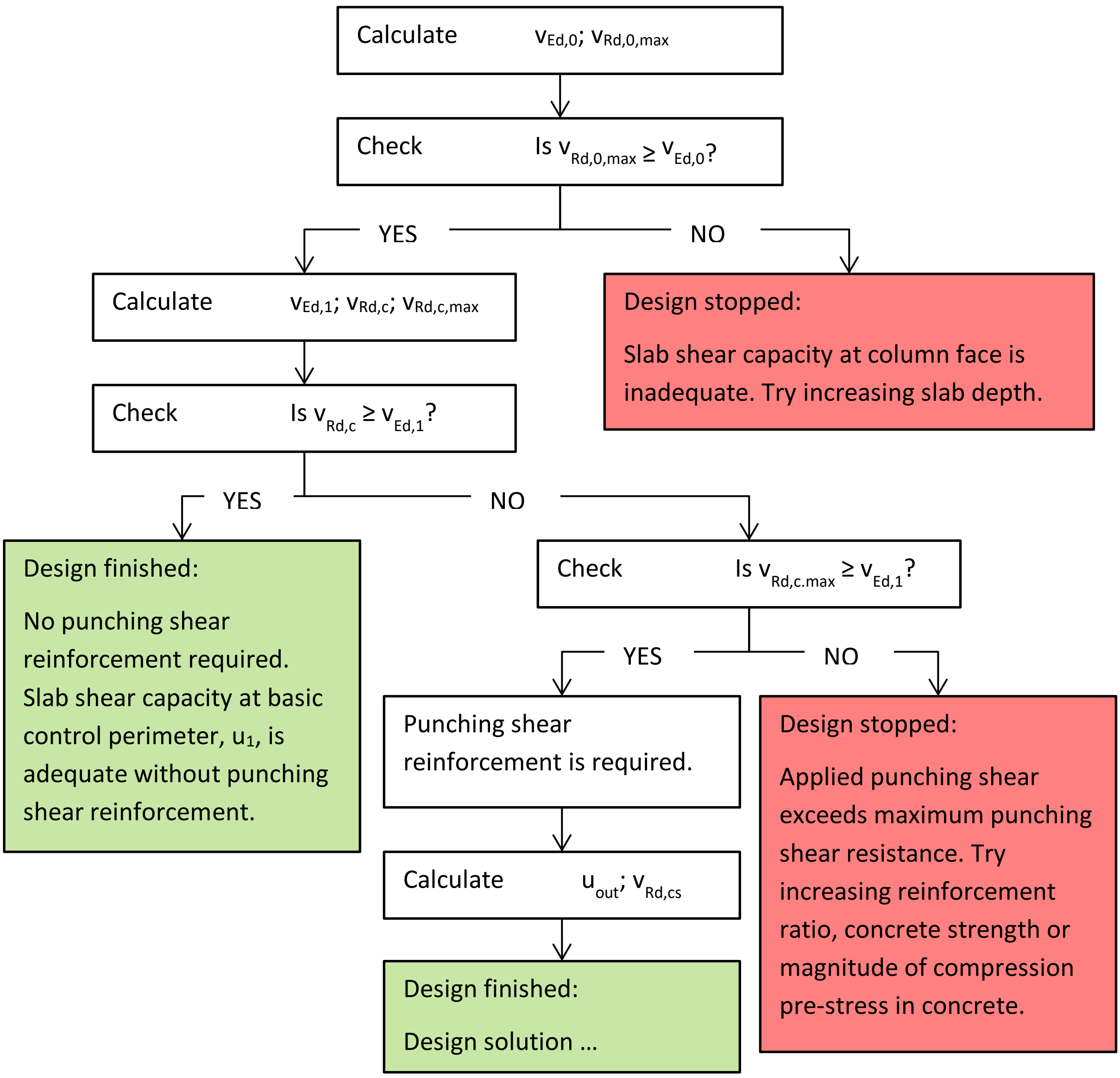


Figure 13 Control perimeter near openings, developed from BS EN 1992-1-1:2004 Figure 6.14

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

where β = 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, $v_{Rd,max} = 0.5 v f_{cd}$ [MPa] (NA 6.4.5 (3))

where strength reduction factor, $v = 0.6\left(1 - \frac{f_{ck}}{250}\right)$ NA 6.2.2 (6)

f_{ck} = cylinder strength of concrete (MPa)

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, $v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 \times d}$ (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,

$$v_{Rd,c} = C_{Rd,c} k (100 \rho_l f_{ck})^{1/3} + k_1 \sigma_{cp} \geq (v_{min} + k_1 \sigma_{cp}) \qquad \text{eq. (6.47)}$$

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))

$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0$ 6.4.4 (1)

ρ_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. [N] 6.4.4 (1)

A_c = area of concrete according to the definition of N_{Ed} [mm^2] 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:

$$u_{out} = \frac{\beta V_{Ed}}{v_{Rd,c} \times d} \qquad \text{eq. (6.54)}$$

The outer perimeter of shear studs must be within a distance of 1.5d from that perimeter. The shape of the outer control perimeter u_{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, $v_{Rd,cs} = 0.75v_{Rd,c} + 1.5\left({d}/{s_r}\right)A_{sw}f_{ywd,ef}\left({1}/{u_1 d}\right)\sin\alpha$ 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 = 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] 6.4.5(1)
design yield strength of punching shear reinforcement, $f_{ywd} = {f_{yk}}/{\gamma_s}$ [MPa] 3.2.7(2)
characteristic yield strength of punching shear reinforcement, f_{yk} = 500 MPa
partial safety factor for reinforcing steel, γ_s = 1.15 Table 2.1N (NA 2.4.2.4(1))

Also, the minimum area of a single shear stud can be determined from:

$$A_{sw,min}(1.5\sin\alpha + \cos\alpha)/{s_r s_t} \geq {0.08\sqrt{f_{ck}}}/{f_{yk}} \quad \text{eq. (9.11)}$$

where α = the angle between the shear reinforcement and the main steel.
For Shearfix, α = 90° therefore sin α = 1, cos α = 0.

Therefore equation (9.11) can be rearranged and simplified:

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

where s_t = 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.

National Annex parameters	Clauses	Purpose of parameter
$C_{Rd,c} = 0.18/\gamma_c$ $v_{min} = 0.035k^{3/2}f_{ck}{}^{1/2}$ $k_1 = 0.1$	6.4.4(1)	To calculate the design punching shear resistance of slabs without shear reinforcement, $v_{Rd,c}$
$v_{Rd,max} = 0.5vf_{cd}$	6.4.5(3)	The maximum limiting punching shear resistance at the column face
$k_{max}v_{Rd,c} = 2v_{Rd,c}$	6.4.5(1)	The maximum limiting punching shear resistance of the slab with shear reinforcement
Factor of distance, $k = 1.5$	6.4.5(4)	The outermost perimeter of shear reinforcement should be placed at a distance not greater than kd within u_{out} or $u_{out,ef}$.
☑ shear rail min'm length to 1.5d from column face	6.4.5(4)	This clause sits in the UK National Annex and effectively prescribes a minimum of 3 studs per rail.

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:

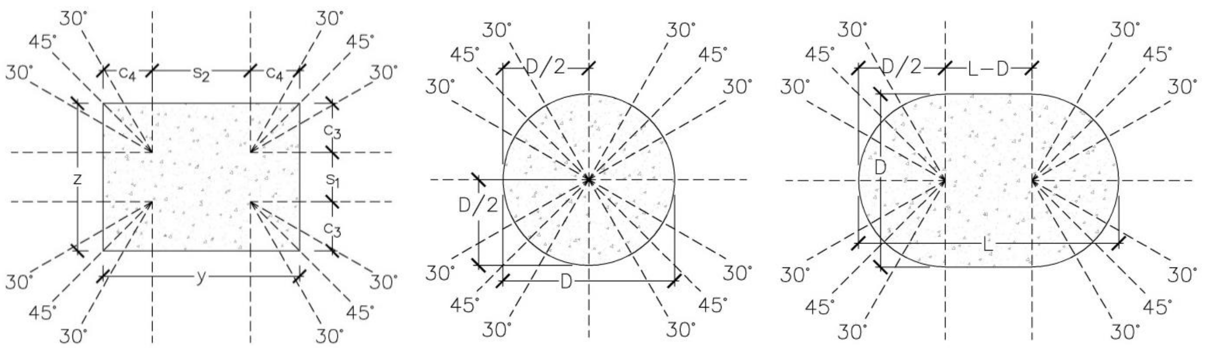
- Punching shear reinforcement should be detailed in accordance with BS EN 1992-1-1:2004 and its associated National Annex.
- The first stud is to be placed between 0.3d and 0.5d from the column face. (BS EN 1992-1-1:2004, Figure 9.10 a) and 9.4.3 (4).) (The default value is 0.5d.)
- Radial spacing of 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.

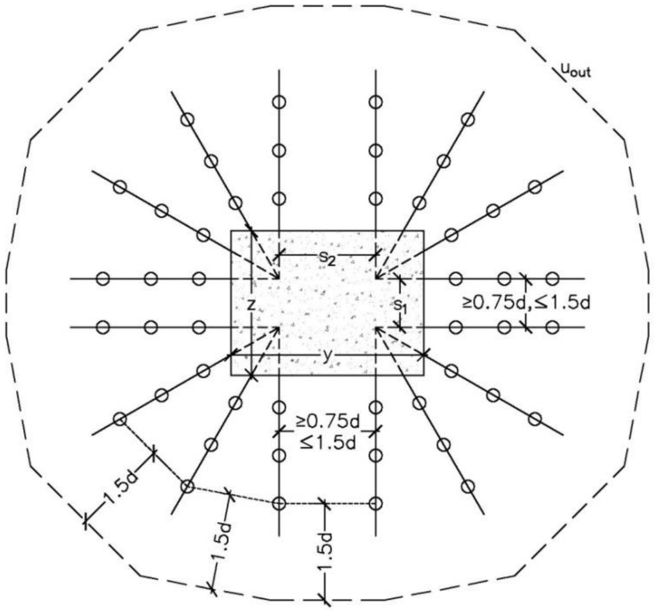


Figure 15 Radial layout of rails for internal rectangular column with associated outer control perimeter

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_{r0} 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).

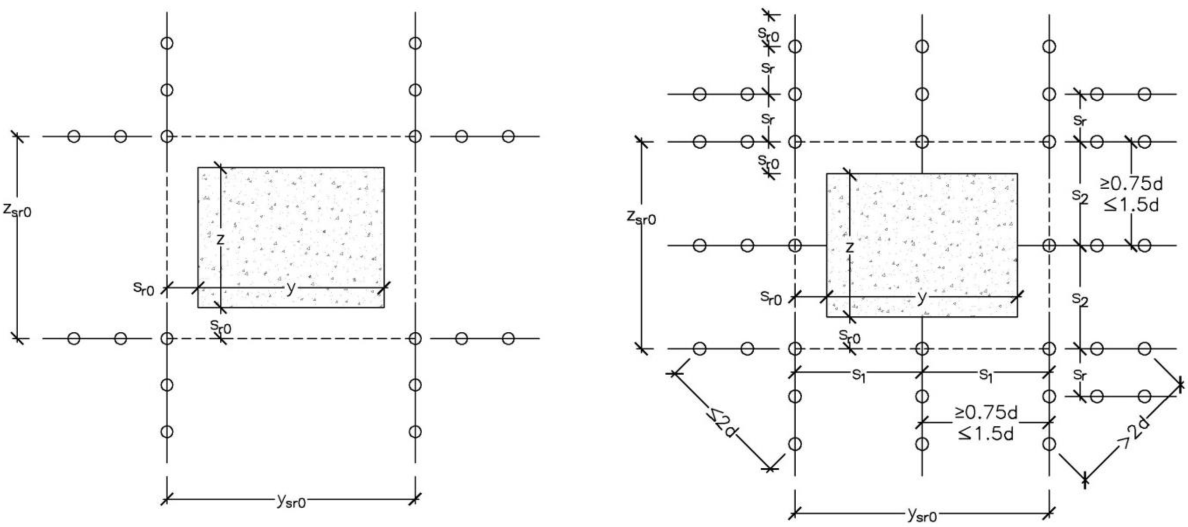


Figure 16 (i) and (ii) Cruciform layout procedure

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.

