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PART 1 – BASIC ASSUMPTIONS

1.1 GENERAL

In these calculations certain assumptions has been made about dimensions and qualities in the precast concrete elements that may not always be the case. Therefore the following calculations of anchorage of the units and the resulting reinforcement must be considered as an example to illustrate the calculation model.

In beams it must always be checked that the forces from the anchorage reinforcement can be transferred to the beam's main reinforcement. The recommended shear reinforcement (stirrups) includes all necessary stirrups in the beam end; i.e. the normal shear reinforcement in beam ends and an addition due to the cantilever action of the beam unit from the beam.

The information found here and in the memos assumes that the design of the elements and the use of the units in structural elements are carried out under the supervision of a structural engineer with knowledge about the behaviour of concrete structures.

1.2 STANDARDS

The calculations are carried out according to:

Eurocode 2: Design of concrete structures. Part 1-1. General rules and rules for buildings.

Eurocode 3: Design of steel structures. Part 1-1: General rules and rules for buildings.

Eurocode 3: Design of steel structures. Part 1-8: Design of joints.

EN 10080: Steel for the reinforcement of concrete. Weldable reinforcing steel. General.

For all NPDs in the Eurocodes the recommended values are used.

These NDPs are: In EC 2: γ_c ; γ_s ; α_{cc} ; α_{ct} ; k_1 ; k_2 and $\emptyset_{m,min}$. In EC 3: γ_{M0} ; γ_{M1} and γ_{M2} .

1.3 LOADS

Vertical ultimate limit state load = $F_V = 600$ kN

Horizontal ultimate limit state load = $F_H = 0,3 \times F_V = 180$ kN

The design is carried out with a horizontal force of 30 % of the vertical force. Recommended capacity for transfer of active forces (as wind loads) may be assumed to be 20 % of smallest vertical load present at the same time.

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1.4 QUALITIES

Concrete grade C45/55: $f_{cd} = \alpha_{cc} \cdot f_{ck} / \gamma_c = 1,0 \cdot 45 / 1,5 = 30,0 \text{ MPa}$

$$f_{ctd} = \alpha_{ct} \cdot f_{ctk,0,05} / \gamma_c = 1,0 \cdot 2,70 / 1,5 = 1,80 \text{ MPa}$$

$$f_{bd} = 2,25 \cdot \eta_1 \cdot \eta_2 \cdot f_{ctd} = 2,25 \cdot 1,0 \cdot 1,0 \cdot 1,80 = 4,05 \text{ MPa}$$

Reinforcement B500C: $f_{yd} = f_{yk} / \gamma_s = 500 / 1,15 = 435 \text{ MPa}$

Tension in threaded bars: 8.8 quality steel: $f_{yd} = f_y / \gamma_{M2} = 640 / 1,25 = 512 \text{ MPa}$

Structural steel S355:

$$f_{yd} = f_y / \gamma_{M0} = 355 / 1,00 = 355 \text{ MPa} < f_u / \gamma_{M2} = 510 / 1,25 = 408 \text{ MPa}$$

Shear: $f_{sd} = f_y / (\gamma_{M0} \cdot \sqrt{3}) = 355 / (1,00 \cdot \sqrt{3}) = 205 \text{ MPa}$

Welds: $f_{vw,d} = \frac{f_u}{\gamma_{M2} \sqrt{3}} \times \frac{1}{\beta_w} = \frac{510}{1,25 \times \sqrt{3}} \times \frac{1}{0,9} = 262 \text{ MPa}$

Half round steel S275 N/NL:

