Shear

IN ACCORDANCE WITH

European Standards CEN/TC 250
Structural Eurocodes (EN 1992-1-1)

UK National Annex

EUROCODES
SPREADSHEETS
Structural Design

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First Edition
• Ebook •

First Edition: April 2014

Author/Publisher: Sigmund, Carlo <1971->

ISBN n.:

ID contenuto:

Ebook: Shear EC2

The sponsoring editor for this document and the production supervisor was Carlo Sigmund.

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Beijing national stadium; Architect: Herzog & de Meuron, ArupSport, China Architectural Design & Research Group

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Contents

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Section 1 Shear_EC2_UKNA

1.1 General: ShearReinforcementBeamSlab.xls

This sheet allows for the design of a section of solid slab or a rectangular beam section. The spreadsheet checks beams or slabs for shear and calculates any shear reinforcement required in accordance with EN 1992-1-1:2004 Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings and BS NA EN 1992-1-1 (2004) (English): UK National Annex to Eurocode 2. Design of concrete structures. General rules and rules for buildings.

The user is required to input desired characteristic strength of the materials, amount of concrete cover to shear reinforcement (c_{nom} - EN 1992-1-1 Exp. 4.1) and the longitudinal reinforcement (A_{sl}) which extends $\geq$ $(l_{bd} + d)$ beyond the section considered. All applied load and stress should be ultimate and positive.

With regard the concrete, the minimum strength used is C12/15 (Table 3.1). The spreadsheet allows input for grades of concrete up to C50/60. Input is self explanatory but, in order to facilitate use of this spreadsheet, some degree of automation has been introduced.

The design of members with shear reinforcement is based on the truss model given in Figure 6.5 (EN 1992-1-1). The angle θ between the concrete compression strut and the beam axis perpendicular to the shear force is chosen within the range 1,00÷2,50 (Cl. 6.2.3(2) Exp. (6.7N)).

Applied shear force (V_{Ed}) is compared with three values for the resistance (V_{Rd}). $V_{Rd,C}$ represents the shear capacity of concrete alone; $V_{Rd,max}$ is the shear resistance determined by the capacity of the notional concrete struts; and $V_{Rd,s}$ is the capacity of a section with shear reinforcement.

Where more than one vertical links are required per section, the user may choose to use inner links alternative or bent-up bars in order to increase section strength. The spreadsheet takes automatic measures to ensure maximum spacing (longitudinal and transversal) of shear reinforcement is met (Cl. 9.2.2 for Beams and Cl. 9.3.2 for Solid slabs).

Combo-boxes to the right under “DETAILING” Excel® Form define minimum bar sizes to be used. Combo-box to the right under “PreCalculus” Excel® Form define concrete characteristic compressive strength at 28 days.

No check is performed in order to control cracking of the concrete in shear. Therefore the maximum shear force allowed is checked (Exp. 6.5, Cl. 6.2.2(6)).

The value of shear force, V_{Ed}, used can, provided there is diagonal compression and continuity of tension reinforcement (A_{sl}) for at least l_{bd} (design anchorage length), be evaluated at "d" from the face of support (see Figure 6.3).

This method presented in EC2 is known as "*The Variable Strut Inclination Method*". The use of this method allows the designer to seek out economies in the amount of shear reinforcement provided, but recognising that any economy achieved may be at the expense of having to provide additional curtailment and anchorage length to the tension steel over and above the normally required for resistance to bending. Calculations with axial forces in the cross-section due to loading or prestressing are not carried out in this spreadsheet: $N_{Ed} = 0$ with $\sigma_{cp} = 0$.

1.2 Layout

The basic layout for **Shear_EC2** sheet is shown on the following screen dump:

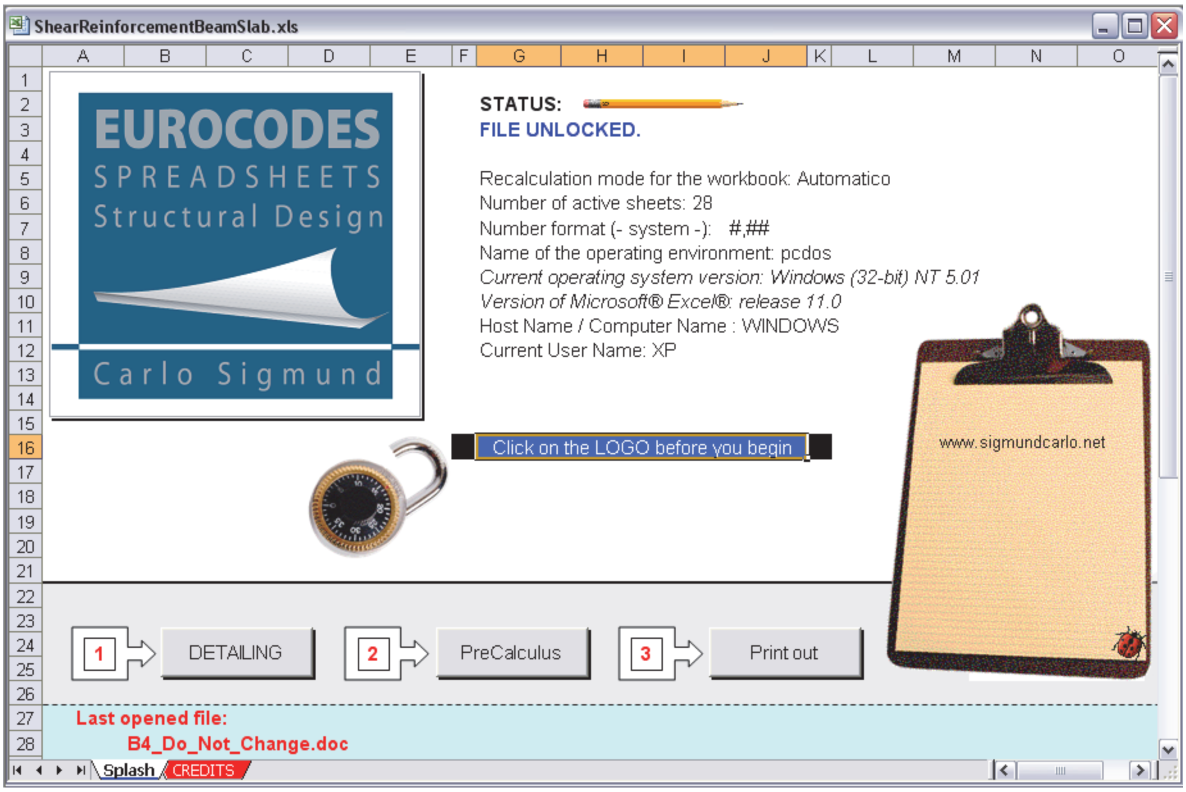


Figure 1.1 Sheet "Splash" from Excel® 2003.

DETAILING Form:

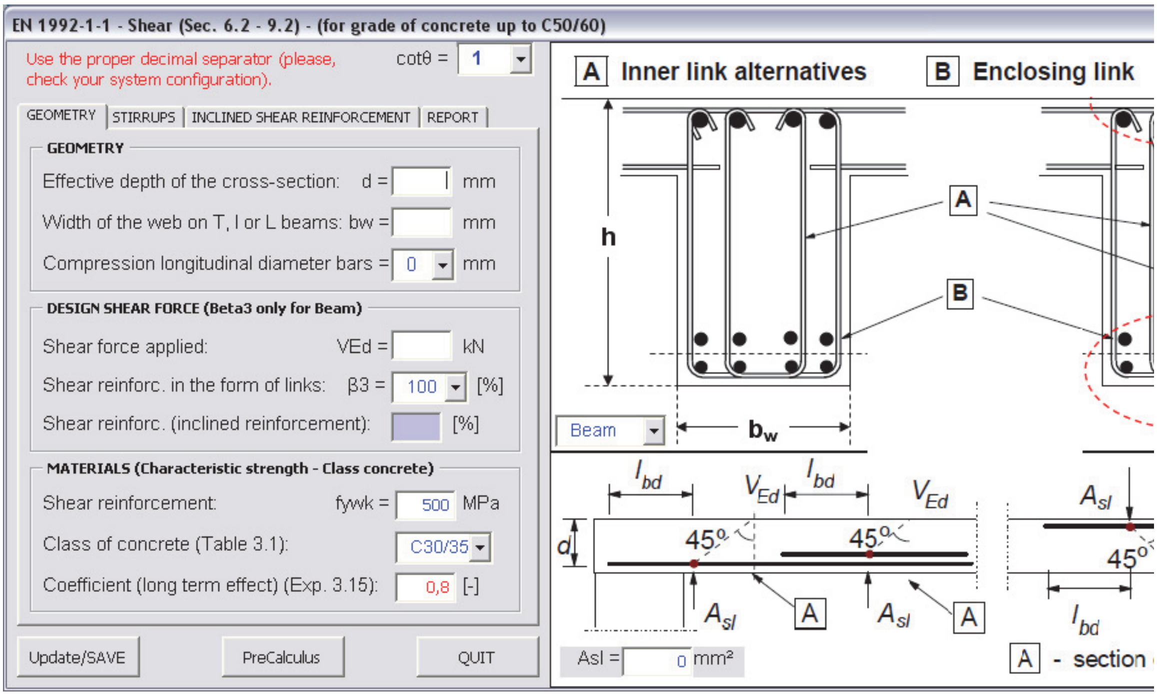


Figure 1.2 Input (white blank test boxes) and calculus (blue text boxes). Default value for α_{cc} = 0,8 (red).

