Version JAB/2

EGT3
ENGINEERING TRIPOS PART IIB

Friday 26 April 2024 9.30 to 11.10

Module 4D10

STRUCTURAL STEELWORK

Answer not more than ***three*** *questions.*

All questions carry the same number of marks.

The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*

Write your candidate number ***not*** *your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Attachment: 4D10 Structural Steelwork data sheet (17 pages).
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

1 An S355 UB 610×229×101 cantilever beam has a span length of 5 m and carries a constant moment. The root radius r of the cross-section is 12.7 mm.

(a) A finite element analysis of the beam, assuming purely elastic material properties but accounting for geometric non-linear effects, determines the lateral-torsional buckling moment to be 265 kN m. Calculate the design moment capacity of the beam. [40%]

(b) Estimate the lateral-torsional buckling capacity of the beam by considering the compressed flange in isolation and equating flexural buckling of the flange about its major axis to lateral-torsional buckling of the beam. Compare your answer to part (a) and discuss the reason(s) for any discrepancies. [40%]

(c) Provide a theoretical justification for the approach in part (b) by considering the equation for the elastic lateral-torsional buckling moment in the datasheets and setting $GJ = 0$. [20%]

2 A steel bridge girder is welded together from a 20×2000 (mm×mm) web plate and 30×400 (mm×mm) top and bottom flanges. All plates are made of S355 steel. The girder carries a 250 mm thick bridge deck made of C40/50 concrete. The spacing between the girder lines is 3.3 m. The girders are simply supported with a span length of 50 m. The bridge needs to carry an (unfactored) traffic load of 6 kPa applied over the whole deck.

(a) Design a shear connector arrangement to ensure fully composite action between the girder and the deck at the ULS in bending. Use headed studs with ultimate tensile strength f_u = 400 MPa. [50%]

(b) Design a shear connector arrangement that satisfies the Fatigue Limit State when the bridge is to be designed for 2 million cycles of the traffic loading. The detail category of headed studs in shear is 90. [50%]

3 A steel plate shear wall in a building consists of a 5 mm thick S355 plate, bolted (with short bolt spacing) to the adjacent beams and columns. The plate has the dimensions shown in Fig. 1. The design (i.e. factored) value of the wind load to be resisted by the shear wall is 188 kN.

(a) Check whether the shear wall has sufficient capacity to resist the design load. [50%]

(b) Problems have arisen in practice with steel plate shear walls, where repetitive buckling and un-buckling of the plate occurs in service conditions, potentially leading to fatigue issues and even noise inside the building. Check whether this phenomenon could potentially be a problem for the shear wall shown in Fig. 1. If so, propose a stiffening scheme. (Note: Only the location of the stiffeners needs to be indicated; the size of the stiffeners need not be determined.) [50%]

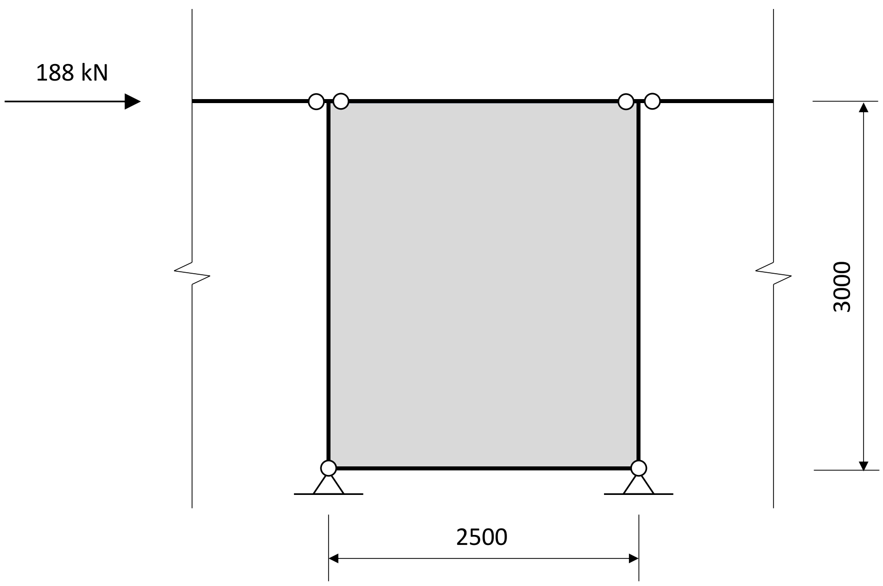


Fig. 1 (All dimensions in mm)