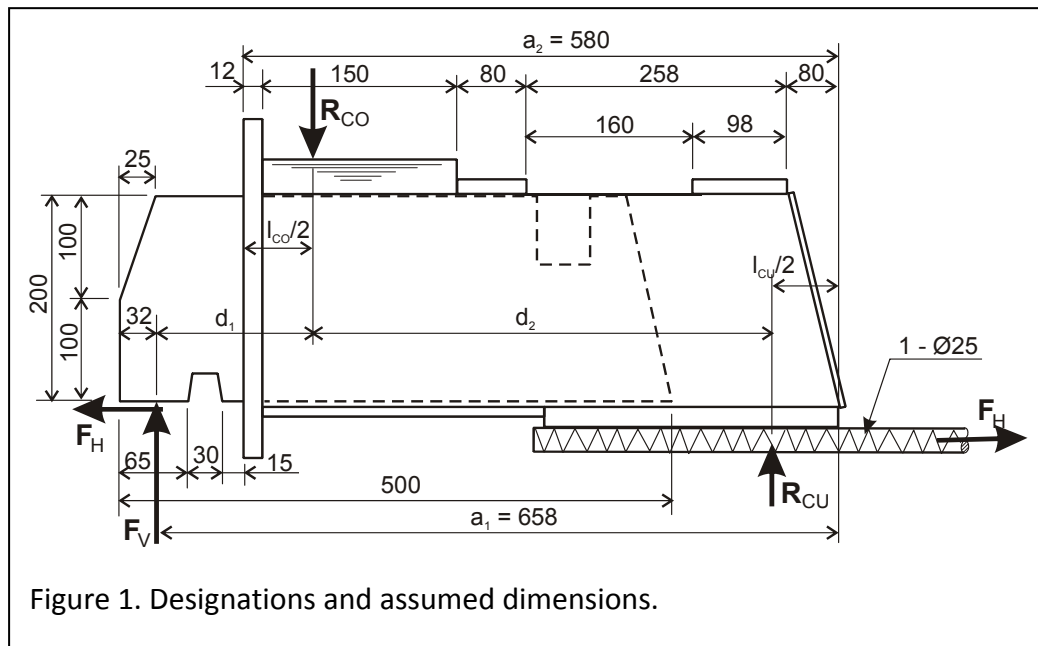
$$f_{yd} = f_y / \gamma_{M0} = 275 / 1,00 = 275 \text{ MPa} < f_u / \gamma_{M2} = 430 / 1,25 = 344 \text{ MPa}$$

Welds: $f_{w,d} = \frac{f_u}{\gamma_{M2} \sqrt{3}} \times \frac{1}{\beta_w} = \frac{430}{1,25 \times \sqrt{3}} \times \frac{1}{0,85} = 233 \text{ MPa}$

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DEL 2 – ANCHORAGE OF THE UNITS

2.1 BEAM UNIT - EQUILIBRIUM



Neglecting the moment created by the small vertical shift in the transfer of F_H .

$$R_{CU} = F_V \times d_1 / d_2$$

$$R_{CO} = F_V + R_{CU}$$

$$l_{CU} = R_{CU} / (f_{cd} \times b) \text{ (b is the width of the beam unit = 80 mm.)}$$

$l_{CO}/2$ is decided by the location of the front reinforcement. Assume 2-Ø20 welded to the front plate plus 3-Ø16 + 1-Ø12 bent over the half round steel:

$$l_{CO}/2 = \frac{314 \times 24 + 201 \times (54 + 86 + 118) + 113 \times 146}{314 + 3 \times 201 + 113} = 74 \text{ mm}$$

$$d_1 = a_1 - a_2 + l_{CO}/2$$

$$d_2 = a_2 - l_{CO}/2 - l_{CU}/2$$

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Use a spread sheet. Assume d_1/d_2 , calculate resulting d_1/d_2 . Change assumed value until they are equal. (Spread sheet "Equilibrium-BSF200-40-beamunit.xls".)

| Equilibrium of BSF beam unit | |
|-----------------------------------|---|
| Concrete grade = C 45/55 | |
| Geometry: | Material coefficient for concrete = 1,5 |
| $a_1 = 658$ mm | $f_{cd} = 30,0$ MPa |
| $a_2 = 580$ mm | |
| Width of beam unit = 80 mm | $F_V = 600$ kN |
| $l_{CO}/2 = 74$ mm | |
| Assumed $d_1 / d_2 = 0,326774$ | |
| $R_{CU} = 196$ kN | $d_1 = 152$ mm |
| $R_{CO} = 796$ kN | $d_2 = 465$ mm |
| $l_{CU} = 82$ mm | |
| Calculated $d_1 / d_2 = 0,326774$ | |

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2.2 BEAM UNIT – ANCHORAGE IN FRONT

2.2.1 Check of capacity

$$A_{s,reqd} = R_{CO}/f_{yd,rein} = 796/0,435 = 1830 \text{ mm}^2$$

$$\text{Assumed } 2\text{-}\varnothing 20 + 3\text{-}\varnothing 16 + 1\text{-}\varnothing 12 =$$

$$= 2 \cdot 314 + 3 \cdot 2 \cdot 201 + 2 \cdot 113 = 2060 \text{ mm}^2 - \text{ok}$$

$$\sigma_s = 796/2,060 = 386 \text{ MPa}$$

2.2.2 Anchorage

As illustrated in figure 2 the reinforcement will be very congested when the beam has minimum dimensions. This must be taken into consideration when calculating the anchorage length (the horizontal part of the front reinforcement). Since the reinforcing bars are so close together this may necessitate considering them as bundled bars. (The main reinforcement in the beam is not shown on the side view.)