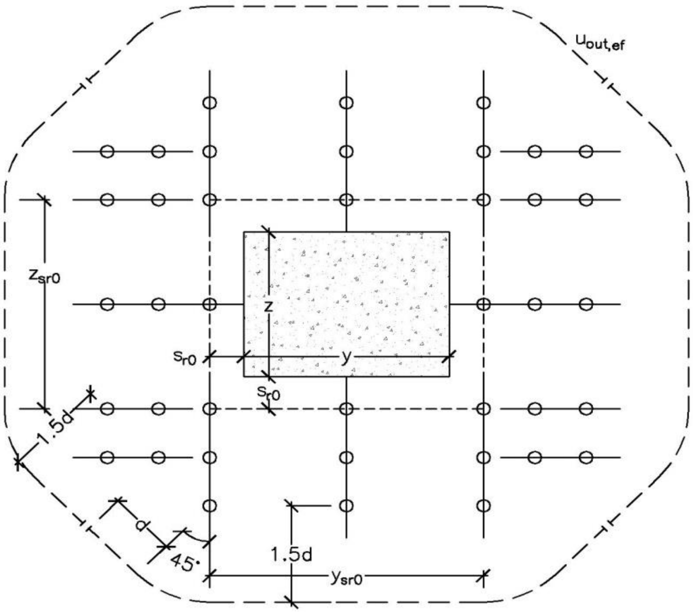


Figure 17 Cruciform rail layout and associated effective outer perimeter

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.)

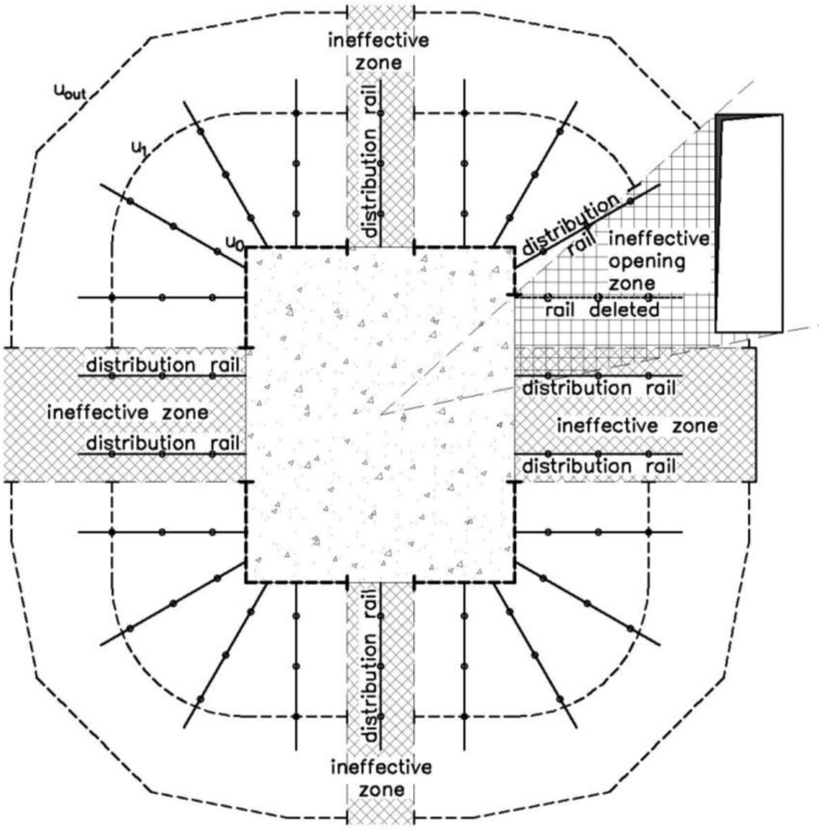


Figure 18 Example rail layout with deleted rails and ineffective main rails

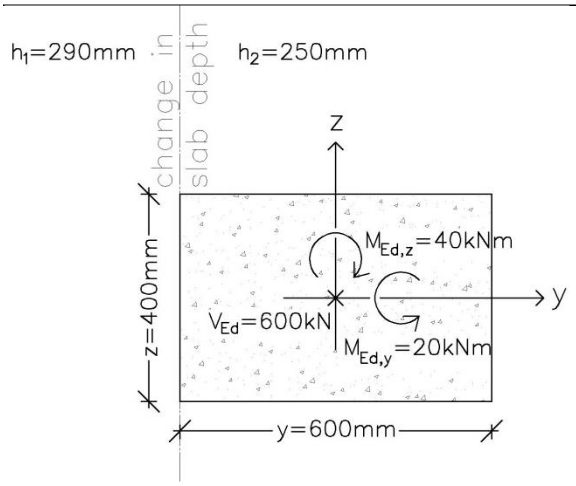
16 Design Examples

Example	Location	Shape	Layout	Notes
1	Interior	Rectangular	Cruciform	Change in slab depth
2	Edge	Oval	Radial	Edge → internal + virtual opening
3	Corner	Rectangular	Optimum	"Elongated" column Rectangular opening Two layers of reinforcement
4	Re-entrant corner	Circular	Radial	Circular opening Two layers of reinforcement

16.1 Internal rectangular column

16.1.1 Inputs

Internal rectangular column				
Dimensions,		y =	600	mm
		z =	400	mm
Slab depth,		h_1 =	290	mm
		h_2 =	250	mm
Change in slab depth: bottom surface		@ y =	0	mm
Concrete grade,	C30/37	f_{ck} =	30	N/mm^2
Top cover,		$c_{nom,t}$ =	30	mm
Bottom cover,		$c_{nom,b}$ =	30	mm
Pre-compression,		σ_{cp} =	0	N/mm^2
Reinforcement,	Layer 1,	y-y	H16 @200 mm c/c	
		z-z	H16 @200 mm c/c	
Loading	Design shear	V_{Ed} =	600	kN
	β	To be calculated		
	Design moments	$M_{Ed,y}$ =	20	kNm
		$M_{Ed,z}$ =	40	kNm
Distance to first stud		S_{r0} =	0.5	d
Shearfix	Layout	Cruciform		
	Stud ø	Automatic optimal		
	Rail placing	Bottom-up		
	Large and elongated columns	Best Practice		
	Include distribution rails	Yes		



16.1.2 Design

Design parameters

Effective depth, based on minimum slab depth, $h = min(h_1, h_2) = h_2$

$$d_{y1} = h - c_{nom,t} - \emptyset_{y1}/2 \qquad = 212mm$$

$$d_{z1} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1}/2 \qquad = 196mm$$

$$d = (d_{y1} + d_{z1})/2 \qquad \underline{= 204mm}$$

Control perimeters, $a = max(y, z) = 600mm \qquad b = min(y, z) = 400mm$

$$a_1 = min(a, 4b, 3d) = min(600,1600,612) = 600mm$$

$$b_1 = min(b, 3d) = min(400,612) = 400mm$$

$$u_0 = 2a_1 + 2b_1 \qquad \underline{= 2000mm}$$
$$u_1 = 2a_1 + 2b_1 + 4\pi d \qquad \underline{= 4564mm}$$

Reinforcement ratio,

$$\rho_{ly} = \frac{A_{sy1}}{A_{cy1}} = 0.00474 \qquad \rho_{lz} = \frac{A_{sz1}}{A_{cz1}} = 0.00513$$
$$\rho_l = \sqrt{\rho_{ly} \times \rho_{lz}} \qquad \underline{= 0.00493} \ (\equiv 0.493\%)$$

Load increase factor,

Internal column with biaxial moments: greatest value of

$$\beta = 1 + k\frac{M'_{Ed}}{V_{Ed}}\frac{u_1}{W_1} \quad \text{and} \quad \beta = 1 + 1.8\sqrt{\left(\frac{e_y}{b_z}\right)^2 + \left(\frac{e_z}{b_y}\right)^2}$$

internal column: $M'_{Ed,y} = M_{Ed,y}$ and $M'_{Ed,z} = M_{Ed,z}$

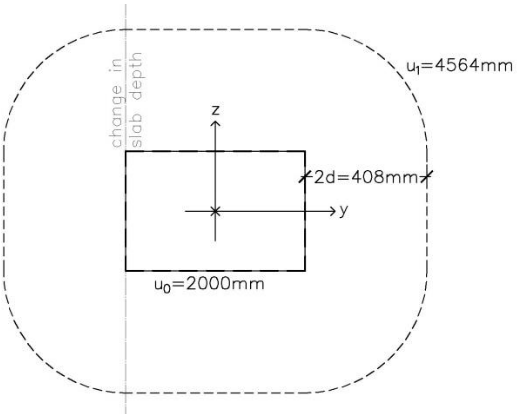
$$\beta = 1 + k\frac{M'_{Ed}}{V_{Ed}}\frac{u_1}{W_1} \qquad \rightarrow \beta = 1.098$$

$$\beta = 1 + 1.8\sqrt{\left(\frac{e_y}{b_z}\right)^2 + \left(\frac{e_z}{b_y}\right)^2} \qquad \rightarrow \beta = 1.107$$

$$1.107 > 1.098 \qquad \underline{\therefore \beta = 1.107}$$

Results so far

Effective depth	d =	204	mm
Control perimeters	u_0 =	2000	mm
	u_1 =	4564	mm
Reinforcement ratios	ρ_l =	0.00493	
Load increase factor	β =	1.107	



Shear at column face

Applied design shear at column face, (6.53) $v_{Ed,0} = \frac{\beta V_{Ed}}{u_0 d}$ $\qquad v_{Ed,0} = 1.63\ MPa$

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

where, NA 6.2.2 (6) $\quad v = 0.6\left[1 - \frac{f_{ck}}{250}\right] = 0.528$

(3.15) $\quad f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c}$

Table 2.1N $\quad \gamma_c = 1.5 \quad$ “persistent and transient”

NA 3.1.6 (1) $\alpha_{cc} = 1.0$ "all other phenomena"

$f_{cd} = 20.0\ MPa$ $v_{Rd,max} = 5.28\ MPa$

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) $v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 d}$ $v_{Ed,1} = 0.71\ MPa$

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

$k = 1 + \sqrt{200/d} \leq 2.0$ $\rightarrow k = 1.99$

$\rho_l = \sqrt{\rho_{lz} \rho_{ly}} \leq 0.02$ $\rightarrow \rho_l = 0.00493$

(NA6.4.4) $k_1 = 0.1$

(NA6.4.4) $v_{min} = 0.035 k^{3/2} f_{ck}^{\ 1/2} = 0.538$

$v_{Rd,c} = 0.586 \geq 0.538$ $v_{Rd,c} = 0.59\ MPa$

Limiting value of punching shear capacity, $v_{Rd,c,max} = 2 \times v_{Rd,c}$ $v_{Rd,c,max} = 1.17\ MPa$

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,

$u_{out,req} = \frac{\beta V_{Ed}}{v_{Rd,c} d}$ $u_{out,req} = 5554\ mm$

Cruciform layout

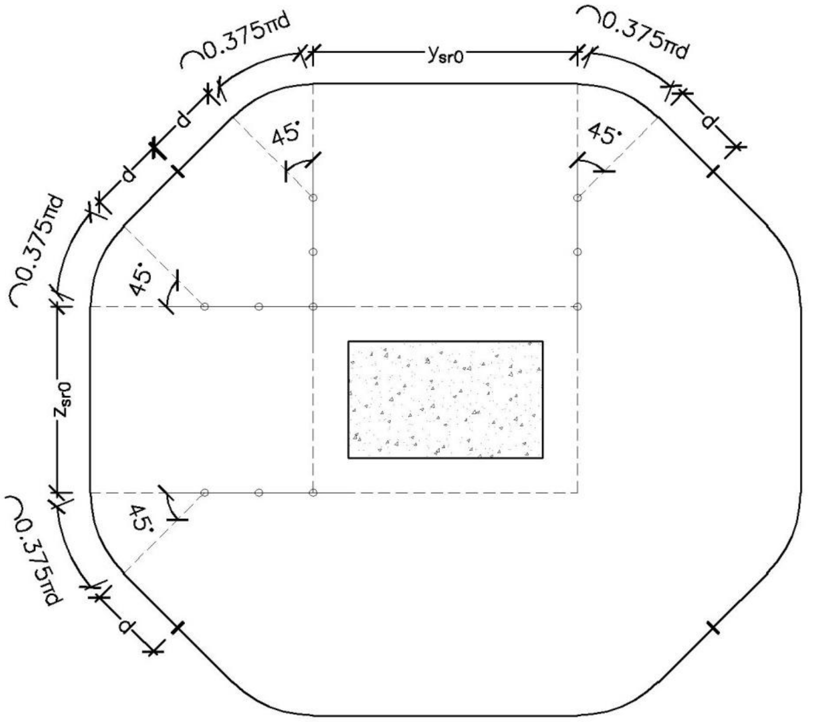
Cruciform layouts limited to shear rails with 3 studs. (Increasing the number of studs does not increase $u_{out,ef}$.)