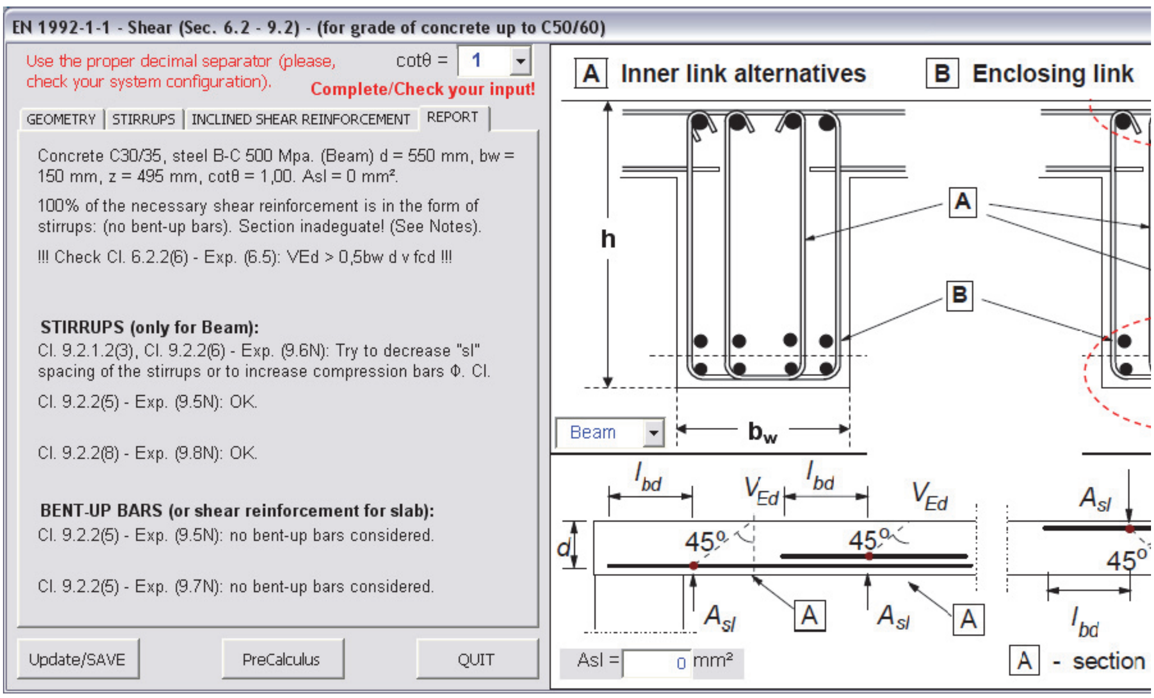


Figure 1.3 Report.

PreCalculus Form:

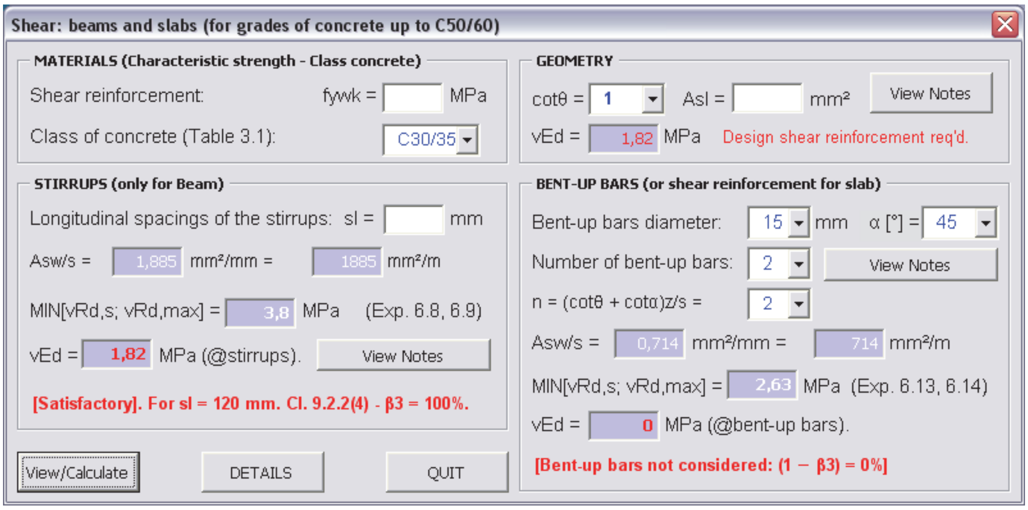
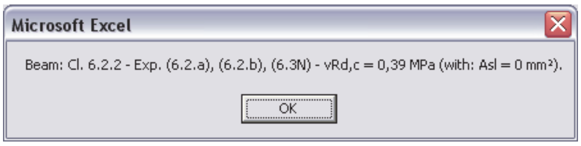
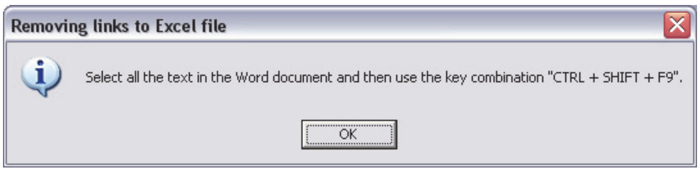


Figure 1.4 Coloured in blue results in output. White text boxes only to change the design values.

View Notes...