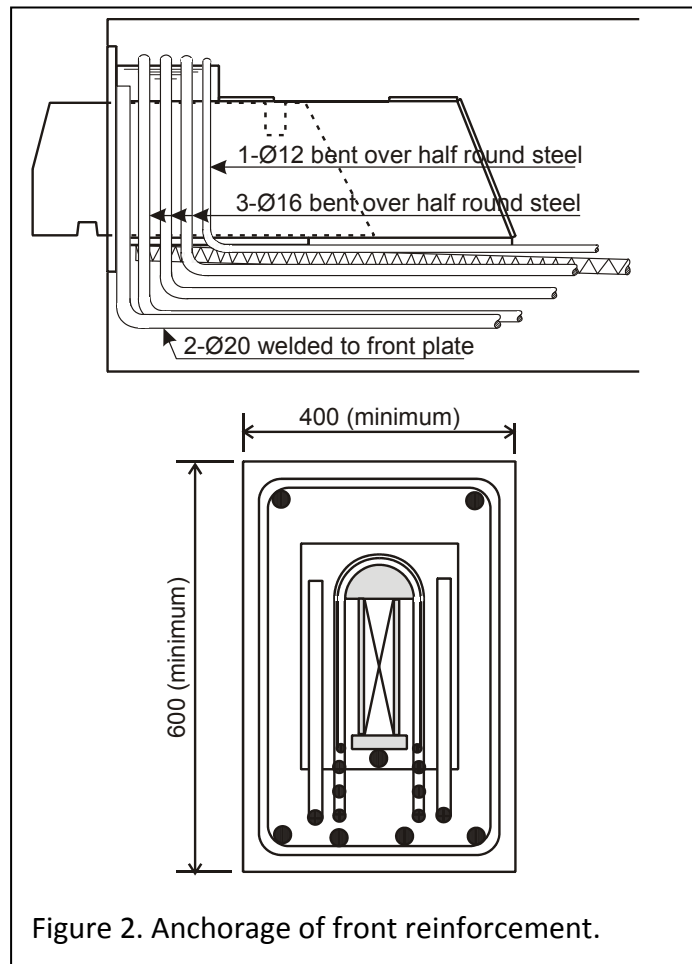


Figure 2. Anchorage of front reinforcement.

According to EC2 clauses 8.4.3 and 8.4.4:

$$l_{bd} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 \cdot \alpha_5 \cdot l_{b,reqd} \geq l_{b,min}$$

$$l_{b,reqd} = \frac{\varnothing}{4} \cdot \frac{\sigma_{sd}}{f_{bd}} = \frac{16}{4} \cdot \frac{386}{4,05} = 381 \text{ mm}$$

$$l_{b,min} = \max(0,3 \cdot l_{b,reqd}; 10 \cdot \varnothing; 100 \text{ mm})$$

$$= 200 \text{ mm}$$

Straight bar:

$$\alpha_1 = 1,0$$

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Concrete cover:

$$c_d = \min(a/2; c_1; c) = \min(20/2; 50; 40) = 10 \text{ mm}$$

$$\alpha_2 = 1 - 0,15 \cdot (c_d - 3 \cdot \emptyset) / \emptyset = 1 - 0,15 \cdot (10 - 3 \cdot 20) / 20 > 1,0$$

$$\alpha_2 = 1,0$$

Confinement by reinforcement: Assume transverse reinforcement $\emptyset 12\text{-c}/c150 \text{ mm}$:

$$\alpha_3 = 1 - K \cdot \lambda = 1 - 0,05 \cdot \frac{113 \cdot \frac{400}{150} - 0,25 \cdot 201}{201} = 0,94$$

Confinement by welded transverse reinforcement:

$$\alpha_4 = 1,0$$

Confinement by transverse pressure:

$$\alpha_5 = 1,0$$

$$l_{bd} = 1,0 \cdot 1,0 \cdot 0,94 \cdot 1,0 \cdot 1,0 \cdot 384 = 361 \text{ mm}$$

It must always be checked that the beam's main reinforcement has sufficient anchorage at the end of the horizontal part of the front anchorage. This will probably lead to greater lengths for the horizontal part of the front anchorage than calculated here.

The force is approximately

$$\left[F_V \times \frac{a}{z} + \frac{F_V}{2} + F_H \frac{x_1}{z} \right]. \text{ Additional}$$

force in the beam's top reinforcement is about $\left[F_H \cdot \frac{x_2}{z} \right]$, but this force leads to a reduction in the compressive stresses and may be neglected. If there is a large distance between the horizontal part of the front anchorage and the beam's main reinforcement, the length of the horizontal part of the front anchorage must be increased with this distance. (This distance is very small in the figure.)