Distance to first stud, $s_{r0} = 0.5d = 102mm$

rounded down to nearest 1mm $\rightarrow s_{r0} = 102mm$

Radial spacing of studs, $s_r = 0.75d = 153mm$

rounded down to nearest 1mm $\rightarrow s_r = 153mm$



$$u_{out,ef} = 2 \times (y_{sr0} + 2d + 0.75\pi d + z_{sr0} + 2d + 0.75\pi d)$$

where $y_{sr0} = y + 2 \times s_{r0} = 804\ mm$

$z_{sr0} = z + 2 \times s_{r0} = 604\ mm$

$$u_{out,ef} = 6371\ mm \geq u_{out,req} = 5554\ mm$$

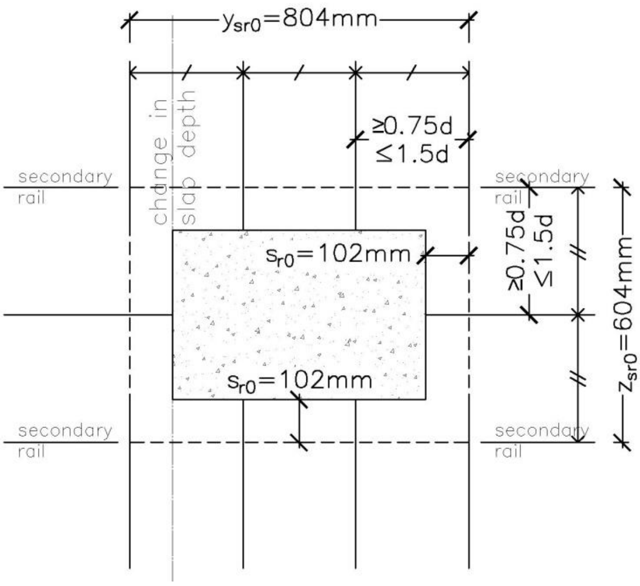
Therefore, a cruciform layout is possible for this case.

Number of main rails

$y_{sr0} > 1.5d$ → $\frac{y_{sr0}}{1.5d} = \frac{804}{306} = 2.63$ → 4 rails perpendicular to y-face

$z_{sr0} > 1.5d$ → $\frac{z_{sr0}}{1.5d} = \frac{604}{306} = 1.97$ → 3 rails perpendicular to z-face

→ 10 main rails + 4 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

$A_{sw} = {}^{(v_{Ed,1} - 0.75v_{Rd,c})s_r u_1}/_{1.5f_{ywd,ef}}$ and $A_{sw,min} \geq {}^{0.08 s_r s_t \sqrt{f_{ck}}}/_{1.5f_{yk}}$

where $f_{yk} = 500\ MPa$

$f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$

$f_{ywd} = \frac{f_{yk}}{1.15} = 435\ MPa$

$f_{ywd,ef} = 301 \leq 435$

$s_r = 153\ mm$

$s_t = 433\ mm$

$A_{sw} = 424\ mm^2\ per\ perimeter$

$A_{sw,min} = 39\ mm^2\ per\ stud$

Minimum number of main rail shear studs per perimeter = 10

$A_{stud} = {}^{A_{sw}}/_{n_{mr}} \geq A_{sw,min}$

$A_{stud} = 42.4 \geq 39$

$A_{stud,required} = 42.4$

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

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

Stud height

$h_{stud,h1} = h_1 - c_{nom,t} - c_{nom,b}$

$h_{stud,h1} = 290 - 30 - 30 = 230\ mm$

$h_{stud,h2} = h_2 - c_{nom,t} - c_{nom,b}$

$h_{stud,h2} = 250 - 30 - 30 = 190\ mm$

Therefore, studs are either 230mm high or 190mm high.

Shear capacity with punching shear reinforcement

Shear capacity with reinforcement,

(6.52) $v_{Rd,cs} = 0.75v_{Rd,c} + 1.5\left({}^{d}/_{s_r}\right)A_{sw}f_{ywd,ef}\left({}^{1}/_{u_1 d}\right)\sin\alpha$

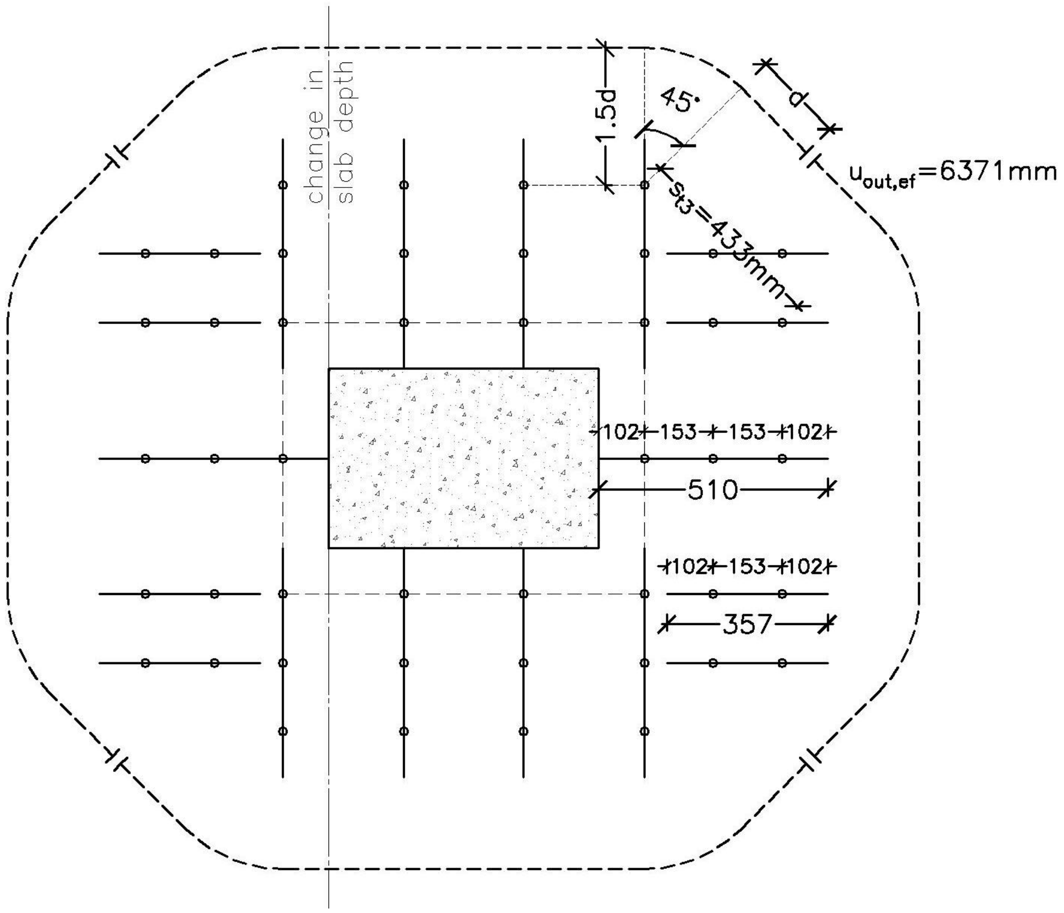
where, $A_{sw} = 10 \times 78.5 = 785\ mm^2$

$\alpha = 90°$ $\rightarrow \sin\alpha = 1$ $\underline{\rightarrow v_{Rd,cs} = 0.95\ MPa}$

16.1.3 Design solution

Cruciform layout

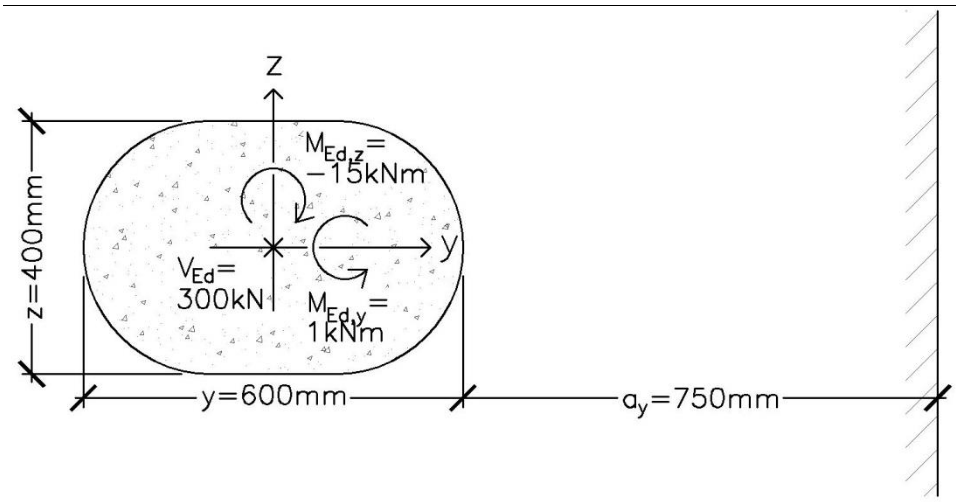
7 no. main rails (3 x 10mm ø studs @ 153mm c/c, 510mm long, 190mm high)
3 no. main rails (3 x 10mm ø studs @ 153mm c/c, 510mm long, 230mm high)
4 no. secondary rails (2 x 10mm ø studs @ 153mm c/c, 357mm long, 190mm high)
4 no. secondary rails (2 x 10mm ø studs @ 153mm c/c, 357mm long, 230mm high)