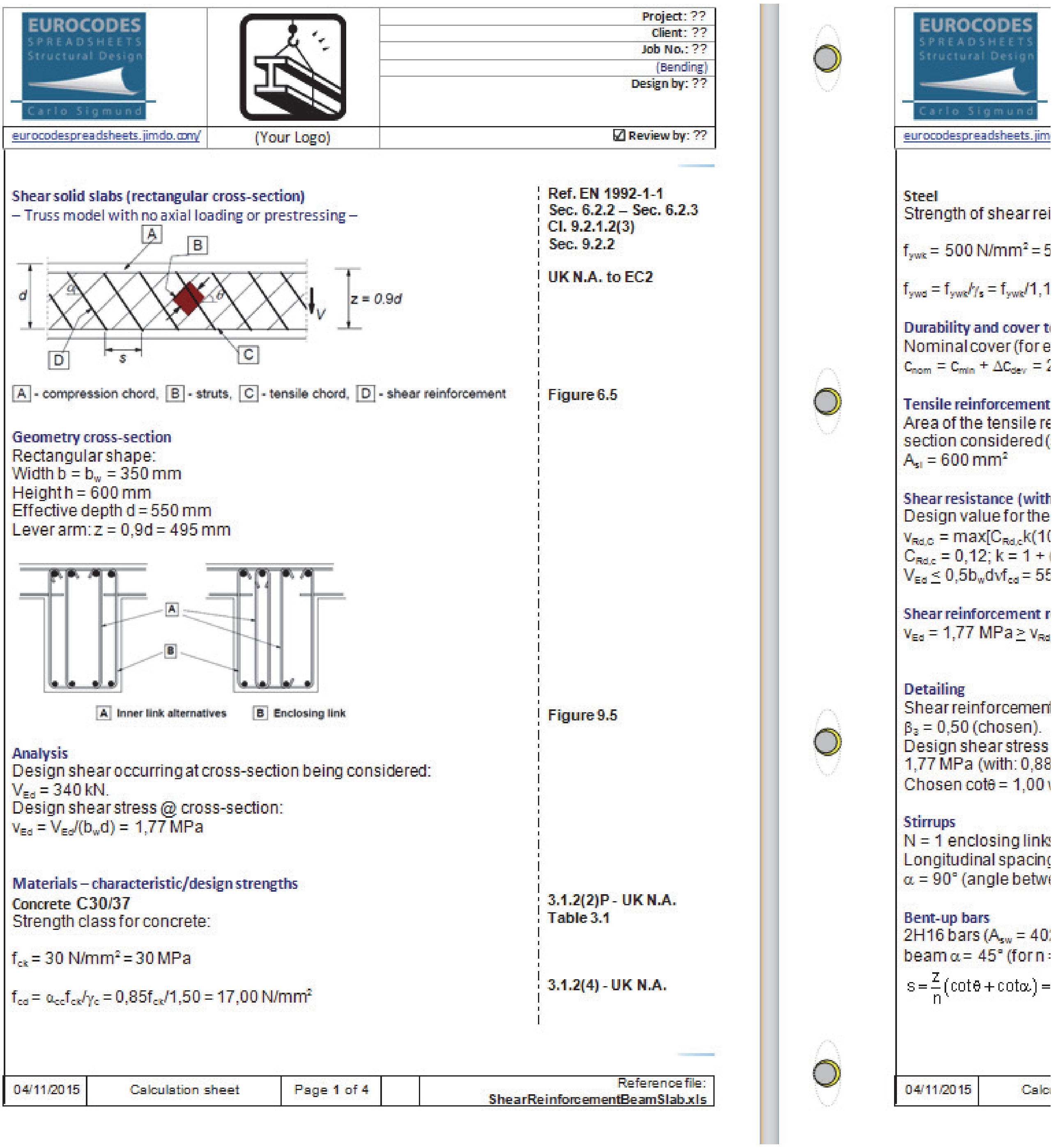


How to remove links to Excel file "ShearReinforcementBeamSlab.xls":



1.3 Output - Word document (calculation sheet)

Example calculation sheet (output):


EUROCODES SPREADSHEETS Structural Design Carlo Sigmund
eurocodespreadsheets.jimdo.com/
(Your Logo)
Project: ??
Client: ??
Job No.: ??
(Bending)
Design by: ??
Review by: ??

Shear solid slabs (rectangular cross-section)
– Truss model with no axial loading or prestressing –

Ref. EN 1992-1-1
Sec. 6.2.2 – Sec. 6.2.3
Cl. 9.2.1.2(3)
Sec. 9.2.2

UK N.A. to EC2

A - compression chord, B - struts, C - tensile chord, D - shear reinforcement

Figure 6.5

Geometry cross-section
Rectangular shape:
Width $b = b_w = 350$ mm
Height $h = 600$ mm
Effective depth $d = 550$ mm
Lever arm: $z = 0{,}9d = 495$ mm

A Inner link alternatives   B Enclosing link

Figure 9.5

Analysis
Design shear occurring at cross-section being considered:
$V_{Ed} = 340$ kN.
Design shear stress @ cross-section:
$v_{Ed} = V_{Ed}/(b_w d) = 1{,}77$ MPa

Materials – characteristic/design strengths
Concrete C30/37
Strength class for concrete:

3.1.2(2)P - UK N.A.
Table 3.1

$f_{ck} = 30\ N/mm^2 = 30$ MPa

$f_{cd} = \alpha_{cc} f_{ck}/\gamma_c = 0{,}85 f_{ck}/1{,}50 = 17{,}00\ N/mm^2$

3.1.2(4) - UK N.A.