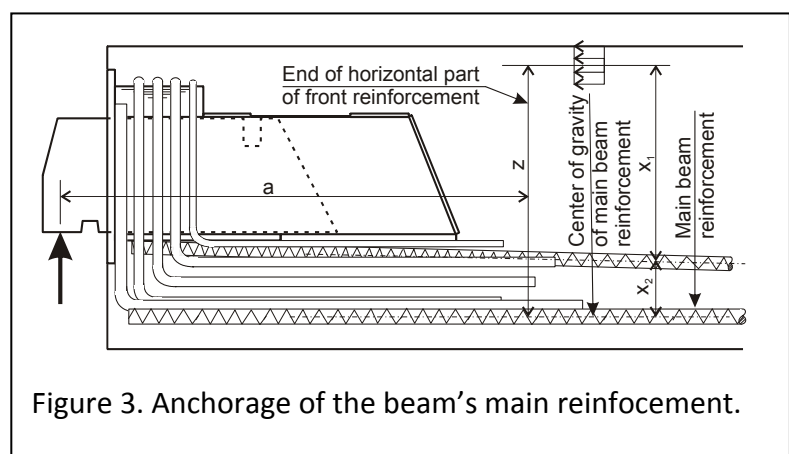


Figure 3. Anchorage of the beam's main reinforcement.

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2.2.3 Bending of front reinforcement and requirements for transverse reinforcement

See figure 4. Stress in the anchorage reinforcement is 386 MPa.

According to EN 1992-1-1, clause 8.3:

$\varnothing_{m,min}$ is generally $7 \cdot 12 = 84$ mm, $7 \cdot 16 = 112$ mm and $7 \cdot 20 = 140$ mm to avoid damage to the reinforcing bars.

To avoid cross bars:

$$\varnothing_{m,min} = \frac{F_{bt} \cdot \left(\frac{1}{a_b} + \frac{1}{2 \cdot \varnothing} \right)}{f_{cd}}$$

Ø 12 bars:

$$\varnothing_{m,min} = \frac{796 \cdot 10^3}{30} \cdot \left(\frac{1}{95} + \frac{1}{2 \cdot 12} \right) = 1384 \text{ mm } \varnothing 16$$

$$\text{bars: } \varnothing_{m,min} = \frac{796 \cdot 10^3}{30} \cdot \left(\frac{1}{100} + \frac{1}{2 \cdot 16} \right) = 1094 \text{ mm}$$

Ø20 bars:

$$\varnothing_{m,min} = \frac{796 \cdot 10^3}{30} \cdot \left(\frac{1}{200} + \frac{1}{2 \cdot 20} \right) = 796 \text{ mm}$$

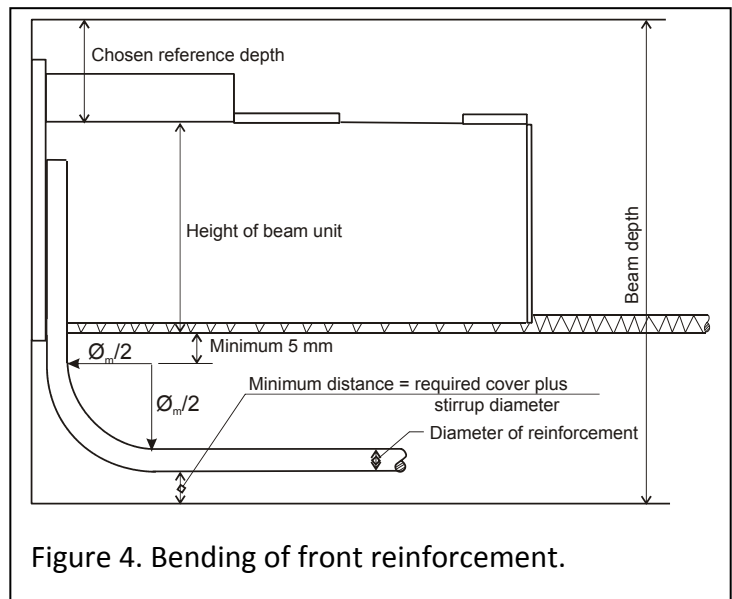


Figure 4. Bending of front reinforcement.