16.2 Edge oval column

16.2.1 Inputs

Edge oval column					
Dimensions,		y =	600	mm	
		z =	400	mm	
	Edge @ right	$a_{e,y}$ =	750	mm	
Slab depth,		h =	230	mm	
Concrete grade,	C28/35	f_{ck} =	28	N/mm²	
Top cover,		$c_{nom,t}$ =	25	mm	
Bottom cover,		$c_{nom,b}$ =	25	mm	
Pre-compression,		σ_{cp} =	0	N/mm²	
Reinforcement,	Layer 1,	y-y	H16 @200 mm c/c		
		z-z	H16 @200 mm c/c		
Loading	Design shear	V_{Ed} =	300	kN	
	β	To be calculated			
	Design moments	$M_{Ed,y}$ =	1	kNm	
		$M_{Ed,z}$ =	-15	kNm	Towards interior
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,

$$d_{y1} = h - c_{nom,t} - \emptyset_{y1}/2 \qquad = 197mm$$

$$d_{z1} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1}/2 \qquad = 181mm$$

$$d = (d_{y1} + d_{z1})/2 \qquad \underline{= 189mm}$$

Control perimeters,

$$L = max(y,z) = 600mm \qquad D = min(y,z) = 400mm$$

$$L_1 = min(L - D, 3D, 3d) = min(200,1200,567) = 200mm$$

$$L_{1u0} = min(L - D, 3D, 1.5d) = min(200,1200,283.5) = 200mm$$

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

$u_{0,edge} = 2L_{1u0} + \frac{\pi}{2}D$ $\underline{= 1028mm}$

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

$u_{0,int} = 2L_1 + \pi D$ $\underline{= 1657mm}$

$u_{1,int} = 2L_1 + \pi(D + 4d)$ $\underline{= 4032mm}$

$u_{1,int} < u_{1,edge}$ → design as <u>internal column</u>

$a_y < 6d$ → treat edge as <u>virtual opening:</u>

opening: $l_y = \frac{y}{2} + a_{e,y} + \frac{y'}{2} = 1100mm$, $l_z = 0mm$,
$y' = 100mm$, $z' = z + 12d = 2668mm$

… with opening reduction,

$u_0 =$ $\underline{= 1134mm}$

$u_1 =$ $\underline{= 2829mm}$

Reinforcement ratio,

$\rho_{ly} = \frac{A_{sy1}}{A_{cy1}} = 0.00510$ $\rho_{lz} = \frac{A_{sz1}}{A_{cz1}} = 0.00555$

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

Load increase factor,

Internal column with biaxial moments: greatest value of

$\beta = 1 + k\frac{M'_{Ed}}{V_{Ed}}\frac{u_1}{W_1}$ and $\beta = 1 + 1.8\sqrt{\left(\frac{e_y}{b_z}\right)^2 + \left(\frac{e_z}{b_y}\right)^2}$

internal column: $M'_{Ed,y} = M_{Ed,y}$ and $M'_{Ed,z} = M_{Ed,z}$

$u_1 = 4032\ mm$ (without opening reduction)

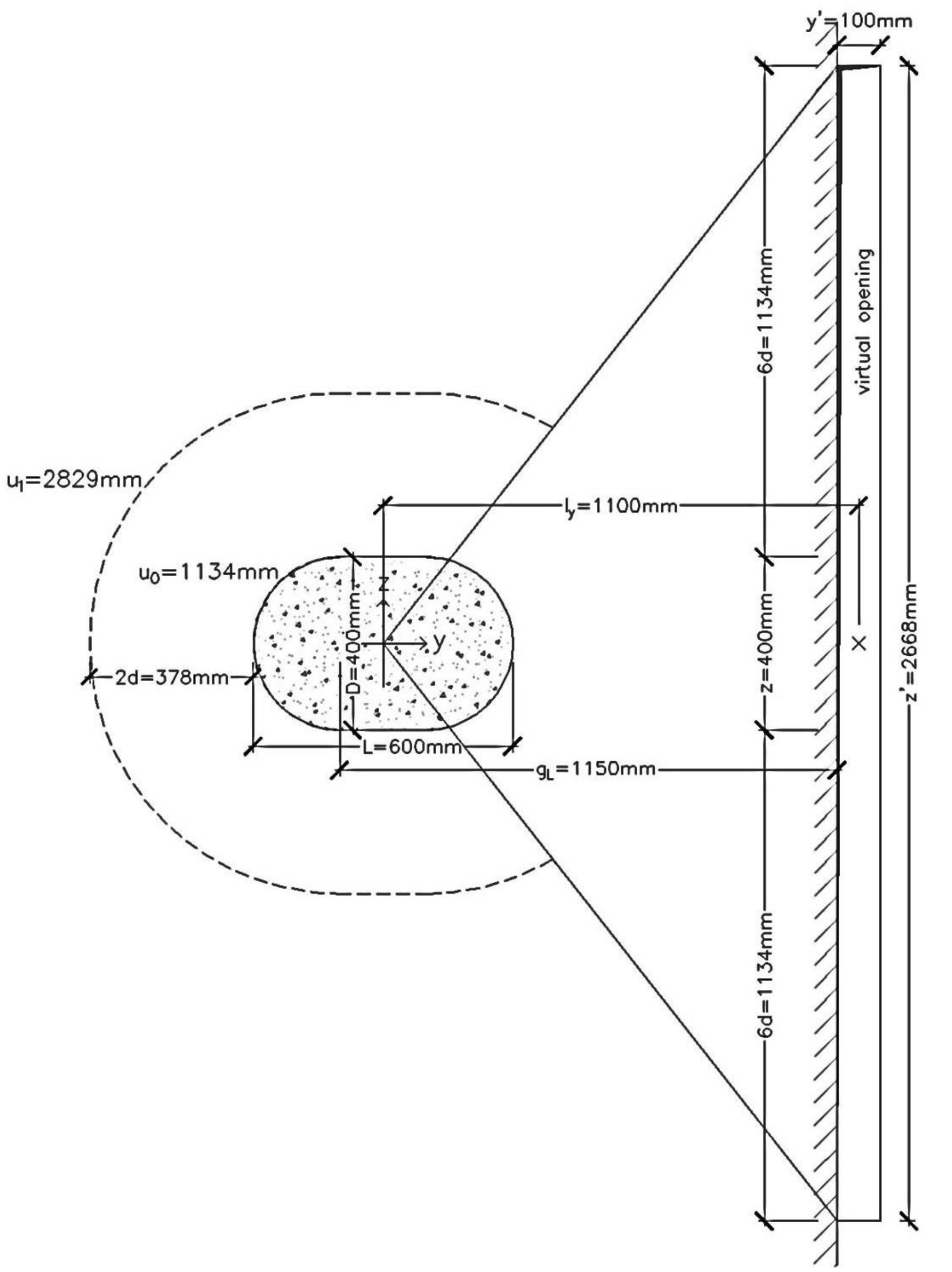
$\beta = 1 + k\frac{M'_{Ed}}{V_{Ed}}\frac{u_1}{W_1}$ $\rightarrow \beta = 1.076$

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

$1.078 > 1.076$ $\underline{\therefore \beta = 1.078}$

Results so far

Effective depth	d =	189	mm
Control perimeters	u_0 =	1134	mm
	u_1 =	2829	mm
Reinforcement ratios	ρ_l =	0.00532	
Load increase factor	β =	1.078	



Shear at column face

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

where, $u_0 = 1134\ mm$ (with opening reduction) $v_{Ed,0} = 1.51\ MPa$

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

where, (6.6N) $v = 0.6\left[1 - \frac{f_{ck}}{250}\right] = 0.533$

(3.15) $f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c}$

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

(3.1.6) $\alpha_{cc} = 1.0$ “all other phenomena”

$f_{cd} = 18.67\ MPa$ $v_{Rd,max} = 4.97\ MPa$

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) $v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 d}$

where, $u_1 = 2829\ mm$ (with opening reduction) $v_{Ed,1} = 0.60\ MPa$

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

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

$\rho_l = \sqrt{\rho_{lz}\rho_{ly}} \leq 0.02$ $\rightarrow \rho_l = 0.00532$

(NA6.4.4) $k_1 = 0.1$

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

$v_{Rd,c} = 0.591 \geq 0.524$ $v_{Rd,c} = 0.59\ MPa$

Limiting value of punching shear capacity, $v_{Rd,c,max} = 2 \times v_{Rd,c}$ $v_{Rd,c,max} = 1.18\ MPa$

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,

$u_{out,req} = \frac{\beta V_{Ed}}{v_{Rd,c}d}$ $u_{out,req} = 2897\ mm$

45° Radial layout

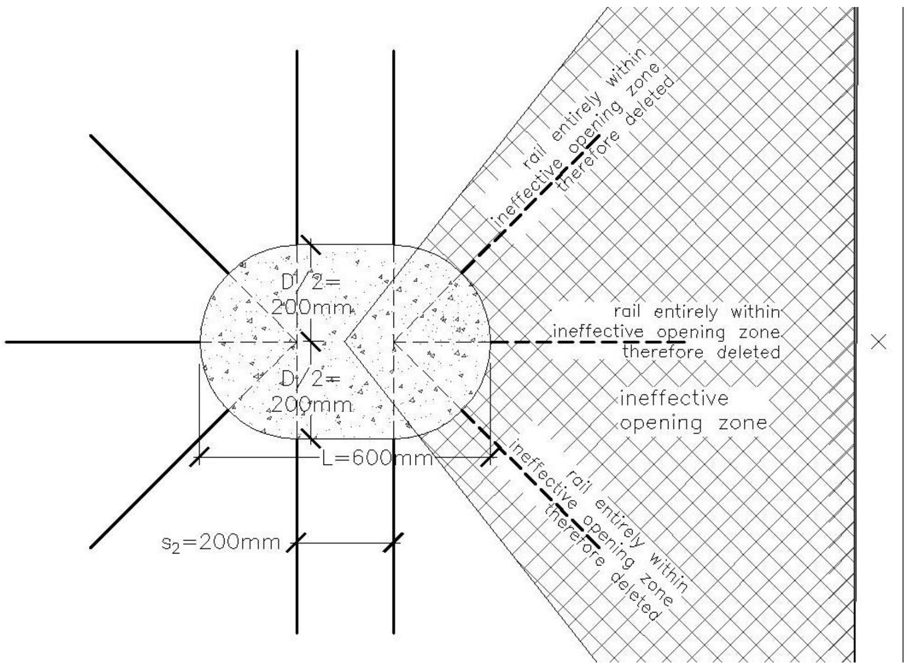
Number of main rails

$D/_2 = 200\ mm$

$s_2 = L - D = 200\ mm \geq 0.75d$ $\leq 1.5d$ →2 rails perpendicular to y-face

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

Three rails located entirely within ineffective opening zone, therefore, <u>7 main rails</u> required.



Length of main rails

Distance to first stud, $s_{r0} = 0.5d = 94.5mm$

rounded down to nearest 1mm $\rightarrow s_{r0} = 94mm$

Radial spacing of studs, $s_r = 0.75d = 141.75mm$

rounded down to nearest 1mm $\rightarrow s_r = 141mm$

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

Number of studs per main rail	Length of outer perimeter	Sufficient?
3	4054 mm	≥ 2829 sufficient

Therefore, <u>three studs</u> per main rail required.

Secondary rails

Maximum tangential spacing inside basic control perimeter, 1.5d = 283.5 mm

Stud number	Maximum tangential spacing	Secondary rail required?
3	441 mm	> 1.5d secondary rail required
2	333 mm	> 1.5d secondary rail required
1	225 mm	< 1.5d secondary rail not required

Therefore, <u>six secondary rails</u> required with <u>two shear studs</u> per rail.

Shear stud size

$A_{sw} = {(v_{Ed,1} - 0.75v_{Rd,c})s_r u_1}/{1.5f_{ywd,ef}}$ and $A_{sw,min} \geq {0.08 s_r s_t \sqrt{f_{ck}}}/{1.5f_{yk}}$

where $f_{yk} = 500\ MPa$

$f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$

$f_{ywd} = \frac{f_{yk}}{1.15} = 435\ MPa$

$f_{ywd,ef} = 297 \leq 435$

$s_r = 141\ mm$

$s_t = 441\ mm$

$A_{sw} = 145.0\ mm^2\ per\ perimeter$

$A_{sw,min} = 35.1\ mm^2\ per\ stud$

Minimum number of effective main rail shear studs per perimeter = 7

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

$A_{stud} = 20.7 < 35.1$

$A_{stud,required} = 35.1$

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

Therefore, optimal stud diameter for a 45° radial layout is <u>10mm ø</u>

Stud height $h_{stud} = h - c_{nom,t} - c_{nom,b}$

$h_{stud} = 230 - 25 - 25 = 180\ mm$

Therefore, studs are <u>180mm high</u>.

