TECHNICAL REPORT

Increase of punching shear resistance of footings and ground slabs - S-shaped double headed elements - Calculation of design

TR 079

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EUROPEAN ORGANISATION FOR TECHNICAL ASSESSMENT

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Contents

1 GENERAL

1.1 Scope

This Technical Report contains a method for punching shear calculation of footings and ground slabs under static, quasi-static and fatigue loading.

Reinforcement elements according to Annex A are used for the increase of the punching shear resistance of footings and ground slabs under static, quasi-static and fatigue loading.

The reinforcement elements are located adjacent to columns or high concentrated loads. This TR covers the following specifications of the intended use:

- footings and ground slabs made of reinforced normal weight concrete of strength class C12/15 to C50/60 according to EN 206-1 [1],
- footings and ground slabs with a minimum height of h = 230 mm,
- reinforcement elements according to Annex A of the same diameter and type in the punching area around a column or high concentrated load,
- reinforcing steel for the elements according to EN1992-1-1 [2] may be used with $f_{yk} \geq 500$ N/mm^2, in design only f_{yk} = 500 N/mm^2 is allowed,
- reinforcement elements according to Annex A installed in an upright position,
- reinforcement elements according to Annex A directed radially towards the column or high concentrated load and distributed evenly in the critical punching area,
- reinforcement elements according to Annex A positioned such that the anchorage plate of the element reach at least to the outside of the uppermost layer of the flexural reinforcement,
- reinforcement elements according to Annex A positioned such that the lower bend reach at least to the outside of the lowest layer of the flexural reinforcement,
- reinforcement elements positioned according to Annex A such that the concrete cover complies with the provisions according to EN 1992-1-1 [2],
- reinforcement elements according to Annex A positioned such that the minimum and maximum distances between the elements as arranged around a column or area of high concentrated load complies with the provisions according to section 3,
- The provisions according to section 3 are kept on site with an accuracy of 0,1h (h height of the slab),
- This document was written to represent current best practice. However, users should verify that applying its provisions allows local regulatory requirements to be satisfied.,
- The design for static, quasi-static and fatigue loading of the footings and ground slabs shall base on EN 1992-1-1 [2].

1.2 Assumptions

It is assumed that:

- The load-bearing capacity of the column as well as the local compressive stress at the joint between slab and column are each verified individually and by taking into account of national provisions and guidelines.
- The load-bearing capacity of the concrete slab outside the punching shear reinforced area is verified separately and in accordance with the relevant national provisions.
- The moment resistance of the entire slab is verified in accordance with the relevant national provisions.
- The flexural reinforcement has to be designed and detailed in accordance with the relevant national provisions.
- The position, the type, the size and the length of the reinforcement elements are indicated on the design drawings. The material of the reinforcement elements is given additionally on the drawings.

1.3 Specific terms used in this TR

Indices

c	concrete
d	design value
E	action effects
fo	footing or ground slab
k	characteristic value
max	maximum
min	minimum
pu	punching shear
R	resistance
re	reinforcement
s	steel
V	shear force
y	yield

Actions and resistances

f_{cd}	design compressive cylinder strength (150 mm diameter by 300 mm cylinder)
f_{yd}	design steel yield strength
f_{yk}	characteristic value of yield stress of the shear reinforcement element (≥ 500 MPa)
f_{ywd}	design value of the yield strength of the shear reinforcement element
γ	partial safety factor
V_{Ed}	design value of the applied shear force
v_{Ed}	shear stress calculated along the area defined by the basic perimeter and the effective depth ($u_1 \cdot d$)
v_{min}	minimum punching shear resistance along the critical diameter u_1
$V_{Rd,c}$	punching shear resistance without shear reinforcement
$V_{Rd,cs}$	punching shear resistance of the shear-reinforced area
$V_{Rd,max}$	maximum punching shear resistance along the critical diameter u_1
$V_{Rd,out}$	maximum punching shear resistance along the critical diameter u_{out}

Concrete, reinforcement and punching shear element

A	area of the footing (area within the line of contraflexure for the bending moment in radial direction in a continuous ground slab)
A_{crit}	area within the critical perimeter u_{crit} at the iteratively determined distance a_{crit} from the column face
a_{crit}	distance from column face to control perimeter
β	coefficient taking into account the effects of load eccentricity
β_{red}	reduced coefficient taking into account the effects of load eccentricity at the outer critical section
d	effective depth according to EN 1992-1-1 [2]
d_A	shaft diameter of the shear reinforcement element
γ_s	product dependent partial safety factor for shear reinforcement elements = 1,15
κ	coefficient to take into account size effects
l_s	distance between column face and outermost row of shear reinforcement element
n_1	number of shear reinforcement elements in the first row
n_2	number of shear reinforcement elements in the second row
ρ	reinforcement ratio
s_r	radial distance between different rows of shear reinforcement elements

u_0 column perimeter

u_1 perimeter of the critical section at a distance of $a_{crit} \cdot d$ from the column face

u_{out} perimeter of the critical section at a distance of $1{,}5 \cdot d$ from the outermost row of shear reinforcement element

2 PUNCHING SHEAR CALCULATION

2.1 General rules and basic control perimeter

The design of punching shear reinforcement typically consists of the following steps:

- Resistance of the slab without punching shear reinforcement at critical perimeter u_1

$$V_{Ed} \leq V_{Rd,c} \tag{2.1}$$

- Maximum resistance of the slabs at critical perimeter u_1

$$V_{Ed} \leq V_{Rd,max} \tag{2.2}$$

- Resistance of the shear-reinforced area:

$$V_{Ed} \leq V_{Rd,cs} \tag{2.3}$$

- Resistance of the slabs at the outer perimeter u_{out}

$$V_{Ed} \leq V_{Rd,out} \tag{2.4}$$

The verification of the load bearing capacity at ultimate limit state is performed as follows: The ultimate limit state of punching shear shall be assessed along control perimeters. The slab shall be designed to resist a minimum of bending moments according to national guidelines. Outside the control perimeter the verification of the ultimate limit state design for shear and bending shall be carried out according to national guidelines.

For the determination of the punching shear resistance, an inner critical perimeter u_1 perpendicular to the footing or ground slab surface at the distance $a_{crit} \cdot d$ (d = effective depth of the slab) around the column and an outer control perimeter u_{out} at a distance of $a_{crit} \cdot d$ from the outermost row of the punching shear reinforcement are considered. The distance a_{crit} has to be calculated with an iterative method.

The critical perimeter may be determined as stated above for columns with a perimeter u_0 less than $12 \cdot d$ (or according to NA to EN1992-1-1 [2]) and a ratio of the longer column side to the shorter column side not larger than 2,0. For columns with an arbitrary shape the perimeter u_0 is the shortest length around the loaded area. The critical perimeters are affine to the perimeter u_0.

If these conditions are not fulfilled, the shear forces are concentrated along the corners of the column and the critical perimeter has to be reduced.

2.2 Verifications

The load bearing capacity of footings and ground slabs with punching shear reinforcement is verified as follows:

$$\beta \cdot V_{Ed,red} \leq V_{Rd,cs} \quad \text{and} \quad \beta \cdot V_{Ed,red} \leq V_{Rd,max} \tag{2.6}$$

where

$V_{Rd,cs}$ is determined as in section 2.4 of this TR

$V_{Rd,max}$ is determined as in section 2.4 of this TR

u_1 is the control perimeter determined by iterative calculation as in section 2.3 of this TR

In general:

$$\beta \cdot V_{Ed,red} = \beta \cdot (V_{Ed} - \Delta V_{Ed}) = \beta \cdot \left(V_{Ed} - \sigma_{gd} \cdot A_{crit}\right) \tag{2.7}$$

(with σ_{gd} being the mean value of the soil pressure inside the critical area A_{crit})

With uniform soil pressure distribution:

$$\beta \cdot V_{Ed,red} = \beta \cdot V_{Ed} \cdot \left(1 - \frac{A_{crit}}{A}\right) \quad (2.8)$$

A_{crit}: Area within the critical perimeter u_1 at the iteratively determined distance a_{crit} from the column face

A: Area of the footing (area within the line of contra flexure for the bending moment in radial direction in a continuous ground plate)

For structures where the lateral stability does not depend on frame action between the slabs and the columns, and where the adjacent spans do not differ in length by more than 25 %, constant values for β may be used. If not given otherwise in NA to EN 1992-1-1 [2], the following values may be used:

- interior columns: β = 1,10
- edge columns: β = 1,40
- corner columns: β = 1,50
- corner of wall: β = 1,20
- end of wall: β = 1,35

Alternatively, the more detailed calculation according to EN 1992-1-1, section 6.4.3 (3) may be used to determine the factor β. The applicability of the reduced basic control perimeter according to EN 1992-1-1 [2], section 6.4.3 (4) may be limited by NA.

2.3 Punching shear resistance without shear reinforcement

For footings and ground slabs, the punching shear resistance along the basic perimeter is determined as follows.

The punching shear resistance without shear reinforcement $v_{Rd,c}$ for footings and ground slabs is defined according to the following Equation (2.9) or according to NA to EN1992-1-1 [2]:

$$v_{Rd,c} = C_{Rd,c} \cdot \kappa \cdot \sqrt[3]{100 \cdot \rho_l \cdot f_{ck}} \cdot \frac{2 \cdot d}{a_{crit}} \geq v_{min} \cdot \frac{2 \cdot d}{a_{crit}} \quad (2.9)$$

$C_{Rd,c}$: 0,15 / γ_c

a_{crit}: The distance from the column face to the control perimeter considered

The governing distance a_{crit} (≤ 2 d) leads to the minimum value of $v_{Rd,c}$ and can be determined iteratively.

2.4 Punching shear resistance with shear reinforcement elements

The maximum punching shear resistance in the critical perimeter u_1 is defined by a multiple value of the resistance of the footing without shear reinforcement:

$$V_{Rd,max} = k_{pu,fo} \cdot v_{Rd,c} \cdot u_1 \cdot d \quad (2.10)$$

The value $k_{pu,fo}$ is product dependent and given in the ETA and $v_{Rd,c}$ in Equation (2.10) is the calculated punching shear resistance according to Equation (2.9) and not according to the NA to EN 1992-1-1 [2], taking into account the relevant partial safety factors for material properties.