04/11/2015	Calculation sheet	Page 1 of 4		Reference file: ShearReinforcementBeamSlab.xls

EUROCODES SPREADSHEETS Structural Design Carlo Sigmund
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Steel
Strength of shear rei
$f_{ywk} = 500\ N/mm^2 = 5$
$f_{ywd} = f_{ywk}/\gamma_s = f_{ywk}/1{,}1$

Durability and cover t
Nominal cover (for e
$c_{nom} = c_{min} + \Delta c_{dev} = 2$

Tensile reinforcement
Area of the tensile re
section considered (
$A_{sl} = 600\ mm^2$

Shear resistance (with
Design value for the
$v_{Rd,c} = \max[C_{Rd,c}k(1($
$C_{Rd,c} = 0{,}12;\ k = 1 + ($
$v_{Ed} \leq 0{,}5 b_w d v f_{cd} = 55$

Shear reinforcement r
$v_{Ed} = 1{,}77\ MPa \geq v_{Rd}$

Detailing
Shear reinforcemen
$\beta_3 = 0{,}50$ (chosen).
Design shear stress
1,77 MPa (with: 0,88
Chosen $\cot\theta = 1{,}00$

Stirrups
N = 1 enclosing links
Longitudinal spacing
$\alpha = 90°$ (angle betw

Bent-up bars
2H16 bars ($A_{sw} = 40$
beam $\alpha = 45°$ (for n
$s = \frac{z}{n}(\cot\theta + \cot\alpha) =$

04/11/2015	Calc

Figure 1.5 Sample print with compression steel (Word® Office® must be installed on your system).

1.4 Shear_EC2 (Beams and slabs) derived formulae

The following notation is used in the equations for the shear design:

- V_{Ed} the shear force due to the actions at the ultimate limit state occurring at cross-section being considered (see Figure 6.3)
- $V_{Rd,max} = V_{Rd,max}(\cot\theta; \tan\alpha)$ is the design value of the maximum shear force which can be sustained by the member, limited by crushing of the compression struts
- $V_{Rd,s} = V_{Rd,s}(\cot\theta; \tan\alpha)$
- θ is the angle between the concrete compression strut and the beam axis perpendicular to the shear force
- α is the angle between shear reinforcement and the beam axis perpendicular to the shear force
- d effective depth of the cross-section
- b_w width of the web on T, I or L beams
- f_{ywk} characteristic yield strength of shear reinforcement
- $f_{ywd} = f_{ywk}/1,15 = 0,87f_{ywk}$ design yield of shear reinforcement
- A_{sw} is the cross-sectional area of the shear reinforcement
- s is the longitudinal spacing of the shear reinforcement bars
- f_{ck} characteristic compressive cylinder strength of concrete at 28 days
- $f_{cd} = \alpha_{cc}f_{ck}/1,50$ design value of concrete compressive strength
- α_{cc} is the coefficient taking account of long term effects on the compressive strength and of unfavourable effects resulting from the way the load is applied
- α_{cw} is a coefficient taking account of the state of the stress in the compression strut
- $\nu = \nu_1 = 0,6(1 - f_{ck}/250) \cdot (1 - 0,5\cos\alpha)$ is a strength reduction factor for concrete cracked in shear.

Shear reinforcement is not normally required provided the design ultimate shear force V_{Ed} does not exceed $V_{Rd,C}$:

$$V_{Rd,C} = C_{Rd,C}k(100\rho_l f_{ck})^{1/3}b_w d \quad \textbf{(Eq. 1-1)}$$

but not less than:

$$v_{min}b_w d = 0,035k^{3/2}f_{ck}^{1/2}b_w d \quad \textbf{(Eq. 1-2)}$$

where:

$k = 1 + \sqrt{200/(d[mm])} \le 2,0$ and $\rho_l = A_{sl}/(b_w d) \le 0,02$. Where A_{sl} is the area of tensile reinforcement, which extends $\geq (l_{bd} + d)$ beyond the section considered (see EN 1992-1-1, Figure 6.3).

When, on the basis of the design shear calculation, no shear reinforcement is required, minimum shear reinforcement should nevertheless be provided according to 9.2.2.

Where V_{Ed} exceeds $V_{Rd,C}$ shear reinforcement is required.

The beam section should be considered inadequate whether at least one of the following two conditions is not met:

$$V_{Ed} \le 0,5 b_w d \nu f_{cd} \qquad \textbf{(Eq. 1-3)}$$

$$V_{Ed} \le V_{Rd,max} = V_{Rd,max}(\cot\theta = 1,00). \qquad \textbf{(Eq. 1-4)}$$

In such case the section should be resized or the materials strength increased.

If Eq. 1-3 and 1-4 are met:

a. if $V_{Ed} \le V_{Rd,max} = V_{Rd,max}(\cot\theta = 2,50)$ the design value of the shear force which can be sustained by the yielding shear is given by $V_{Rd,s} = V_{Rd,s}(\cot\theta = 2,50)$

b. if $V_{Ed} > V_{Rd,max} = V_{Rd,max}(\cot\theta = 2,50)$ calculate angle θ, of strut for full shear force at end of beam $\theta^\circ = 0,5 \arcsin\{(2V_{Ed})/[(\alpha_{cw}\nu_1 f_{cd})b_w z]\}$

c. if $21,80° \le \theta^\circ \le 45°$ the design value of shear force is given by $V_{Rd,s} = V_{Rd,s}(\cot\theta^\circ)$

d. if $\theta^\circ < 21,80°$ the design value of the shear force is given by: $V_{Rd,s} = V_{Rd,s}(\cot\theta = 2,50)$.