Shear capacity with punching shear reinforcement

Shear capacity with reinforcement,

(6.52) $v_{Rd,cs} = 0.75v_{Rd,c} + 1.5\left({d}/{s_r}\right)A_{sw}f_{ywd,ef}\left({1}/{u_1 d}\right)\sin\alpha$

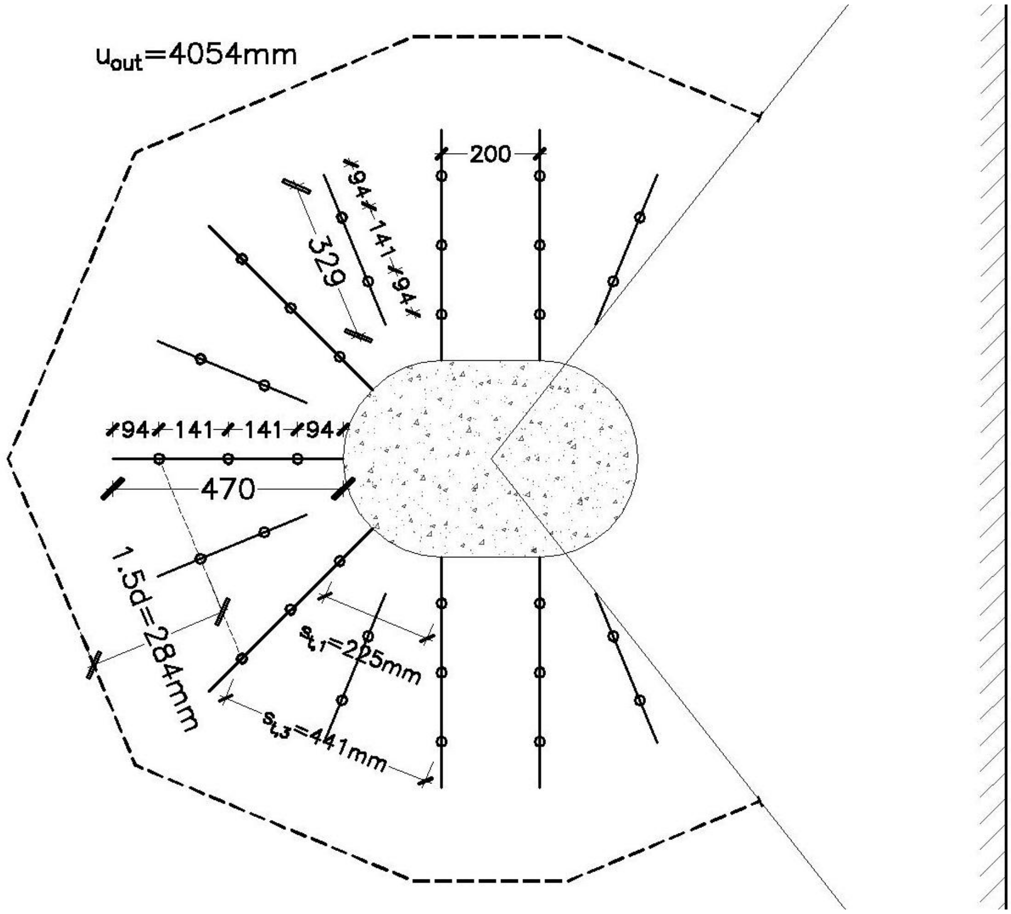
where, $A_{sw} = 7 \times 78.5 = 550\ mm^2$

$\alpha = 90°$ $\rightarrow \sin\alpha = 1$ $\underline{\rightarrow v_{Rd,cs} = 1.06\ MPa}$

16.2.3 Design solution

45° radial layout

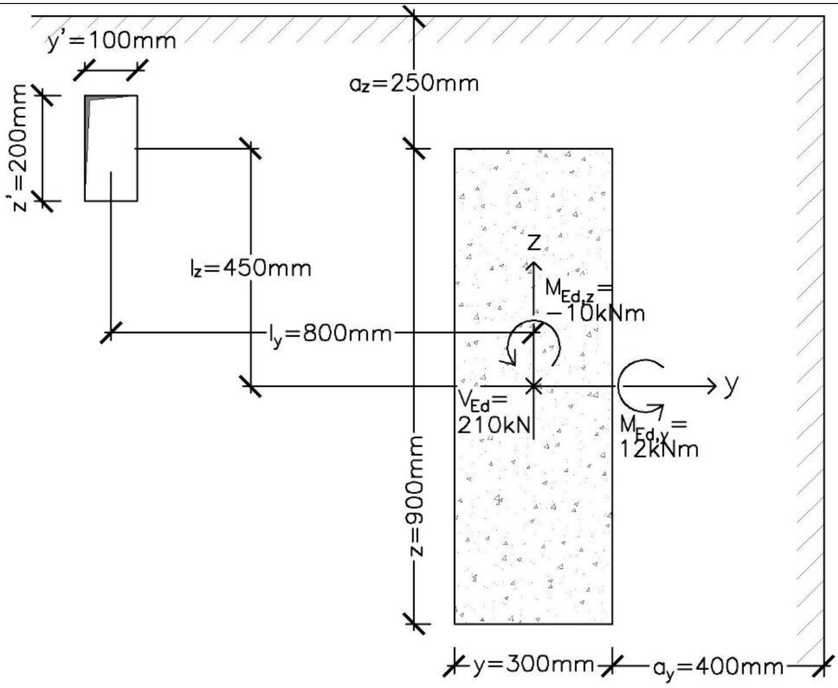
7 no. main rails (3 x 10mm ø studs @ 141mm c/c, 470mm long, 180mm high)
6 no. secondary rails (2 x 10mm ø studs @ 141mm c/c, 329mm long, 180mm high)



16.3 Corner rectangular column

16.3.1 Inputs

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



16.3.2 Design

Design parameters

Effective depth, $d_{y1} = h - c_{nom,t} - \emptyset_{y1}/2 \qquad = 219mm$

$d_{z1} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1}/2 \qquad = 207mm$

$d_{y2} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1} - \emptyset_{y2}/2 \qquad = 193mm$

$d_{z2} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1} - \emptyset_{y2} - \emptyset_{z2}/2 \quad = 177mm$

$d = (d_{y1} + d_{z1} + d_{y2} + d_{z2})/4 \qquad \underline{= 199mm}$

Opening, $l_1 = 100mm, \quad l_2 = 200mm, \quad \sqrt{l_1 \times l_2} = 141.42mm$

where l_3 found using CAD: $l_3 = 222.04mm \geq \sqrt{l_1 l_2} \qquad \therefore l_3 = 222mm$

Control perimeters, $a = max(y, z) = 900mm \qquad b = min(y, z) = 300mm$

$g_a = a_{e,z} = 250\ mm \qquad g_b = a_{e,y} = 400\ mm$

$a_1 = min(a, 4b, 3d) = min(900{,}1200{,}597) = 597mm$

$a_{1u0} = min(a, 4b, 1.5d) = min(900{,}1200{,}298.5) = 298.5mm$

$b_1 = min(b, 3d) = min(300{,}597) = 300mm$

$b_{1u0} = min(b, 1.5d) = min(300{,}298.5) = 298.5mm$

without opening, $u_0 = a_{1u0} + b_{1u0} \qquad \underline{= 597mm}$

$u_1 = a_1 + b_1 + g_a + g_b + \pi d \qquad \underline{= 2172mm}$

with opening, $u_0 \qquad \underline{= 597mm}$

$u_1 \qquad \underline{= 1996mm}$

Reinforcement ratio,

$\rho_{ly} = \frac{A_{sy1}}{A_{cy1}} + \frac{A_{sy2}}{A_{cy2}} = 0.0104 \qquad \rho_{lz} = \frac{A_{sz1}}{A_{cz1}} + \frac{A_{sz2}}{A_{cz2}} = 0.0112$

$\rho_l = \sqrt{\rho_{ly} \times \rho_{lz}} \qquad \underline{= 0.01079}\ (\equiv 1.079\%)$

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.

$y_0 = 265.3\ mm$

$z_0 = 409.6\ mm$

where $u_1 = 2172\ mm$ (without opening reduction)

moment about centroid of basic control perimeter,

$M'_{Ed,y} = M_{Ed,y} - z_0 V_{Ed} = -74.02\ kNm \qquad \leq 0 \qquad \therefore$ towards exterior

$M'_{Ed,z} = M_{Ed,z} - y_0 V_{Ed} = -45.71\ kNm \qquad \leq 0 \qquad \therefore$ towards exterior

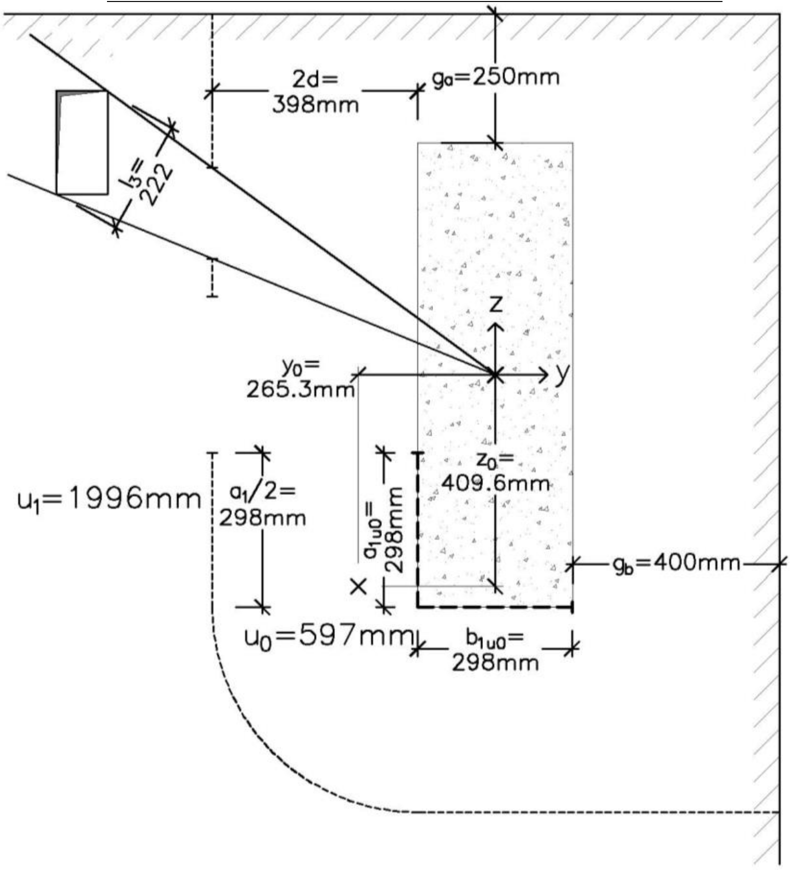
Therefore, load increase factor:

$\beta = 1 + k \frac{M'_{Ed}}{V_{Ed}} \frac{u_1}{W_1} \qquad \underline{\rightarrow \beta = 1.700}$

Results so far

Effective depth	d =	199	mm
Control perimeters	u_0 =	597	mm
	u_1 =	1996	mm

Reinforcement ratios	ρ_l =	0.01079
Load increase factor	β =	1.700



Shear at column face

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

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

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

(3.15) $f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c}$

Table 2.1N $\gamma_c = 1.5$ "persistent and transient"

(3.1.6) $\alpha_{cc} = 1.0$ "all other phenomena"

$f_{cd} = 23.33\ MPa$ $\qquad v_{Rd,max} = 6.02\ MPa$

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) $v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 d}$ $\qquad v_{Ed,1} = 0.90\ MPa$