The amount of shear reinforcement elements in the vicinity of the column or loaded area shall be dimensioned according to the following equations:

$$V_{Rd,cs} = k_s \cdot v_{Rd,c} \cdot u_1 \cdot d + V_{Rd,s} \quad (2.11)$$

with

$$k_s = 0{,}574 + 0{,}326 \cdot \left(\frac{1600 - d\ [mm]}{600}\right) \text{ but} \quad (2.12)$$

$$k_s \geq 0{,}574 \quad \text{and} \quad k_s \leq 0{,}9 \quad (2.13)$$

$V_{Rd,s}$ is the contribution of the shear reinforcement elements to the punching shear resistance and is defined by:

$$V_{Rd,s} = (3{,}2 \cdot n_1 + 1{,}6 \cdot n_2) \cdot \emptyset_{sw}^2 \cdot f_{ywd} \quad (2.14)$$

n_1: Number of shear reinforcement elements in the first row

n_2: Number of shear reinforcement elements in the second row

$ø_{sw}$: Diameter of the shear reinforcement elements

f_{ywd}: Design value of the yielding strength of the shear reinforcement elements

If shear reinforcement is required, a minimum amount shall be placed:

$$A_{sw,min} = \frac{0{,}08}{1{,}5} \cdot \frac{\sqrt{f_{ck}}}{f_{yk}} \cdot u_{0,5d} \cdot d \quad (2.15)$$

$u_{0.5d}$: Perimeter of the critical section at a distance of 0,5·*d* from the column face.

$A_{sw,min}$: Minimum cross-sectional are of shear reinforcement within the first row.

An adequate amount of punching reinforcement elements has to be placed in the slab in order to achieve a sufficient length of the control perimeter. For the calculation of the punching shear resistance outside the shear reinforced zone, it is allowed to subtract the soil pressure inside the outer critical section. The control perimeter u_{out} at which shear reinforcement is not required shall be calculated with the following expression:

$$u_{out} = \frac{\beta_{red} \cdot V_{Ed,red}}{v_{Rd,c} \cdot d} \quad (2.16)$$

u_{out}: Perimeter of the critical section at a distance of *1,5·d* from the outermost row of the punching shear reinforcement (see Annex B.1).

$V_{Ed,red}$: Design value of the applied shear force. It is allowed to subtract the soil pressure inside the outermost row of shear reinforcement.

β_{red}: Reduced factor for taking into account the effects of eccentricity in perimeter u_{out}.

$v_{Rd,c}$: Design punching shear resistance without punching shear reinforcement according to Equation (2.17), with $C_{Rd,c}$ may be taken from the national guidelines for members not requiring design shear reinforcement; the recommended value is 0,15 / γ_c.

$$v_{Rd,c} = C_{Rd,c} \cdot \kappa \cdot \sqrt[3]{100 \cdot \rho_l \cdot f_{ck}} \geq v_{min} \quad (2.17)$$

For the determination of the shear resistance along the outer perimeter (u_{out}) of edge and corner columns, a reduced factor β_{red} for the verification along the outer perimeter may be used.

Edge columns:

$$\beta_{red} = \frac{\beta}{1{,}2 + \frac{\beta}{20} \cdot \frac{l_s}{d}} \geq \beta_{int,col} \quad (2.18)$$

Corner columns:

$$\beta_{red} = \frac{\beta}{1{,}2 + \frac{\beta}{15} \cdot \frac{l_s}{d}} \geq \beta_{int,col} \quad (2.19)$$

Corners of walls, ends of walls, interior columns:

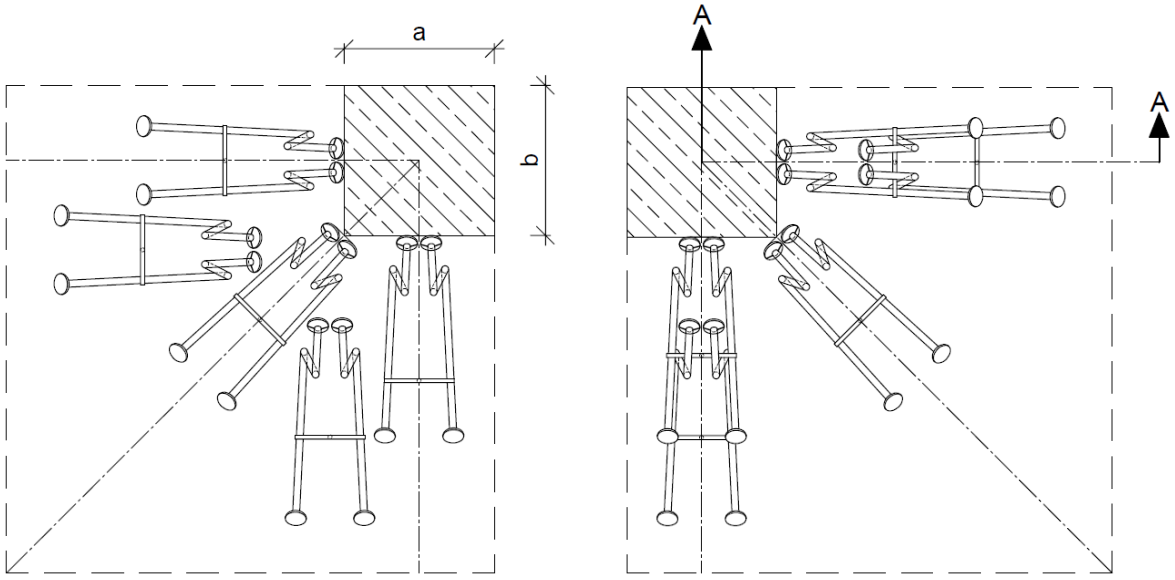
$$\beta_{red} = \frac{\beta}{1{,}2 + \frac{\beta}{40} \cdot \frac{l_s}{d}} \geq \beta_{int,col} \quad (2.20)$$