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If cross bars are required the total area of this reinforcement shall be at least 40% of the area of the bent bars. (This last requirement is from the Norwegian concrete design code, as EC2 does not contain any particular requirements for such reinforcement.) It is the opinion of this structural engineer that it may be reduced according to the stress in the anchorage reinforcement. The cross bars shall consist of at least two bars placed inside the bend. The cross bars can be anchored with 90° hook at the ends or by being shaped like a U-bar.

| Bar diameter | Mandrel diameter | Transverse reinforcement |
|--------------|-------------------|--------------------------|
| 12 | ≥1384 mm | Not required |
| | <1384 mm; ≥84 mm | Required |
| 16 | ≥1094 mm | Not required |
| | <1094 mm; ≥112 mm | Required |
| 20 | ≥796 mm | Not required |
| | <796 mm; ≥140mm | Required |

Assumed concrete grade is C45/55. For other concrete grades and bar diameters the mandrel diameters will be different.

2.2.4 Minimum beam depth

See figure 4 and Memo 10.

The recommended reference depth is 80 mm and the height of the beam unit is 225 mm. Assume Ø12 stirrups that will require 15 mm space, and assume 25 mm concrete cover. Also assume that a 16 mm bar requires 20 mm space.

To avoid cross bars the minimum beam depth will be $80+225+5+(1384/2)+15+15+25 = 1057 \text{ mm} \approx 1100 \text{ mm}$.

Accepting cross bars the minimum beam depth will be $80+225+5+(140/2)+20+15+25 = 440 \text{ mm} \approx 450 \text{ mm}$.

However, with the horizontal part of the front anchorage so close to the bottom of the beam unit, the unit and the bars may be torn out as one piece. Therefore a minimum beam depth of 600 mm is recommended.

If cross bars are required: $0,4 \cdot 2060 \cdot 389 / 435 = 737 \text{ mm}^2$

If U-shaped bars are used they will be properly anchored in one end only. Hence the total reinforcement area must be twice of the calculated area. Each bar has two legs:

Select two Ø12 U-shaped stirrups inserted from each side:

$4 \cdot 2 \cdot 112 \cdot 2 = 1792 \text{ mm}^2 > 737 \cdot 2 = 1474 \text{ mm}^2$.

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2.3 BEAM UNIT – ANCHORAGE OF HORIZONTAL FORCES

2.3.1 Check of capacity

$F_H = 180 \text{ kN}$ (see clause 1.3)

$$A_{s, \text{reqd}} = 180/0,435 = 414 \text{ mm}^2$$

1-Ø25 is assumed (491 mm²) – ok

2.3.2 Anchorage length

According to EC2 clause 8.4.4:

$$l_{bd} = \alpha_1 \cdot \alpha_2 \cdot \alpha_3 \cdot \alpha_4 \cdot \alpha_5 \cdot l_{b, \text{reqd}} \geq l_{b, \text{min}}$$

$$l_{b, \text{reqd}} = \frac{\sigma_{sd}}{4 \cdot f_{bd}} = \frac{25}{4} \cdot \frac{180/0,491}{4,05} = 566 \text{ mm}$$

$$l_{b, \text{min}} = \max(0,3 \cdot l_{b, \text{reqd}}; 10 \cdot \emptyset; 100 \text{ mm}) = 250 \text{ mm}$$

Straight bar:

$$\alpha_1 = 1,0$$

Concrete cover:

$$c_d = \min(a/2; c_1; c) = \min(62/2; 50; 40) = 31 \text{ mm}$$

$$\alpha_2 = 1 - 0,15 \cdot (c_d - 3 \cdot \emptyset) / \emptyset = 1 - 0,15 \cdot (31 - 3 \cdot 25) / 25 > 1,0$$

$$\alpha_2 = 1,0$$

Confinement by reinforcement: Assume transverse reinforcement Ø12-c/c150 mm

$$\alpha_3 = 1 - K \cdot \lambda = 1 - 0,05 \cdot \frac{113 \cdot \frac{400}{150} - 0,25 \cdot 491}{491} = 0,98$$

Confinement by welded transverse reinforcement:

$$\alpha_4 = 1,0$$

Confinement by transverse pressure:

$$\alpha_5 = 1,0$$

$$l_{bd} = 1,0 \cdot 1,0 \cdot 0,98 \cdot 1,0 \cdot 1,0 \cdot 566 = 555 \text{ mm}$$

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2.4 COLUMN UNIT – ANCHORAGE IN THE COLUMN