Design shear capacity without reinforcement,

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

where, $C_{Rd,c} = 0.18/\gamma_c = 0.12$

$k = 1 + \sqrt{200/d} \leq 2.0$ $\qquad \rightarrow k = 2.0$

$\rho_l = \sqrt{\rho_{lz} \rho_{ly}} \leq 0.02$ $\qquad \rightarrow \rho_l = 0.01079$

(NA6.4.4) $k_1 = 0.1$

(NA6.4.4) $v_{min} = 0.035k^{3/2}f_{ck}^{1/2} = 0.586$

$v_{Rd,c} = 0.805 \geq 0.586$ $v_{Rd,c} = 0.81\ MPa$

Limiting value of punching shear capacity, $v_{Rd,c,max} = 2 \times v_{Rd,c}$ $v_{Rd,c,max} = 1.61\ MPa$

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,

$$u_{out,req} = \frac{\beta V_{Ed}}{v_{Rd,c}d} \qquad u_{out,req} = 2228\ mm$$

30° Radial layout

Number of main rails

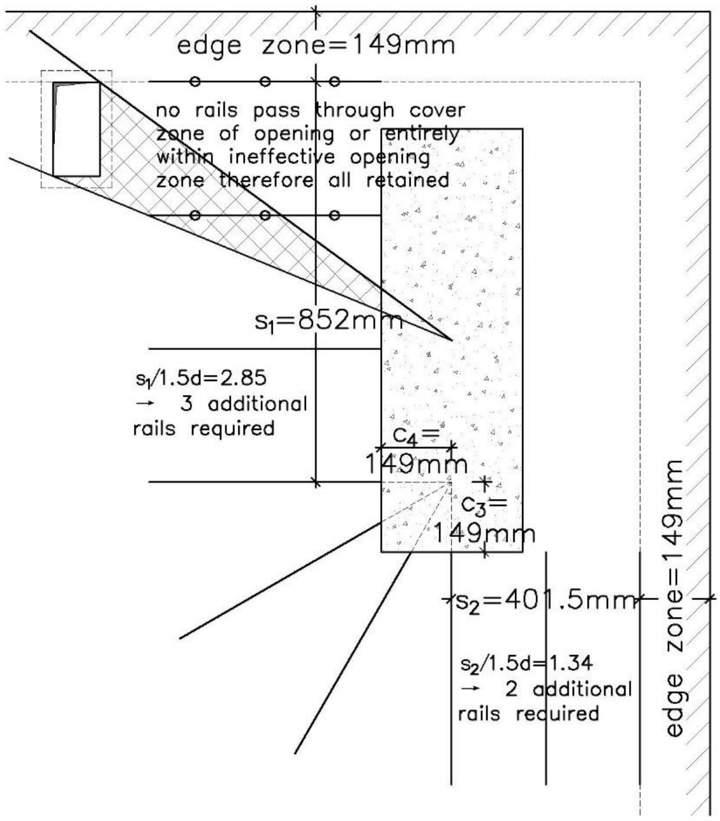
$c_3 = c_4 = min\left(\frac{y}{2}, \frac{z}{2}, 0.75d\right) = 149.25\ mm$

$s_1 = z + g_z - c_3 - 0.75d = 851.5 \quad \geq 1.5d \quad \frac{s_1}{1.5d} = \frac{852}{298.5} = 2.85$ → 3 additional rails

$s_2 = y + g_y - c_4 - 0.75d = 401.5 \quad \geq 1.5d \quad \frac{s_2}{1.5d} = \frac{401}{298.5} = 1.34$ → 2 additional rails

→ 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, <u>9 main rails</u> required.



Length of main rails

Distance to first stud, $s_{r0} = 0.5d = 99.5mm$

rounded down to nearest 1mm $\rightarrow s_{r0} = 99mm$

Radial spacing of studs, $s_r = 0.75d = 149.25mm$

rounded down to nearest 1mm $\rightarrow s_r = 149mm$

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

Number of studs per main rail	Length of outer perimeter	Sufficient?
3	2331 mm	≥ 2228 sufficient

Therefore, <u>three studs</u> per main rail required.

Secondary rails

Maximum tangential spacing inside basic control perimeter, 1.5d = 298.5 mm

Stud number	Maximum tangential spacing	Secondary rail required?
3	295 mm	≤ 1.5d secondary rail not required

Therefore, <u>secondary rails not required</u>.

Shear stud size

$$A_{sw} = {(v_{Ed,1} - 0.75v_{Rd,c})s_r u_1}/{1.5f_{ywd,ef}} \quad \text{and} \quad A_{sw,min} \geq {0.08 s_r s_t \sqrt{f_{ck}}}/{1.5f_{yk}}$$

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

Therefore, optimal stud diameter for a 30° radial layout is <u>10mm ø</u>

Stud height $h_{stud} = h - c_{nom,t} - c_{nom,b}$

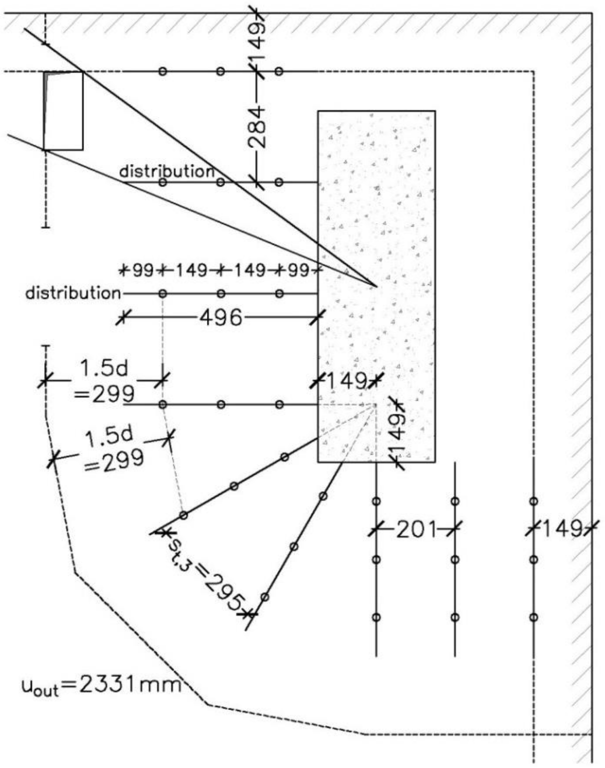
$$h_{stud} = 250 - 25 - 25 = 200\ mm$$

Therefore, studs are <u>200mm high</u>.

30° radial solution:

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)



45° Radial layout

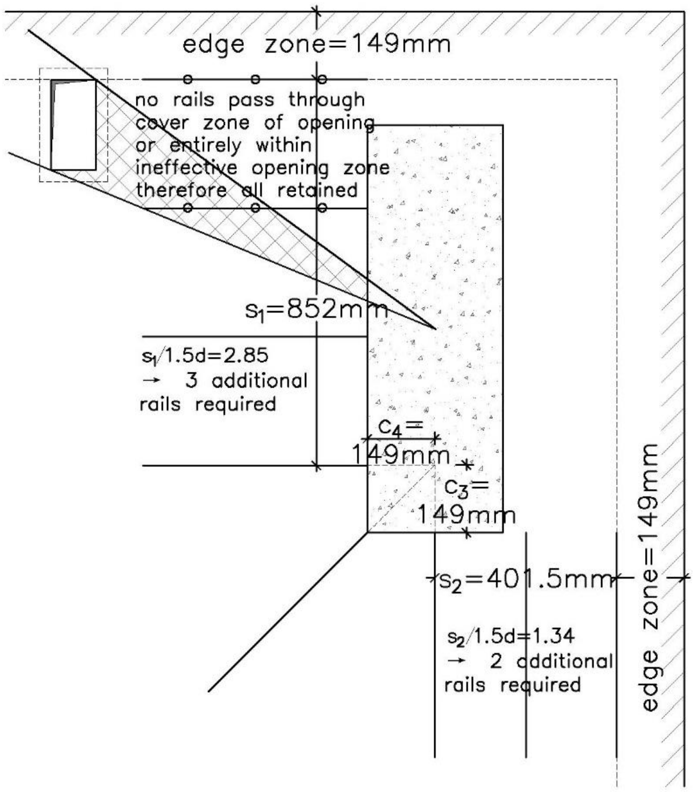
Number of main rails

As for 30° radial layout, $c_3 = c_4 = 149.25\ mm$

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

→ 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, <u>8 main rails</u> required.



Length of main rails

As for 30° radial layout, $s_{r0} = 99mm$ $s_r = 149mm$

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

Number of studs per main rail	Length of outer perimeter	Sufficient?
3	2369 mm	≥ 2228 sufficient

Therefore, <u>three studs</u> per main rail required.

Secondary rails

Maximum tangential spacing inside basic control perimeter, 1.5d = 298.5 mm

Stud number	Maximum tangential spacing	Secondary rail required?
3	445 mm	> 1.5d secondary rail required
2	333 mm	> 1.5d secondary rail required
1	221 mm	≤ 1.5d secondary rail not required

Minimum rail length = 2 studs

Therefore, <u>2 secondary rails</u> required with <u>two shear studs</u> per rail.

Shear stud size

$A_{sw} = {(v_{Ed,1} - 0.75v_{Rd,c})s_r u_1} / {1.5f_{ywd,ef}}$ and $A_{sw,min} \geq {0.08 s_r s_t \sqrt{f_{ck}}} / {1.5f_{yk}}$

As for 30° radial layout, $A_{sw} = 195.1\ mm^2\ per\ perimeter$

$s_r = 149\ mm$

$s_t = 445\ mm$

$A_{sw,min} = 41.9\ mm^2\ per\ stud$

Minimum number of effective main rail shear studs per perimeter = 6

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

$A_{stud,required} = 32.5 < 41.9$

$A_{stud,required} = 41.9$

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

Therefore, optimal stud diameter for a 45° radial layout is <u>10mm ø</u>

Stud height

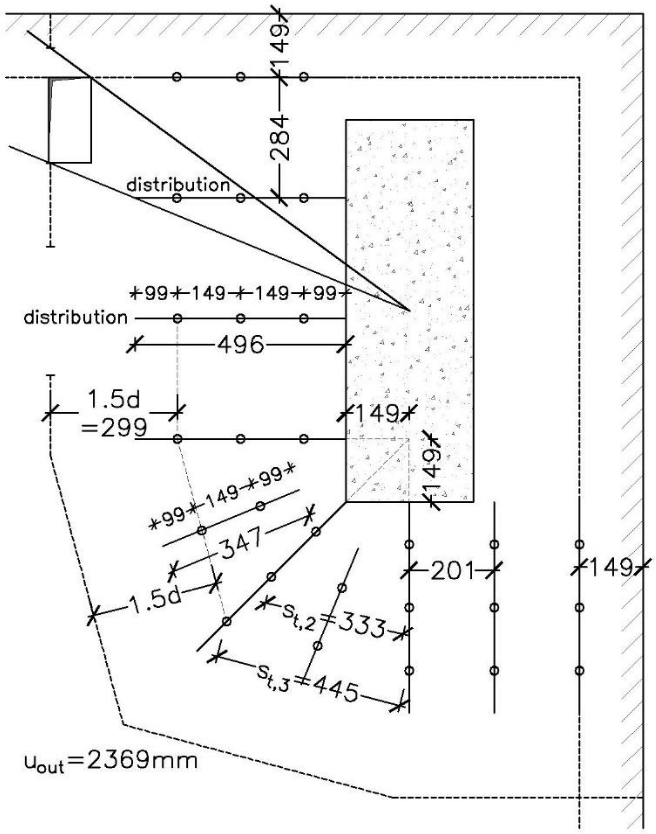
As for 30° radial layout, studs are <u>200mm high</u>.