l_s: Distance between the face of the column and the outermost shear reinforcement element

$\beta_{int,col}$: β value for an interior column according to NA to EN1992-1-1 [2]

3 POSITIONING OF THE REINFORCEMENT ELEMENTS

The reinforcement elements shall be placed according to following Figures.

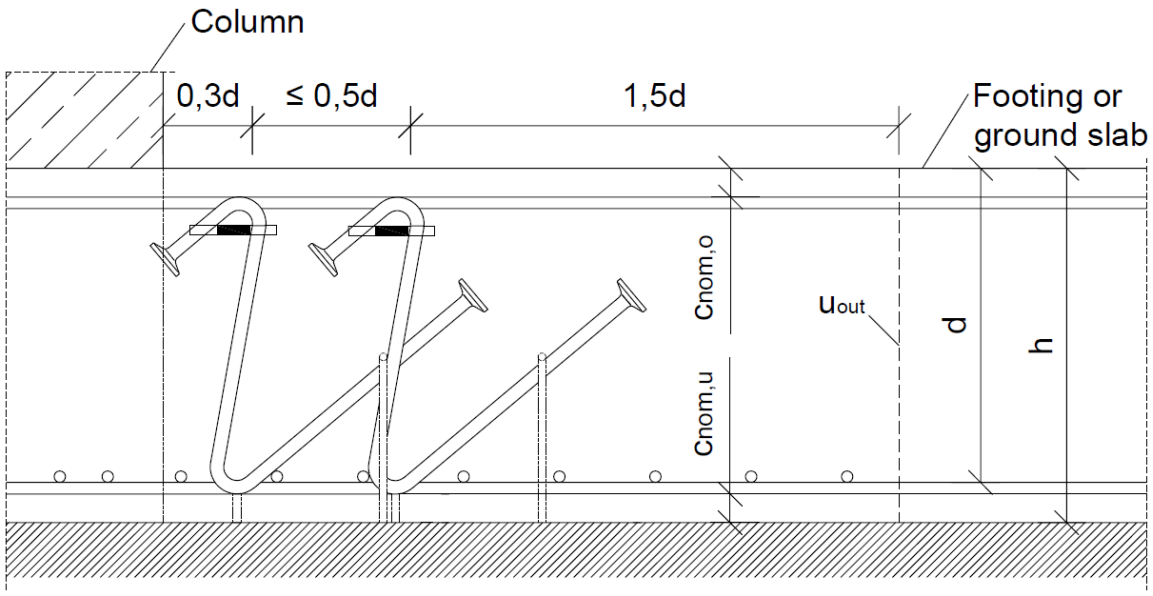


Variant 1:
Staggered arrangement of the second row

Variant 2:
Crossed arrangement of the second row

Legend: a = column width side A, b = column width side B

Figure 3.1 Position of the S-shaped reinforcement elements (Floor plan)



Legend:

$c_{nom,u}$ = concrete cover bottom, $c_{nom,o}$ = concrete cover above, u_{out} = outer control perimeter,

d = effective depth, h = height of foundation

Figure 3.2 Position of the S-shaped reinforcement elements (Section A-A)

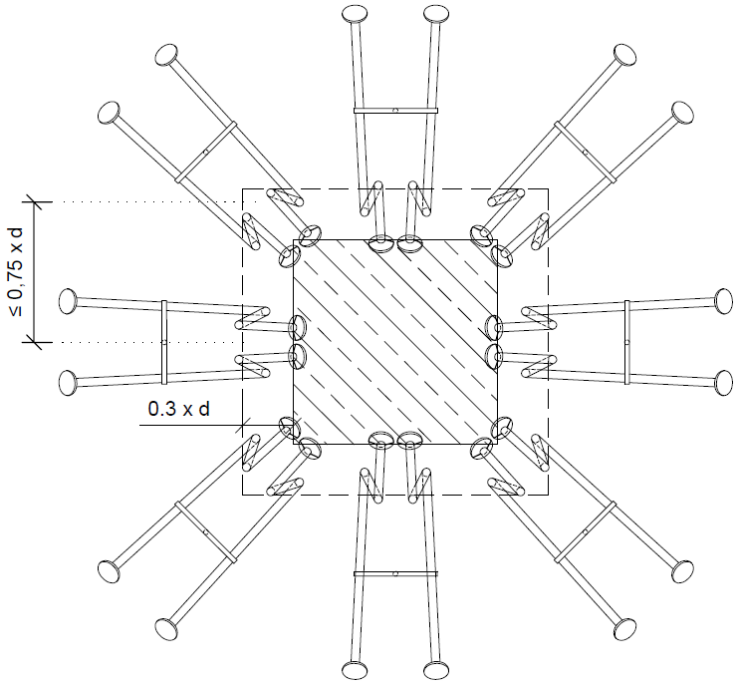


Figure 3.3 Distances of the S-shaped reinforcement elements Row 1 (round columns analogous to the shown variant)