2.4.1 Check of capacity

$$M = F_H \times (20 + 20/2) + F_V \times \{[(135 + 12)/2] - 48\} = 600 \times (0,3 \times 30 + 25) = 20400 \text{ kNmm}$$

$$S = 20400 / 293 = 69,6 \text{ kN}$$

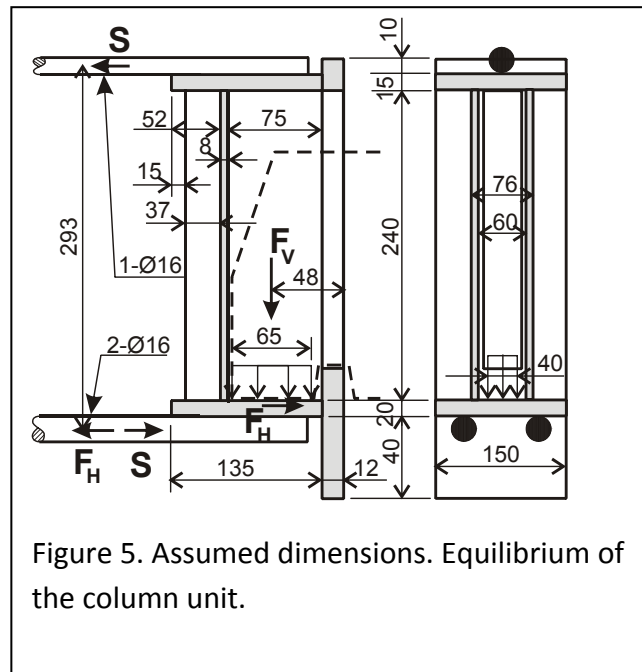
$$A_s = 69,6 / 0,435 = 160 \text{ mm}^2$$

1-Ø16 = 201 mm² at the top - ok.

$$F_H - S = 0,3 \times 600 - 70 = 110 \text{ kN}$$

$$A_s = 110 / 0,435 = 253 \text{ mm}^2$$

2-Ø16 at the bottom are sufficient.



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2.4.2 Anchorage of welded reinforcement

Normally there are similar units on opposite sides of the column. The easiest anchorage is then to connect the units as shown in Memo 43.

If anchorage bars bent up and down are used, the amount of reinforcement must be as calculated in clause 2.4.1.

If a U-shaped bar is used the area of the reinforcing bar may be half of that calculated in clause 2.4.1, because two sections are providing the anchorage. It will improve the anchorage considerably if a bar is placed in the bend of the U-shaped bars.

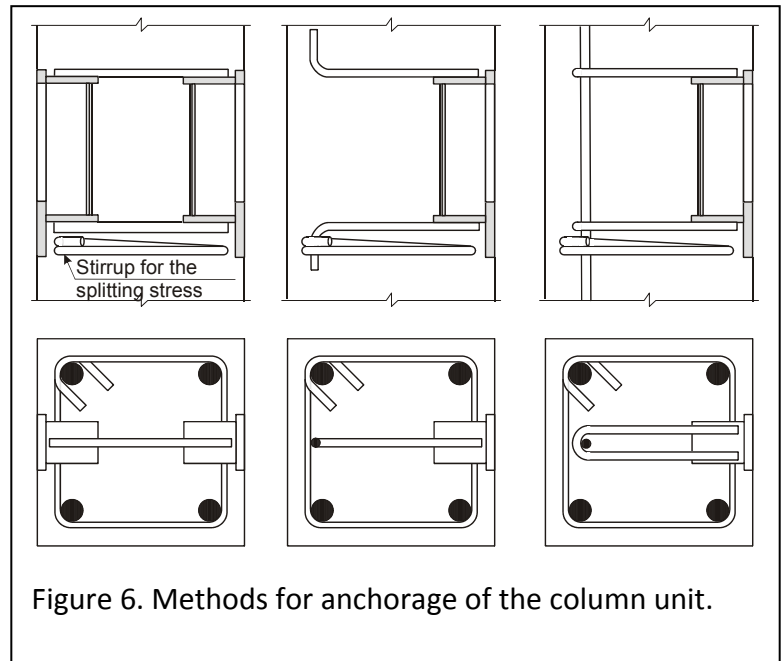


Figure 6. Methods for anchorage of the column unit.

Necessary welding of reinforcing bars is shown in clause 2.5.

The stirrup for the splitting stress is calculated in clause 3.4.

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2.5 WELDING OF REINFORCEMENT TO THE UNITS

Selecting to always weld for the capacity of the bar.

Assuming welds on both sides of the bar. Length of weld = l_w .