4 A 5 m long UB 406×140×39 simple span beam carries an unfactored dead load (inclusive of the self-weight of the beam) of 12 kN m^{-1} and an unfactored live load of 20 kN m^{-1}. The connection between the beam and the adjacent columns is pictured in Fig. 2. The thickness of the flag plate is 5 mm.

(a) Check the adequacy of the bolted connection. M20 grade 4.6 bolts are used. All steel components (i.e. the beam and the flag plate) are grade S355 (f_u = 490 MPa). [40%]

(b) Check the adequacy of the 3 mm fillet welds between the flag plate and the column face. (<u>Note</u>: The effective length of a fillet weld is the total length minus two times the throat thickness.) [40%]

(c) (i) The bearing stiffness of a single M20 bolt against a 5 mm thick S355 plate is 108 kN mm^{-1} and the bearing stiffness of the same bolt against a 6.4 mm thick S355 plate is 135 kN mm^{-1}. Estimate the rotational stiffness of the connection. [10%]

(ii) EN1993-1-8 stipulates that a connection can be considered as 'pinned' if the rotational stiffness S satisfies the following equation:

$$S \leq (0.5)\, EI_{yy} / L$$

where E is the elastic modulus, I_{yy} is the second moment of area about the major axis and L is the span length. Check whether this is the case for the connection under consideration. [10%]

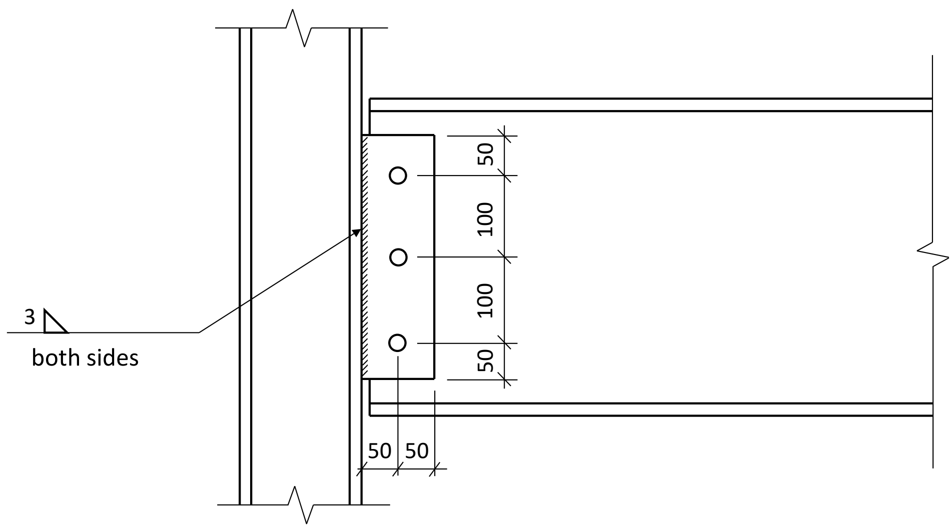


Fig. 2 (All dimensions in mm)