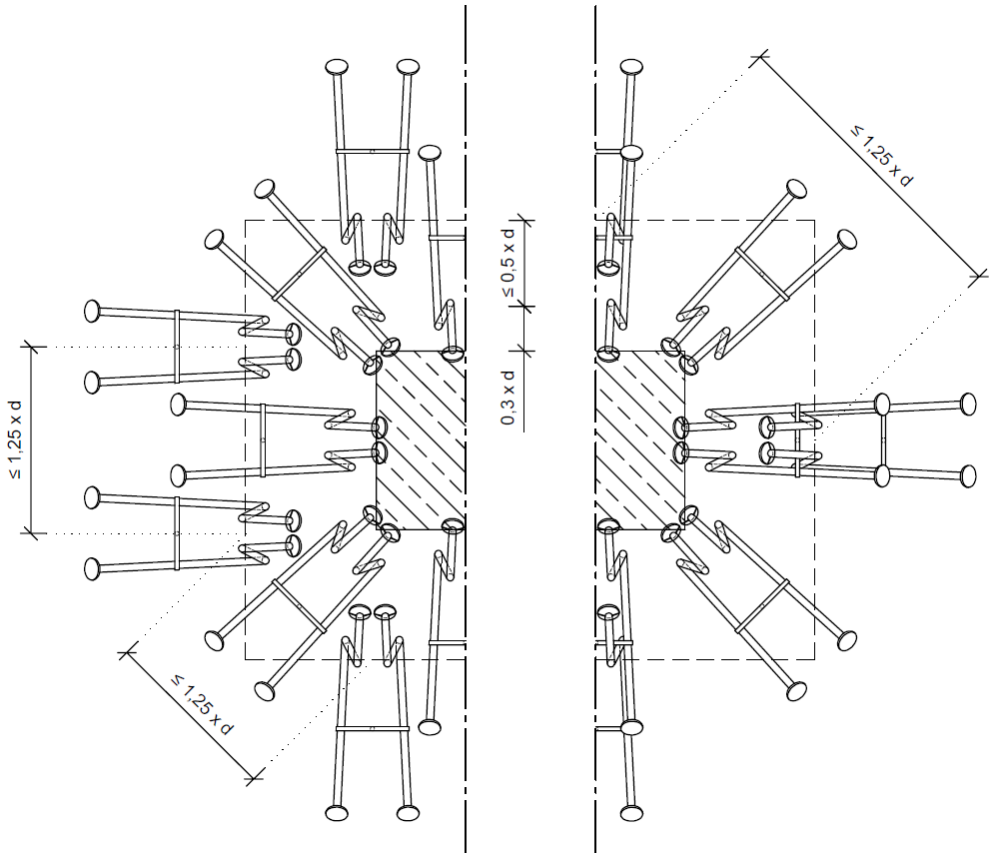
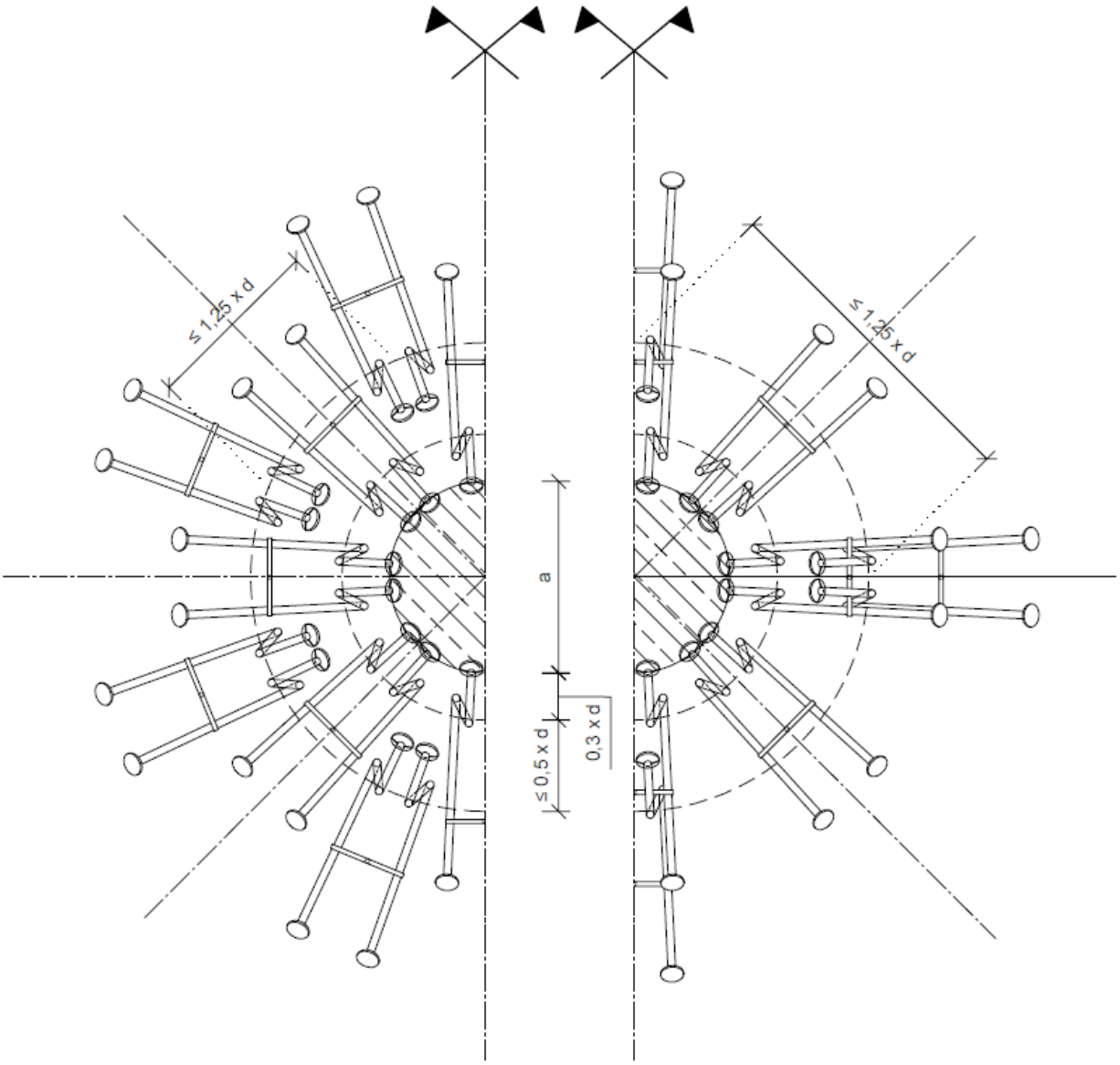