45° radial solution:

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

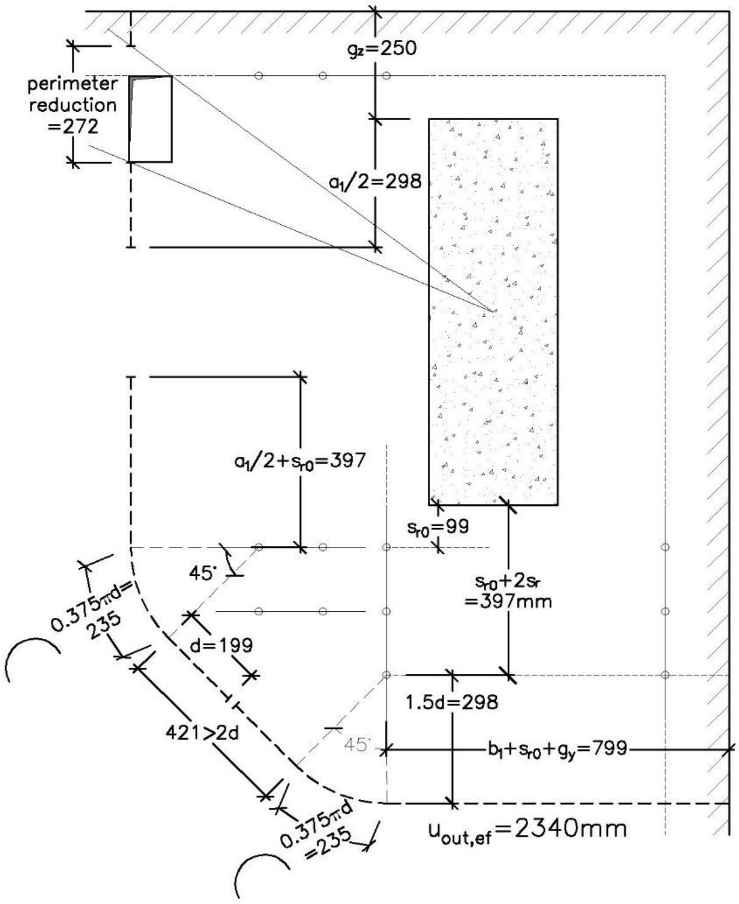
2 no. distribution rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)

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 $u_{out,ef}$.)



$$u_{out,ef} = 2340\ mm \geq u_{out,req} = 2228\ mm$$

Therefore, a cruciform layout is possible for this case.

Number of main rails

$y + s_{r0} + g_y - 0.75d > 0.75d \rightarrow$ $\quad \frac{y+s_{r0}+g_y-0.75d}{1.5d} = \frac{650.0}{298.5} = 2.18 \rightarrow$

4 rails perpendicular to y-face

$z + s_{r0} + g_z - 0.75d > 0.75d \rightarrow$ $\quad \frac{z+s_{r0}+g_z-0.75d}{1.5d} = \frac{1100.0}{298.5} = 3.68 \rightarrow$

5 rails perpendicular to z-face

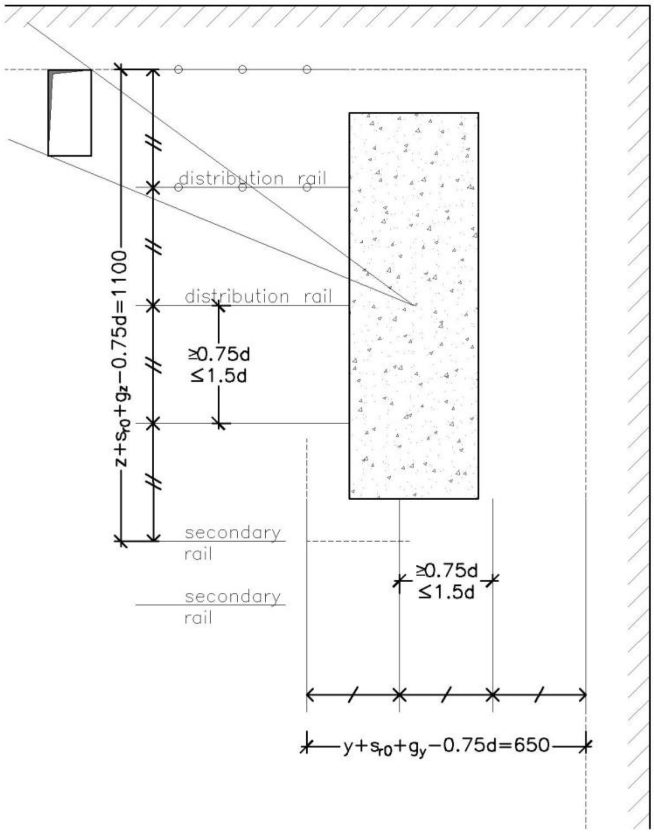
Secondary rails

Maximum permitted tangential spacing of studs, 2d = 398 mm

Actual tangential spacing of outermost studs, $\sqrt{8{s_r}^2} = 421 > 398$

Therefore, a further secondary rail at the corner is required.

→ 6 main rails + 2 distribution rails + 2 secondary rails as illustrated.



Length of main rails

Cruciform layout → There must be three studs per main rail.

Shear stud size

$A_{sw} = \left(v_{Ed,1} - 0.75v_{Rd,c}\right)s_r u_1 / 1.5f_{ywd,ef}$ and $A_{sw,min} \geq 0.08 s_r s_t \sqrt{f_{ck}} / 1.5f_{yk}$

As for 30° radial layout, $A_{sw} = 195.1\ mm^2\ per\ perimeter$

$s_r = 149\ mm$

$$s_t = 421\ mm$$

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

Minimum number of main rail shear studs per perimeter = 6

$$A_{stud} = {}^{A_{sw}}/_{n_{mr}} \geq A_{sw,min}$$

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

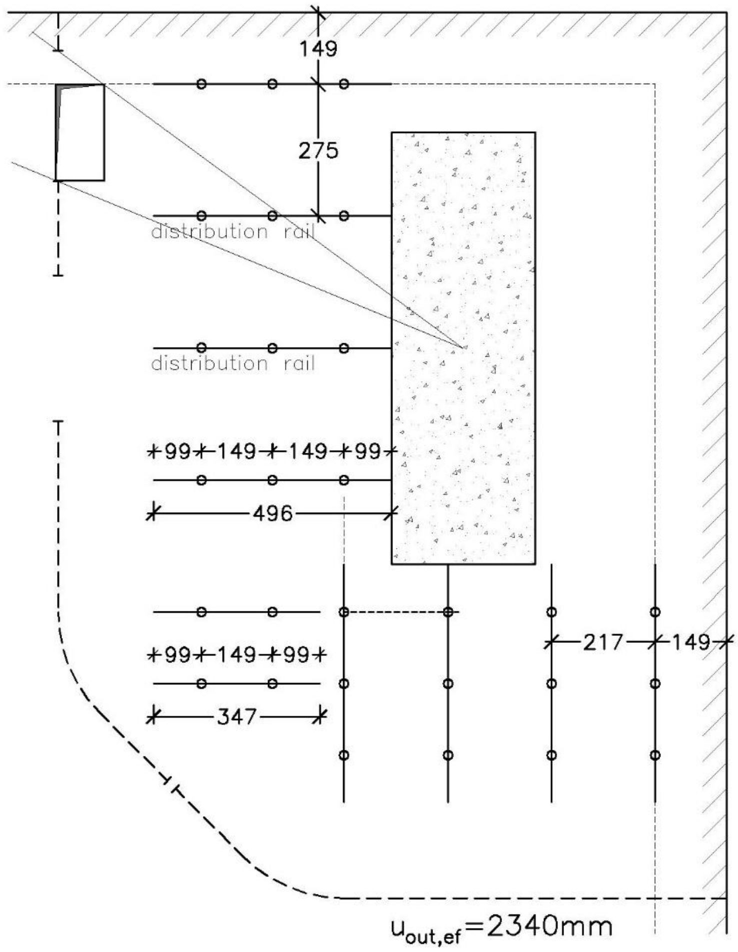
$$A_{stud,required} = 39.6$$

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

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

Layout	Total number of shear studs	Total number of rails
30° radial	27	9
45° radial	28	10
Cruciform	28	10

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) $v_{Rd,cs} = 0.75 v_{Rd,c} + 1.5\left({}^{d}/_{s_r}\right) A_{sw} f_{ywd,ef} \left({}^{1}/_{u_1 d}\right) \sin\alpha$

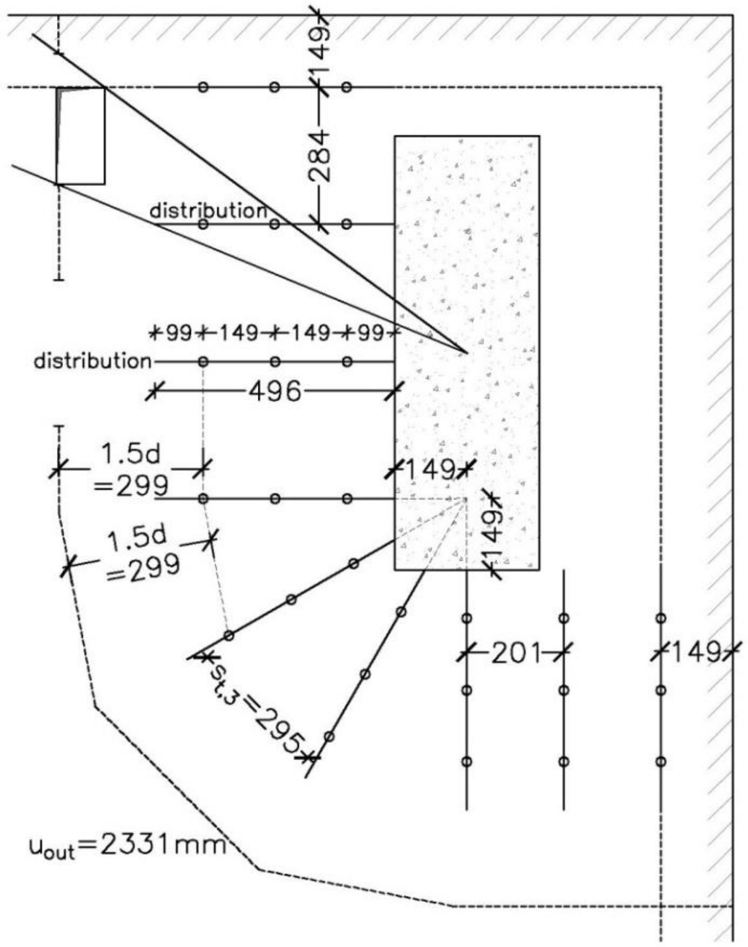
where, $A_{sw} = 6 \times 78.5 = 471\ mm^2$

$\alpha = 90°$ $\rightarrow \sin\alpha = 1$ $\underline{\rightarrow v_{Rd,cs} = 1.32\ MPa}$

16.3.3 Design solution

30° radial layout

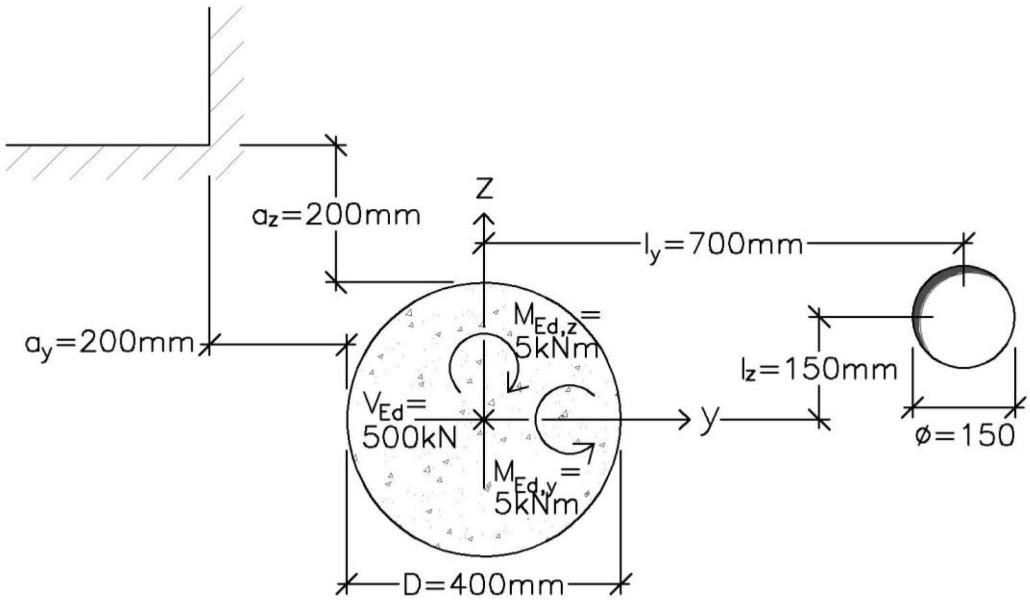
7 no. main rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high) 2 no. distribution rails (3 x 10mm ø studs @ 149mm c/c, 496mm long, 200mm high)