The shear force applied to the section must be limited so that excessive compressive stresses do not occur in the diagonal compressive struts, leading to compressive failure of the concrete. Thus the maximum design shear force $V_{Rd,max}$ is limited by the ultimate crushing strength of the diagonal concrete member in the analogous truss and its vertical component. According to EN 1992-1-1:

- for members with vertical shear reinforcement:

$$V_{Rd,max} = \alpha_{cw} b_w z \nu_1 \frac{f_{cd}}{(\cot\theta + \tan\theta)} \qquad \textbf{(Eq. 1-5)}$$

- for members with inclined shear reinforcement:

$$V_{Rd,max} = \alpha_{cw} b_w z \nu_1 f_{cd} \frac{(\cot\theta + \tan\alpha)}{(1 + \cot^2\theta)} \qquad \textbf{(Eq. 1-6)}$$

where $z = 0,9d$ is the lever arm due to bending with shear.

In the case of "section adequate" with $V_{Ed} > V_{Rd,C}$, all shear will be resisted by $(V_{Rd,s})$ the provisions of shear reinforcement bars with no direct contribution from the shear capacity of the concrete itself. According to EN 1992-1-1:

- for members with vertical shear reinforcement:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta \qquad \textbf{(Eq. 1-7)}$$

- for members with inclined shear reinforcement:

$$V_{Rd,s} = \frac{A_{sw}}{s} z f_{ywd} (\cot\theta + \cot\alpha) \sin\alpha \qquad \textbf{(Eq. 1-8)}$$

where $z = 0,9d$ is the lever arm due to bending with shear. For bent-up bars according to the truss model in Figure 6.5 the longitudinal spacing between shear assemblies is given by:

$$s = \frac{z}{n}(\cot\theta + \cot\alpha) \qquad \textbf{(Eq. 1-9)}$$

where "n" is the number of shear assemblies along the beam axis. The area of each shear assemblies is A_{sw}. In the case of only one shear assembly (n = 1) the longitudinal spacing to be considered in the shear calculations is given by:

$$s = z(\cot\theta + \cot\alpha) \qquad \textbf{(Eq. 1-10)}$$

where $45° \le \alpha < 90°$.

1.5 Verification tests

SHEARREINFORCEMENTBEAMSLAB.XLS. 5.58 MB. Created: 26 December 2013. Last/Rel.-date: 04 November 2015. Sheets:

— Splash

— CREDITS.

EXAMPLE 1-A- Pre-dimensioning and checking shear reinforcement (UK National Annex to EC2) - **test1**

Given: The beam cross-section in Figure below is given. The characteristic material strengths are C30/37 for the concrete and $f_{ywk} = 500$ MPa for the steel. Check if the shear reinforcement in the form of vertical link ($\beta_3 = 50\,\%$) and bent-up bars can support, in shear, the given ultimate load $V_{Ed} = 340$ kN.

Solution: Take an effective depth $d = 557\text{ mm} \approx 550\text{ mm}$. The breadth of section $b = b_w = 350\text{ mm}$. The nominal cover to links $c_{nom} = 25\text{ mm}$. Level arm $z = 0,9d = 495\text{ mm}$.

Design shear stress occurring at cross-section being considered:

$v_{Ed} = V_{Ed}/(b_w d) = (340 \cdot 10^3)/(350 \cdot 550) = 1,77\text{ MPa}$.

Design materials strengths:

concrete $f_{cd} = \alpha_{cc} f_{ck}/1,50 = (0,85 \cdot 30)/1,50 = 17,00\text{ MPa}$

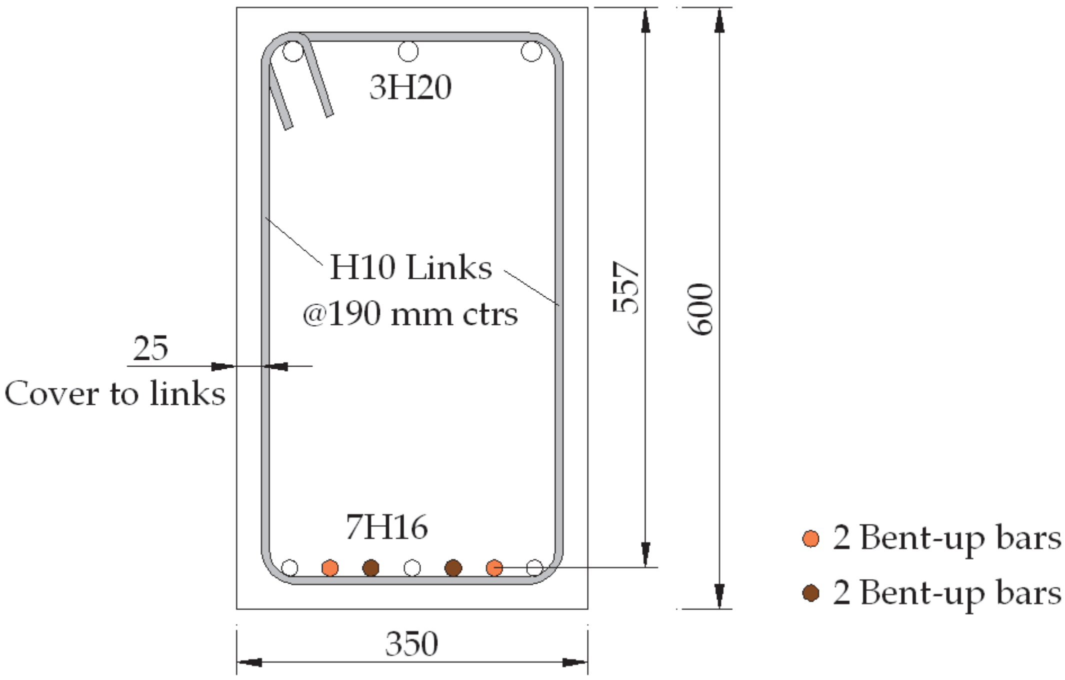

Figure 1.6 Beam cross-section.