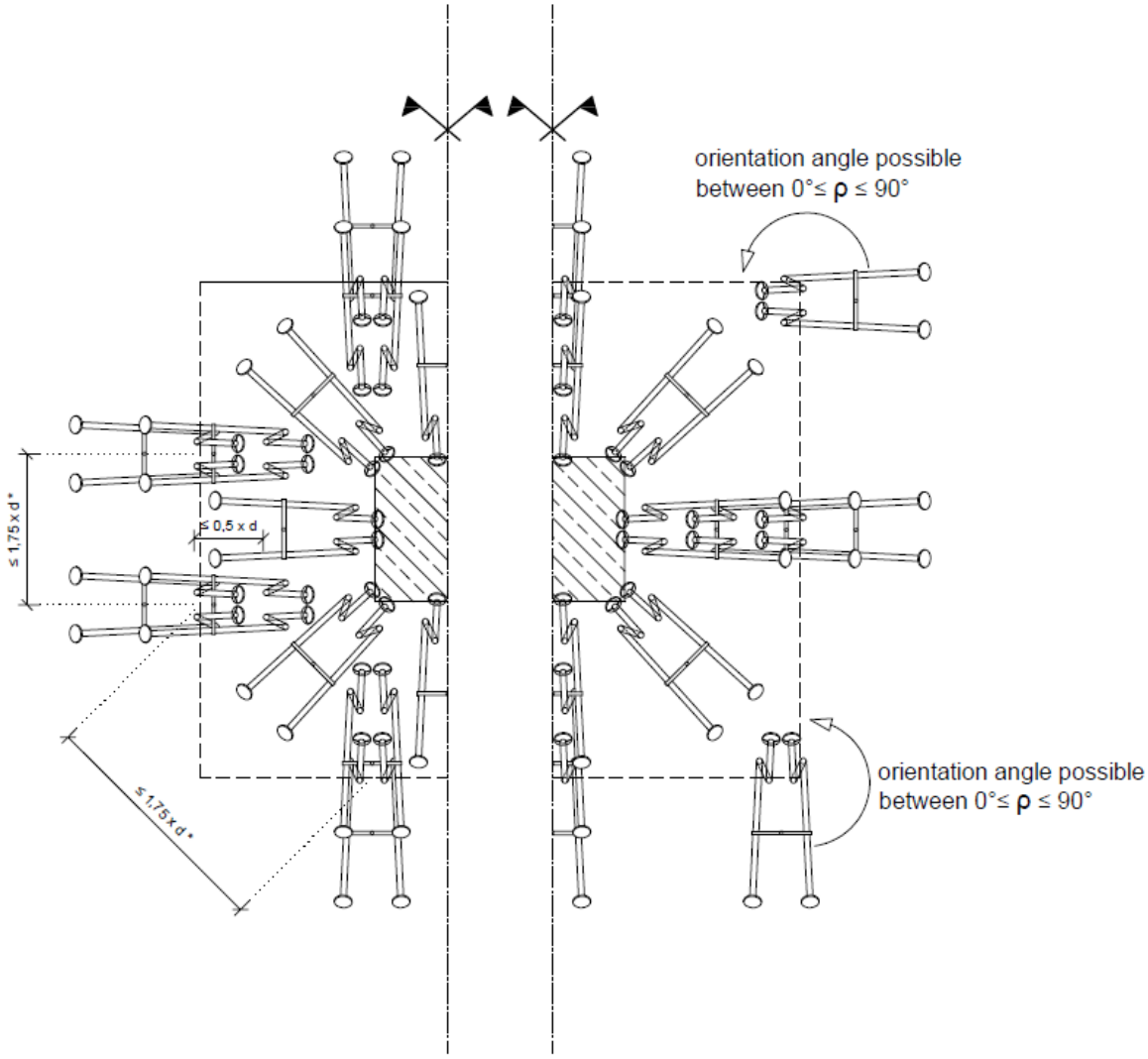