For reinforcing bar Ø16:

$$l_w \cdot a = (201 \cdot 0,435) / (0,262 \cdot 2) = 167 \text{ mm}^2$$

Select $a = 4 \text{ mm}$; i.e. $l_{w,\min} = 42 \text{ mm}$

For reinforcing bar Ø20:

$$l_w \cdot a = (314 \cdot 0,435) / (0,262 \cdot 2) = 261 \text{ mm}^2$$

Select $a = 5 \text{ mm}$; i.e. $l_{w,\min} = 52 \text{ mm}$

For reinforcing bar Ø25:

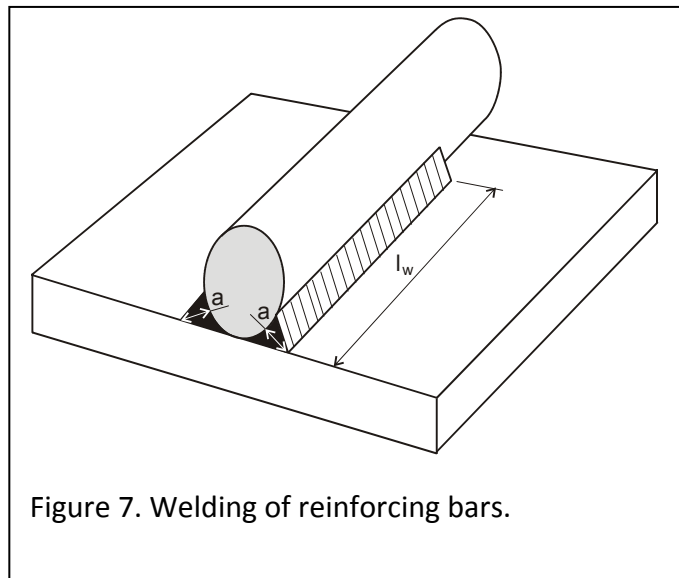
$$l_w \cdot a = (491 \cdot 0,435) / (0,262 \cdot 2) = 408 \text{ mm}^2$$

Select $a = 5 \text{ mm}$; i.e. $l_{w,\min} = 82 \text{ mm}$

For reinforcing bar Ø32:

$$l_w \cdot a = (804 \cdot 0,435) / (0,262 \cdot 2) = 667 \text{ mm}^2$$

Select $a = 6 \text{ mm}$; i.e. $l_{w,\min} = 111 \text{ mm}$



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PART 3 – REINFORCEMENT

3.1 BEAM – REINFORCEMENT IN THE REAR

$$A_{s, reqd} = R_{CU}/f_{sd} = 201/0,435 = 462 \text{ mm}^2,$$

corresponding to $462/(3 \times 2 \times 113) = 0,68$; i.e. 3 – Ø12 stirrups.

3.2 BEAM – SHEAR STIRRUPS

Use a strut-and-tie model with compressive diagonals at 45°.

The shear force within the central part of the beam unit is assumed to be $R_{CO} = 796 \text{ kN}$.

Assume $z = 520 \text{ mm}$ and stirrup diameter Ø12.

$$s = A_{sw} \cdot z \cdot f_{yd} \cdot \cot \theta / V$$

$$s = 2 \times 113 \times 520 \times 435 \times \cot 45^\circ / 796 \times 10^3 = 64 \text{ mm}$$

Select Ø12 c/c 60 mm.

This reinforcement should be brought approximately 200 mm past the end of the beam unit in order to absorb any splitting effects from the anchorage of reinforcement in the rear.

3.3 BEAM – CHECK OF SHEAR COMPRESSION

Assume beam width of 400 mm and beam depth of 600 mm. (See also clause 2.2.) This means that $z_{min} \approx 600 - 50 - 100 = 450 \text{ mm}$ with one layer of reinforcement in the top of the beam and three layers in the bottom.

The shear reinforcement is calculated based on 45° compressive field. The check of shear compression will be carried out under the same assumption:

$$V_{Rd,max} = \alpha_{cw} \cdot b_w \cdot z \cdot v_1 \cdot f_{cd} / (\cot \theta + \tan \theta)$$

$$V_{Rd,max} = \{1,0 \cdot (400 - 100) \cdot 450 \cdot 0,6 \cdot [1 - (45/250)] \cdot 30,0 / (\cot 45^\circ + \tan 45^\circ)\} \cdot 10^{-3}$$

$$V_{Rd,max} = 996 \text{ MPa} > 796 \text{ MPa} - \text{OK}$$

3.4 COLUMN – SPLITTING STRESS

Splitting stress under the column unit according to Leonhardt $\approx 0,2 \times F_V = 0,2 \times 600 = 120 \text{ kN}$