$\nu f_{cd} = (0,6(1-30/250))17 = 0,528 \cdot 17 = 8,976$ MPa,

$\alpha_{stirrups} = 90°$, $\alpha_{bentupbars} = 45°$, $\alpha^* = \text{MIN}[\alpha_{stirrups}; \alpha_{bentupbars}] = 45°$ (chosen).

$\nu_1 = \nu \cdot (1 - 0,5\cos\alpha^*) = 0,528 \cdot [1 - 0,5 \cdot \cos(45°)] = 0,341$.

Steel (shear reinforcement):

$f_{ywd} = f_{ywk}/1,15 = 500/1,15 = 435$ MPa.

Area of tensile reinforcement which extends $\geq (l_{bd} + d)$ beyond the section considered:

$A_{sl} = 600$ mm² (considered 3H16 at the face of beam support).

SHEAR RESISTANCE (WITHOUT SHEAR REINFORCEMENT).

Design value for the shear stress resistance:

$$\rho_l = \frac{A_{sl}}{b_w d} = \frac{600}{(350)(550)} = 0,0031 \leq 0,02 \text{ (satisfactory)}.$$

$$k = 1 + \sqrt{\frac{200}{d}} = 1 + \sqrt{\frac{200}{550}} = 1,603 \leq 2,0 \text{ (satisfactory)}.$$

$$C_{Rd,C} k (100 \rho_l f_{ck})^{1/3} = 0,12(1,603)[100(0,0031)30]^{1/3} = 0,40 \text{ MPa}$$

$$v_{min} = 0,035 k^{3/2} f_{ck}^{1/2} = 0,035(1,603)^{3/2}(30)^{1/2} = 0,39 \; MPa$$

$$v_{Rd,C} = \max[0,40; 0,39] = 0,40 \text{ MPa}.$$

Shear reinforcement required: $v_{Ed} = 1,77 > v_{RdC} = 0,40$ MPa.

$v_{Ed} \le 0,5\nu f_{cd} = 0,5 \cdot 0,6 \cdot \left(1 - \frac{30}{250}\right) \cdot 17 = 4,49$ MPa (satisfactory)

$$V_{Rd,\,max} = \frac{\alpha_{cw} b_w z \nu_1 f_{cd}}{(1 + \tan\theta)} = \frac{1(350)(495)0,341(17)}{(1+1)} = 502165 \text{ N with:}$$

$$v_{Rd,\,max} = v_{Rd,\,max}(\cot\theta = 1) = \frac{502165}{(350)(550)} = 4,10 \text{ MPa} > v_{Ed} = 1,77 \text{ MPa (beam adequate).}$$

DETAILING. Shear reinforcement for beam (stirrups and bent-up bars) with $\beta_3 = 0,5$ (see Cl. 9.2.2(4)). Design stress at cross-section being considered $v_{Ed} = V_{Ed}/(b_w d) = 1,77$ MPa (with $0,5 \cdot 1,77 = 0,88$ MPa @stirrups and $0,88$ MPa @bent-up bars). Chosen $\cot\theta = 1,00$ with $1,00 \le \theta \le 2,50$ (Cl. 6.2.3(2) - Note - Exp. (6.7N)).

Stirrups: N = 1 enclosing links with diameter H10, and no inner links. Longitudinal spacing (vertical links): $s = 190$ mm (chosen). $\alpha = 90°$ angle between vertical links and the beam axis). $A_{sw} = 2 \cdot (78) = 157$ mm²,

$A_{sw}/s = 157/190 = 0,827 \text{ mm}^2/\text{mm} = 827 \text{ mm}^2/\text{m}$.

Bent-up bars: 2H16 ($A_{sw} = 402$ mm²) bent-up at an angle from the bottom of the beam $\alpha = 45°$ (for 2 times) with a longitudinal spacing given by:

$$s = \frac{z}{n}(\cot\theta + \cot\alpha) = \frac{495}{2}(1+1) = 495 \text{ mm}.$$

Maximum longitudinal spacing (vertical links $\alpha = 90°$):

$s_{l,\,max} = 0,75d(1 + \cot\alpha) = 0,75(550)(1+0) = 413$ mm.

Compression longitudinal reinforcement which is included in the resistance calculation (bending): H20 with $s_{l,\,max} = 15 \cdot (20 \text{ mm}) = 300$ mm.

$\min[413;\ 300] = 300 \text{ mm} \ge s = 190$ mm (satisfactory).

Transverse vertical spacing:

$$s_t = \frac{b_w - 2c_{nom} - \phi_{Enclink}}{N_{innerLink} + 1} = \frac{350 - 2(25) - 10}{0 + 1} = 290 \text{ mm}$$

where $N_{innerLink}$ is the number of inner links.