Figure 3.4 Distances of the S-shaped reinforcement elements Row 2



Variant 1: Staggered arrangement Variant 2: Crossed arrangement

Figure 3.5 Distances of the S-shaped reinforcement elements Row 2 for round columns



* starting from row #4, the tangential distances of the elements shall be $s_t \leq 2{,}0\ d$

Variant 1: Staggered arrangement Variant 2: Crossed arrangement

Figure 3.6 Distances of the S-shaped reinforcement elements Row 3 for round columns (Example)

4 REFERENCE DOCUMENTS

[1] EN 206-1:2000	Concrete Part 1: Specification. Performance and conformity
[2] EN 1992-1-1:2011	Design of concrete structures – Part 1-1: General rules and rules for buildings
EAD 160208-00-0301	S-shaped double headed reinforcement elements for increase of punching shear resistance of footings and ground slabs

ANNEX A SPECIFICATION ON THE REINFORCMENT ELEMENTS

This TR covers shear reinforcement elements with an ETA issued on basis of EAD 160208-00-0301 [3]. Figure A.1 shows an example of the shear reinforcement element.

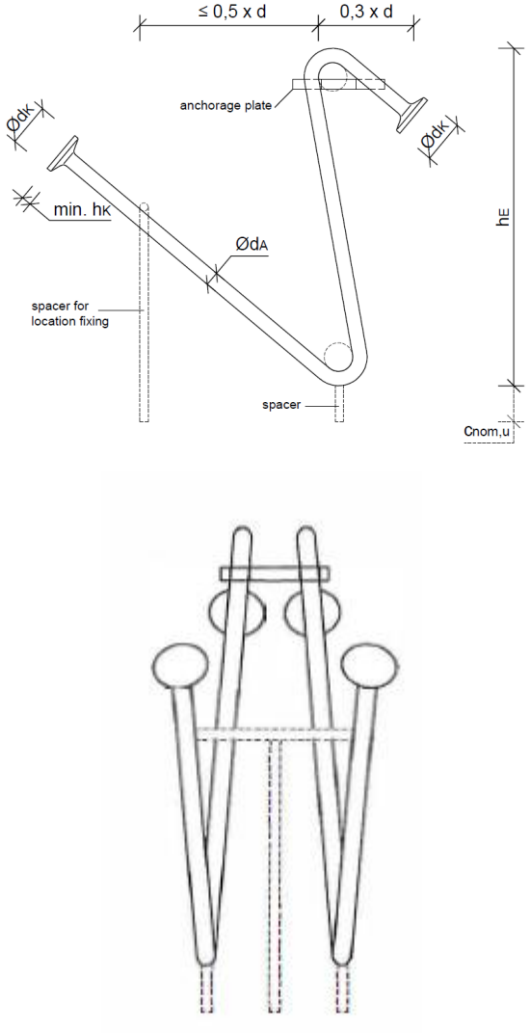
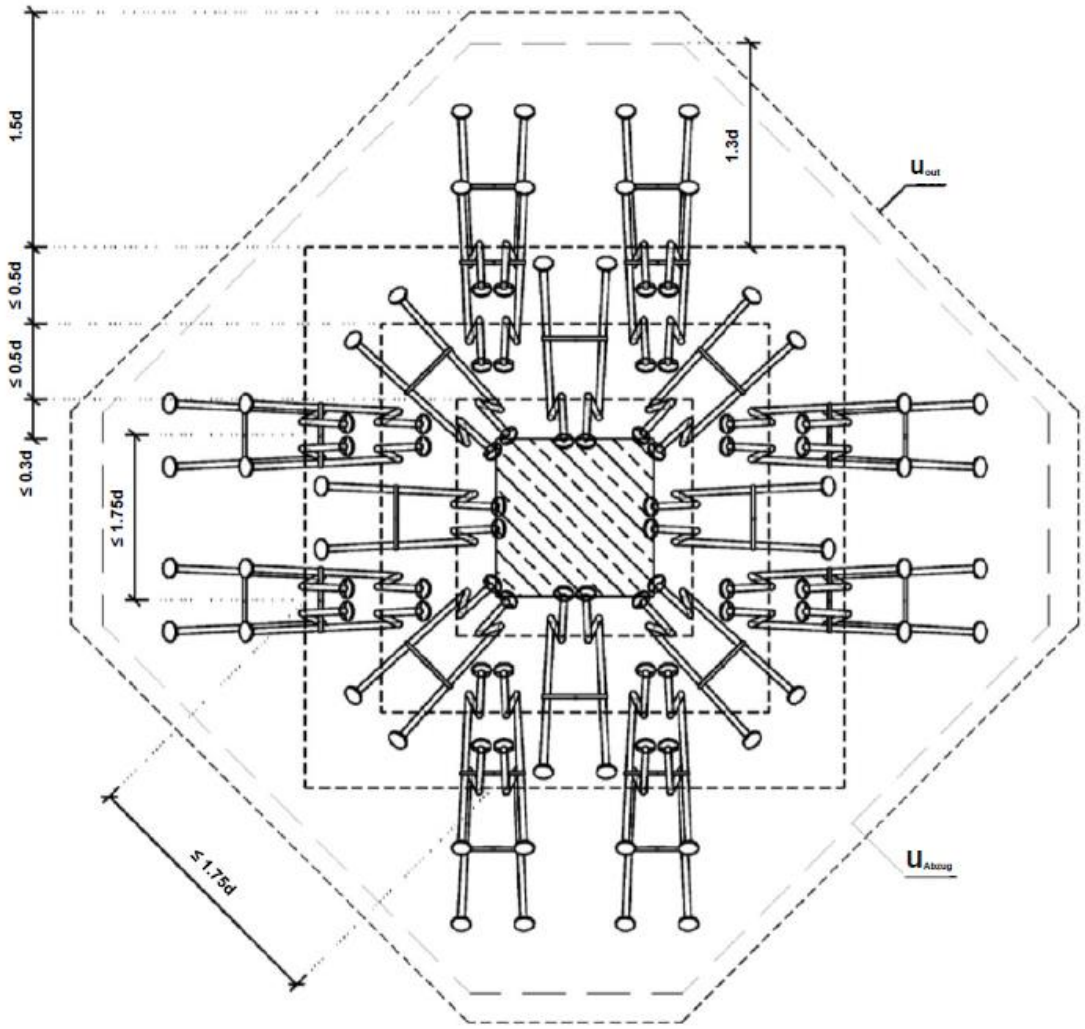