END OF PAPER

Data Sheets

DO NOT USE FOR ACTUAL DESIGN OF STRUCTURAL STEELWORK

DS1: Basic Buckling Resistance Curves

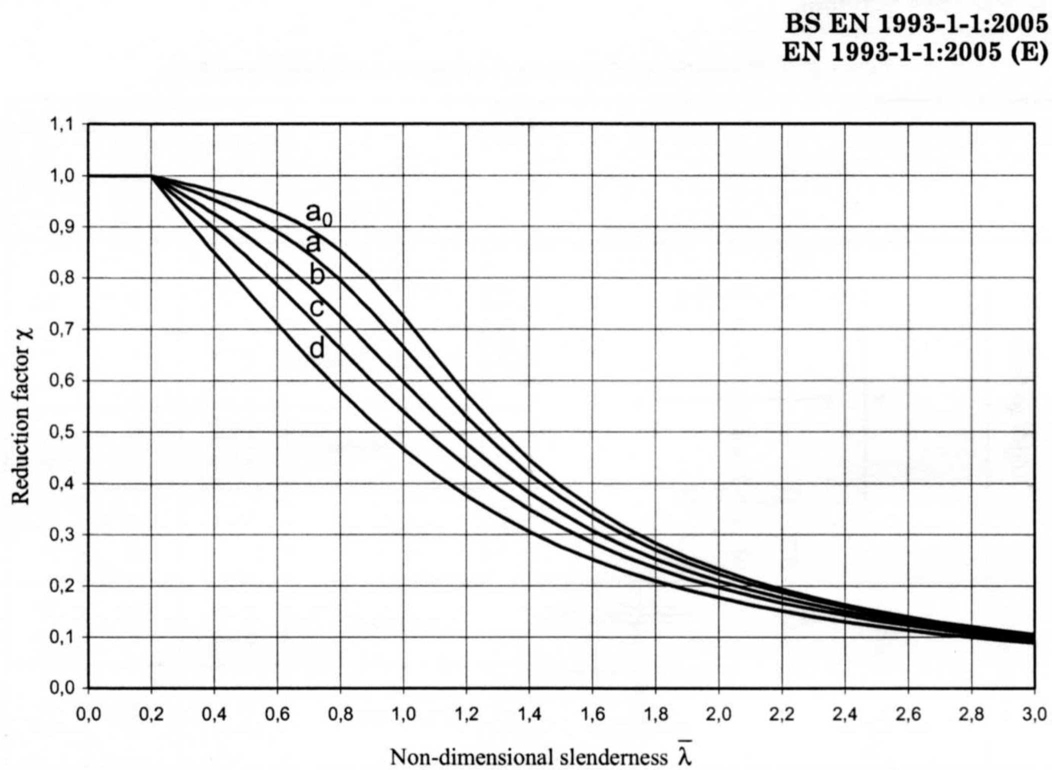


Figure 6.4: Buckling curves

The curves are defined by $\chi = \dfrac{1}{\Phi + \sqrt{\Phi^2 - \bar{\lambda}^2}}$ in which $\Phi \equiv \dfrac{1 + \alpha(\bar{\lambda} - 0.2) + \bar{\lambda}^2}{2}$

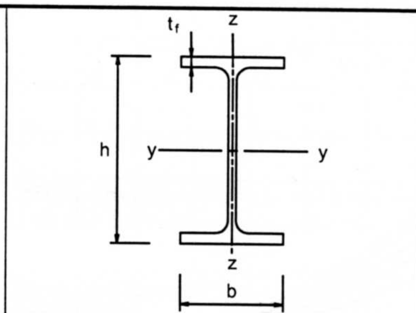
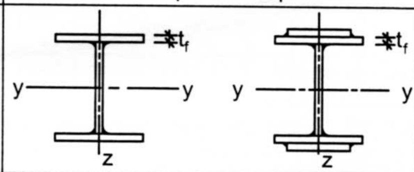
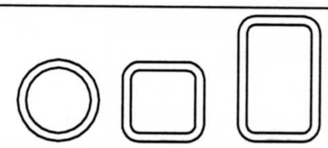
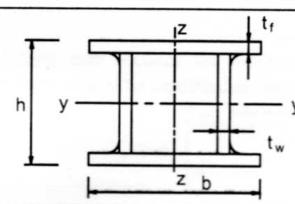
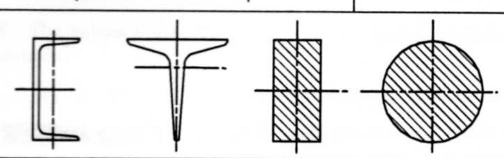
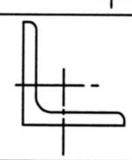
and the imperfection factor α appropriate for each curve is:

Buckling curve	a_0	a	b	c	d
Imperfection factor α	0.13	0.21	0.34	0.49	0.76

DS2: Basic Resistance Curve Selection for Flexural Buckling

BS EN 1993-1-1:2005
EN 1993-1-1:2005 (E)