Minimum shear reinforcement (for $\sin\alpha = 1$):

$$\left(\frac{A_{sw}}{s}\right)_{min} = \rho_{w,\,min} b_w \sin\alpha = \frac{0,08\sqrt{f_{ck}}}{f_{ywk}} \cdot (b_w \cdot 1) = \frac{0,08\sqrt{30}}{500} \cdot (350 \cdot 1) = 0,306 \frac{\text{mm}^2}{\text{mm}} = 306 \frac{\text{mm}^2}{\text{m}}$$

$$\frac{A_{sw}}{s} = 0,827 \text{ mm}^2/\text{mm} \ge \left(\frac{A_{sw}}{s}\right)_{min} \text{ (satisfactory).}$$

SHEAR CAPACITY. Capacity of the concrete section with vertical and inclined shear reinforcement to act as a strut:

$$V_{Rd,\,max} = \frac{\alpha_{cw} b_w z \nu_1 f_{cd}}{(\cot\theta + \tan\theta)} = \frac{1(350)(495)(0,341)(17)}{(1+1)} = 502165\ \mathrm{N}\ \text{(vertical links)}$$

$$V_{Rd,\,max} = \frac{\alpha_{cw} b_w z \nu_1 f_{cd}}{(1+\cot^2\theta)}(\cot\theta + \cot\alpha) = \frac{1(350)(495)(0,341)(17)}{(1+1^2)}(1+1) = 1004330\ N$$

(bent-up bars).

Value used for shear calculations:

$$V_{Rd,\,max} = \min[502165;\ 1004330] = 502165\ \mathrm{N}.$$

SHEAR REINFORCEMENT (VERTICAL LINKS):

$$\frac{A_{sw}}{s} = 0,827\ \mathrm{mm^2/mm}$$

$$\cot\theta = 1,00,\ (\cot\theta + \tan\theta) = 2,00.$$

$$V_{Rd,\,s} = \frac{A_{sw}}{s} z f_{ywd} \cot\theta = (0,827)(495)(435)(1,00) = 178074\ \mathrm{N}.$$

$$\min[V_{Rd,\,s};\ V_{Rd,\,max}]/(b_w d) = \frac{\min[178074;\ 502165]}{(350)(550)} = 0,92\ \mathrm{Mpa} > v_{EdLink} = 0,88\ \mathrm{MPa}$$

(satisfactory).

SHEAR REINFORCEMENT (BENT-UP BARS):

$$\frac{A_{sw}}{s} = \frac{2\cdot(201)}{495} = 0,812\ \mathrm{mm^2/mm}$$

$$(\cot\theta + \cot\alpha) = 2,00,\ \sin\alpha = \sin(45°) = 0,71,\ (1+\cot^2\theta) = 2,00.$$

$$V_{Rd,\,s} = \frac{A_{sw}}{s} z f_{ywd} (\cot\theta + \cot\alpha)\sin\alpha = (0,812)(495)(435)(2,00)(0,71) = 248278\ \mathrm{N}.$$

$$\min[V_{Rd,\,s};\ V_{Rd,\,max}]/(b_w d) = \frac{\min[248278;\ 502165]}{(350)(550)} = 1,29\ \mathrm{Mpa} > v_{EdLink} = 0,88\ \mathrm{MPa}$$

(satisfactory).

NOTE. Provide H10 mm diameter enclosing links, (and no inner link) at 190 mm centres. Provide 2H16 bent-up at $\alpha = 45°$ for $n = 2$ times with a longitudinal spacing $s \le 495\ \mathrm{mm}$.

MAXIMUM EFFECTIVE CROSS-SECTIONAL AREA OF THE SHEAR REINFORCEMENT ($\cot\Theta = 1,00$):

Stirrups:

$$\frac{A_{sw,\,max}}{s} \le 0,5\alpha_{cw}\nu_1 \frac{f_{cd}}{f_{ywd}} b_w = 0,5(1)(0,341)\frac{(17)}{(435)}(350) = 2,332\ \mathrm{mm^2/mm}$$

Bent-up bars:

$$\frac{A_{sw,\,max}}{s} \le 0,5\alpha_{cw}\nu_1 \frac{f_{cd}}{f_{ywd}\sin\alpha} b_w \ = \ 0,5(1)(0,341)\frac{(17)}{(435)(0,71)}(350) \ = \ 3,285 \ mm^2/mm\,.$$

1.6 References

BRITISH STANDARDS INSTITUTION. The structural use of concrete – Part 1: Code of practice for design and construction, BS 8110–1:1997

EN 1992-1-1:2004. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussels: CEN/TC 250 - Structural Eurocodes, December 2004 (DAV)

EN 1992-1-1:2004/AC:2010. Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussels: CEN/TC 250 - Structural Eurocodes, December 2010Reinforced Concrete Design to Eurocode, Bill Mosley, John Bungey and Ray Hulse, Palgrave Macmillan. 7th Edition

BS NA EN 1992-1-1 (2004) (English): UK National Annex to Eurocode 2. Design of concrete structures. General rules and rules for buildings

Reinforced Concrete Design to Eurocode, Bill Mosley, John Bungey and Ray Hulse, Palgrave Macmillan. 7th Edition.