$$A_S = 120/0,435 = 275 \text{ mm}^2$$

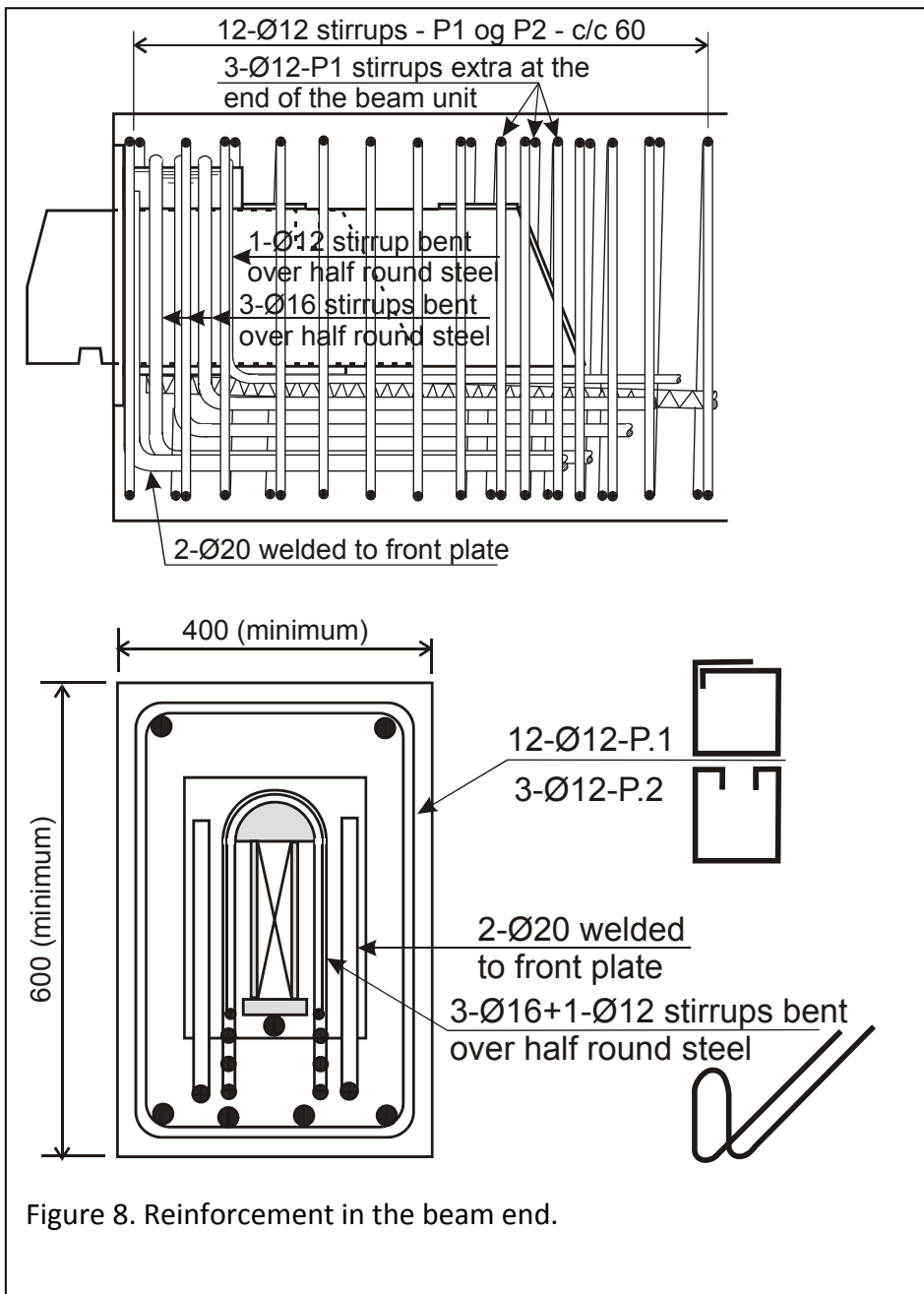
2-Ø10 stirrups ($2 \times 2 \times 78,5 \text{ mm}^2$) are sufficient.

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3.5 CONCLUSION – REINFORCEMENT IN THE BEAM

For clarity the beam's main reinforcement is not shown in the side view. Between the shown stirrups in each end of the beam a normal calculation of the shear reinforcement must be carried out. The main reinforcement in the beam must of course also be calculated.



At the end of the front anchorage it must be checked that the beam's main reinforcement has sufficient anchorage. See clause 2.2.4.

Figure 8. Reinforcement in the beam end.