Table 6.2: Selection of buckling curve for a cross-section

Cross section		Limits		Buckling about axis	Buckling curve: S 235, S 275, S 355, S 420	Buckling curve: S 460
Rolled sections		$h/b > 1,2$	$t_f \leq 40$ mm	y – y	a	a_0
				z – z	b	a_0
			$40 \text{ mm} < t_f \leq 100$	y – y	b	a
				z – z	c	a
		$h/b \leq 1,2$	$t_f \leq 100$ mm	y – y	b	a
				z – z	c	a
			$t_f > 100$ mm	y – y	d	c
				z – z	d	c
Welded I-sections			$t_f \leq 40$ mm	y – y	b	b
				z – z	c	c
			$t_f > 40$ mm	y – y	c	c
				z – z	d	d
Hollow sections			hot finished	any	a	a_0
			cold formed	any	c	c
Welded box sections			generally (except as below)	any	b	b
			thick welds: $a > 0{,}5t_f$; $b/t_f < 30$; $h/t_w < 30$	any	c	c
U-, T- and solid sections				any	c	c
L-sections				any	b	b

DS3: Lateral-Torsional Buckling Equations

Critical Moment

The critical magnitude of equal-and-opposite end-moments to cause elastic lateral torsional buckling of a beam is:

$$M_{LT} = \frac{\pi}{L}\sqrt{EIGJ}\sqrt{1+\frac{\pi^2}{L^2}\frac{E\Gamma}{GJ}}$$

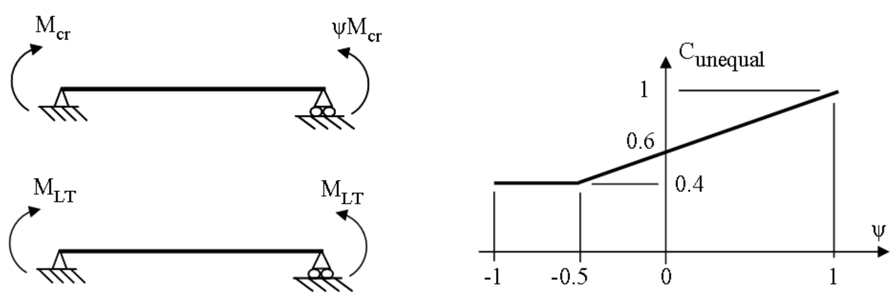
where EI, GJ and $E\Gamma$ are the minor axis flexural rigidity, the torsional rigidity and the warping rigidity respectively. (It is assumed that the supports prevent vertical, lateral and torsional deflections but do not restrain warping.)

For a doubly-symmetric I-beam

$$\Gamma \approx \frac{ID^2}{4}$$

where D is the distance between flange centroids and I is the second moment of area of the section about its minor axis.

Unequal end moments



$$M_{cr} = \frac{M_{LT}}{C_{\text{unequal}}} \quad \text{where} \quad C_{\text{unequal}} = \max(0.6+0.4\psi, 0.4)$$

Lateral torsional buckling curve selection

For lateral torsional buckling, the buckling resistance curves (DS1) may be used, with curves selected via the table below. Height h and width b are defined in DS2.

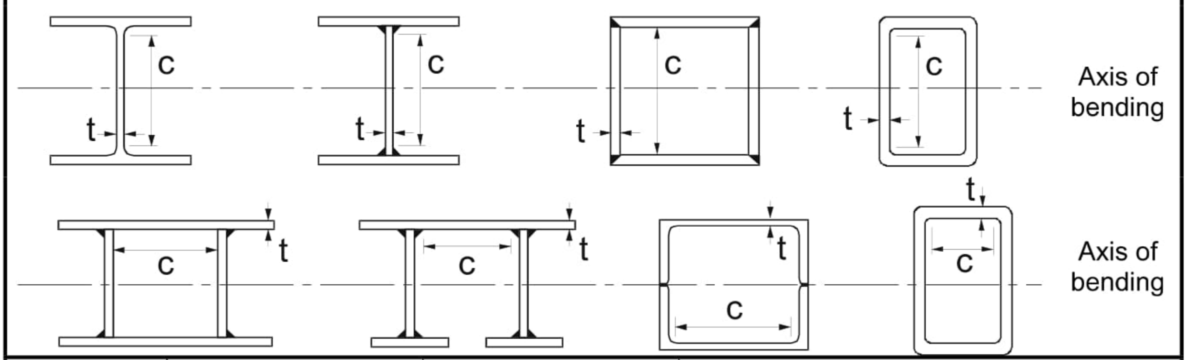
	Limits	Curve
Rolled I-sections	$h/b \leq 2$	a
	$h/b > 2$	b
Welded I-sections	$h/b \leq 2$	c
	$h/b > 2$	d
Other	-	d