Figure A.1: Examples shear reinforcement elements covered within this TR

ANNEX B SPECIFICATION OF DESIGN PARAMETERS (OUTER CONTROL PERIMETER)



Note:
Arrangement from the third perimeter onwards
First perimeter at ≤ 0.3d
from the second perimeter onward at ≤ 0.5d
u_{out} at 1.5d behind the last upper bend of the element

Figure B.1: Exemplary representation of outer control parameter and area to be subtracted due to soil pressure at the base A_{Abzug}

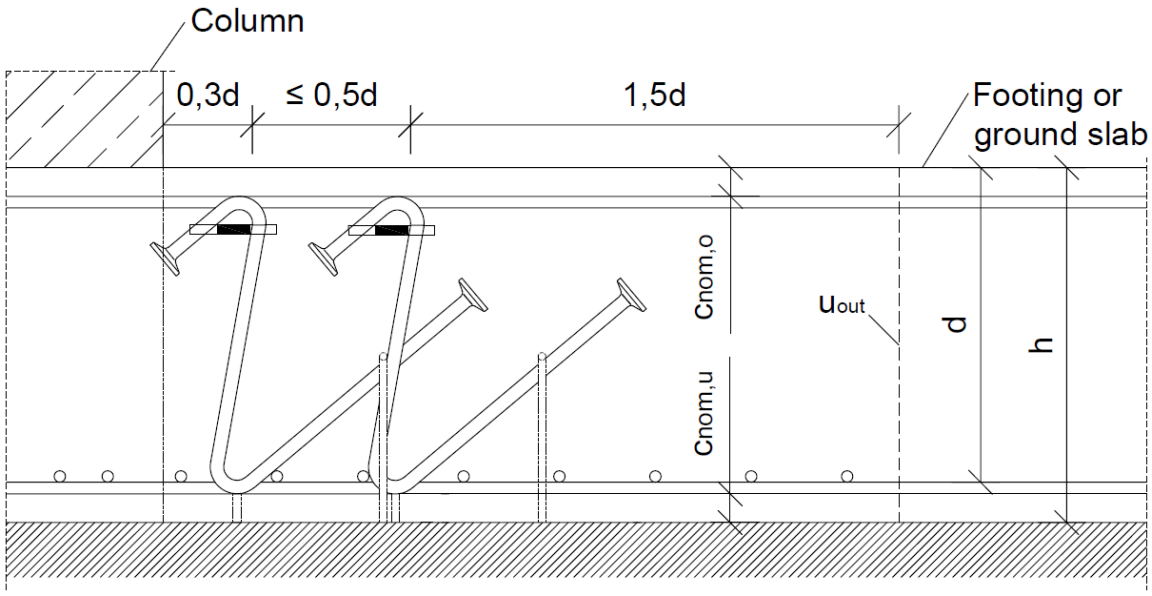


Figure B.2: Exemplary representation of outer control parameter (cross section)