16.4 Re-entrant corner circular column

16.4.1 Inputs

Re-entrant corner circular column					
Dimensions,		D =	400	mm	
	Edge @ left	$a_{e,y}$ =	200	mm	
	Edge @ top	$a_{e,z}$ =	200	mm	
Slab depth,		h =	240	mm	
Concrete grade,	C40/50	f_{ck} =	40	N/mm^2	
Top cover,		$c_{nom,t}$ =	30	mm	
Bottom cover,		$c_{nom,b}$ =	30	mm	
Pre-compression,		σ_{cp} =	0	N/mm^2	
Reinforcement,	Layer 1,	y-y	H12 @150 mm c/c		
		z-z	H12 @150 mm c/c		
	Layer 2,	y-y	H12 @200 mm c/c		
		z-z	H12 @200 mm c/c		
Loading	Design shear	V_{Ed} =	500	kN	
	β	To be calculated			
	Design moments	$M_{Ed,y}$ =	5	kNm	Towards interior
		$M_{Ed,z}$ =	5	kNm	Towards interior
Opening 1	Circular	l_y =	700	mm	
		l_z =	150	mm	
		ø =	150	mm	
Distance to first stud		S_{r0} =	0.5	d	
Shearfix	Layout	45° Radial			
	Stud ø	Automatic optimal			
	Rail placing	Bottom-up			



16.4.2 Design

Design parameters

Effective depth, $d_{y1} = h - c_{nom,t} - \emptyset_{y1}/2 \quad = 204mm$

$d_{z1} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1}/2 \quad = 192mm$

$$d_{y2} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1} - \emptyset_{y2}/2 \qquad = 180mm$$
$$d_{z2} = h - c_{nom,t} - \emptyset_{y1} - \emptyset_{z1} - \emptyset_{y2} - \emptyset_{z2}/2 \quad = 168mm$$
$$d = (d_{y1} + d_{z1} + d_{y2} + d_{z2})/4 \qquad \underline{= 186mm}$$

Control perimeters, $D_{u0} = min(0.25\pi D, 1.5d) = min(314,\ 279) = 279mm$

$g_y = a_{e,y} + \frac{D}{2} = 400mm$

$g_z = a_{e,z} + \frac{D}{2} = 400mm$

without opening, $u_0 = 0.5\pi D + 2D_{u0}$ $\underline{= 1186\ mm}$

$u_1 = \frac{3\pi}{4}(D + 4d) + g_y + g_z$ $\underline{= 3495\ mm}$

with opening, u_0 $\underline{= 1144mm}$

u_1 $\underline{= 3375mm}$

Reinforcement ratio, $\rho_{ly} = \frac{A_{sy1}}{A_{cy1}} + \frac{A_{sy2}}{A_{cy2}} = 0.00683$ $\qquad \rho_{lz} = \frac{A_{sz1}}{A_{cz1}} + \frac{A_{sz2}}{A_{cz2}} = 0.00729$

$\rho_l = \sqrt{\rho_{ly} \times \rho_{lz}}$ $\underline{= 0.00706}$ $(\equiv 0.706\%)$

Load increase factor,

Re-entrant corner, therefore:

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

$y_0 = 5.3\ mm$ $\qquad z_0 = 5.3\ mm$ $\qquad$ (where: $+y_0$ is in +y direction; $+z_0$ is in –z direction)

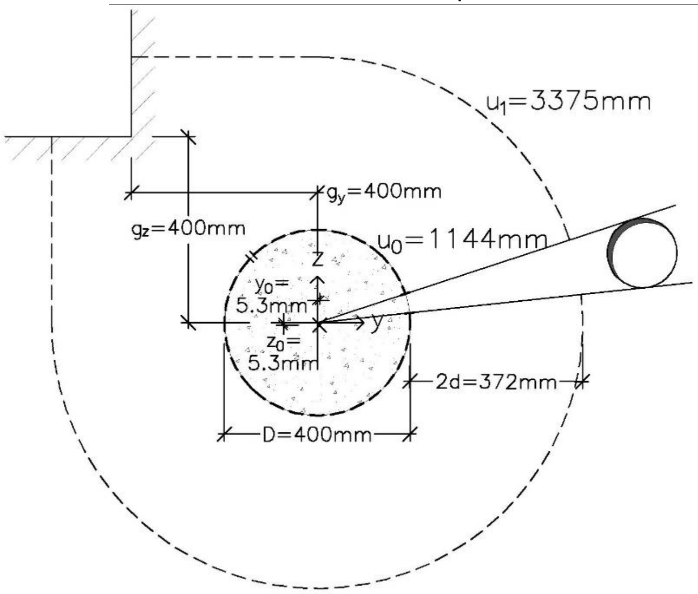
$M'_{Ed,y} = M_{Ed,y} - z_0 V_{Ed} = 2.35\ kNm$

$M'_{Ed,z} = M_{Ed,z} - y_0 V_{Ed} = 2.35\ kNm$

$\beta = 1 + k\frac{M'_{Ed}}{V_{Ed}}\frac{u_1}{W_1}$ $\qquad \underline{\rightarrow \beta = 1.011}$

Results so far

Effective depth	d =	186	mm
Control perimeters	u_0 =	1144	mm
	u_1 =	3375	mm
Reinforcement ratios	ρ_l =	0.00706	
Load increase factor	β =	1.011	



Shear at column face

Applied design shear at column face, (6.53) $v_{Ed,0} = \frac{\beta V_{Ed}}{u_0 d}$ $v_{Ed,0} = 2.38\ MPa$

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

where, (6.6N) $v = 0.6\left[1 - \frac{f_{ck}}{250}\right] = 0.504$

(3.15) $f_{cd} = \frac{\alpha_{cc} f_{ck}}{\gamma_c}$

Table 2.1N $\gamma_c = 1.5$ "persistent and transient"

(3.1.6) $\alpha_{cc} = 1.0$ "all other phenomena"

$f_{cd} = 26.67\ MPa$ $v_{Rd,max} = 6.72\ MPa$

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) $v_{Ed,1} = \frac{\beta V_{Ed}}{u_1 d}$ $v_{Ed,1} = 0.81\ MPa$

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

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

$\rho_l = \sqrt{\rho_{lz} \rho_{ly}} \leq 0.02$ $\rightarrow \rho_l = 0.00706$

(NA6.4.4) $k_1 = 0.1$

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

$v_{Rd,c} = 0.731 \geq 0.626$ $v_{Rd,c} = 0.73\ MPa$

Limiting value of punching shear capacity, $v_{Rd,c,max} = 2 \times v_{Rd,c}$ $v_{Rd,c,max} = 1.46\ MPa$

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,

$u_{out,req} = \frac{\beta V_{Ed}}{v_{Rd,c} d}$ $u_{out,req} = 3718\ mm$

45° Radial layout

Number of main rails

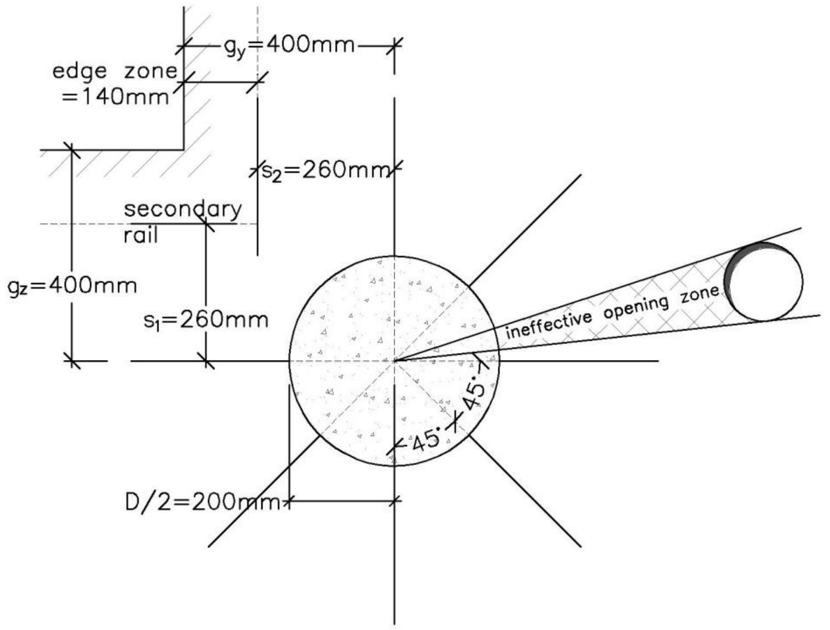
$s_2 = g_y - 0.75d = 260 > 0.75d$ → main rail parallel to edge

$\frac{s_2}{1.5d} = \frac{260}{279} = 0.93$ → no additional rails

$s_1 = g_z - 0.75d = 260 > 0.75d$ → secondary rail parallel to edge

$\frac{s_1}{1.5d} = \frac{260}{279} = 0.93$ → no additional rails

→ <u>8 main rails and 1 secondary rail</u>, 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 $\rightarrow s_{r0} = 93mm$

Radial spacing of studs, $s_r = 0.75d = 139.5\ mm$

rounded down to nearest 1mm $\rightarrow s_r = 139mm$

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

Number of studs per main rail	Length of outer perimeter	Sufficient?
3	4624 mm	≥ 3718 sufficient

Therefore, <u>three studs</u> per main rail required.

Secondary rails

Maximum tangential spacing inside basic control perimeter, 1.5d = 279 mm

Stud number	Maximum tangential spacing	Secondary rail required?
3	437 mm	> 1.5d secondary rail required
2	331 mm	> 1.5d secondary rail required
1	224 mm	≤ 1.5d secondary rail not required

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

Shear stud size

$$A_{sw} = {(v_{Ed,1} - 0.75v_{Rd,c})s_r u_1}\big/{1.5f_{ywd,ef}} \quad \text{and} \quad A_{sw,min} \geq {0.08 s_r s_t \sqrt{f_{ck}}}\big/{1.5f_{yk}}$$

where $f_{yk} = 500\ MPa$

$f_{ywd,ef} = 250 + 0.25d \leq f_{ywd}$

$f_{ywd} = \frac{f_{yk}}{1.15} = 435\ MPa$

$f_{ywd,ef} = 297 \leq 435$

$s_r = 139\ mm$

$s_t = 437\ mm$

$A_{sw} = 270.4\, mm^2\ per\ perimeter$
$A_{sw,min} = 41.0\, mm^2\ per\ stud$
Minimum number of effective main rail shear studs per perimeter = 8

$$A_{stud} = {}^{A_{sw}}/_{n_{mr}} \geq A_{sw,min}$$
$$A_{stud} = 33.8 < 41.0$$
$$A_{stud,required} = 41.0$$

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

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

Stud height $h_{stud} = h - c_{nom,t} - c_{nom,b}$

$$h_{stud} = 240 - 30 - 30 = 180\ mm$$

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)