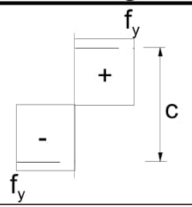
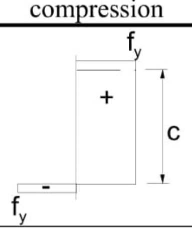
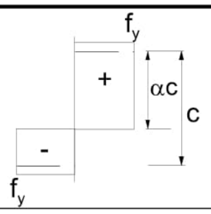
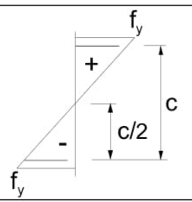
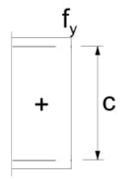
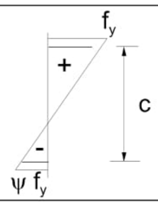
DS4: Thin-walled Structures

Cross-sectional classification

(EN 1993-1-1; Table 5.2)

Internal compression parts

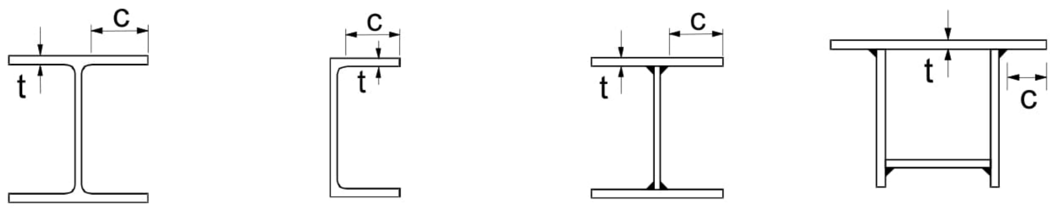


Class	Part subject to bending	Part subject to compression	Part subject to bending and compression
Stress distribution in parts (compression positive)			
1	$c/t \le 72\varepsilon$	$c/t \le 33\varepsilon$	when $\alpha > 0,5$: $c/t \le \dfrac{396\varepsilon}{13\alpha - 1}$ when $\alpha \le 0,5$: $c/t \le \dfrac{36\varepsilon}{\alpha}$
2	$c/t \le 83\varepsilon$	$c/t \le 38\varepsilon$	when $\alpha > 0,5$: $c/t \le \dfrac{456\varepsilon}{13\alpha - 1}$ when $\alpha \le 0,5$: $c/t \le \dfrac{41,5\varepsilon}{\alpha}$
Stress distribution in parts (compression positive)			
3	$c/t \le 124\varepsilon$	$c/t \le 42\varepsilon$	when $\psi > -1$: $c/t \le \dfrac{42\varepsilon}{0,67 + 0,33\psi}$ when $\psi \le -1^{*)}$: $c/t \le 62\varepsilon(1-\psi)\sqrt{(-\psi)}$

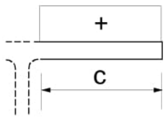
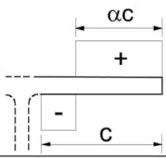
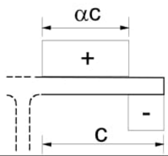
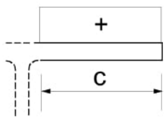
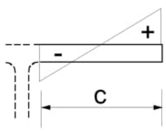
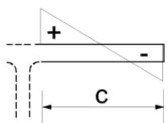
$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

*) $\psi \le -1$ applies where either the compression stress $\sigma \le f_y$ or the tensile strain $\varepsilon_y > f_y/E$

Outstand flanges



Rolled sections | Welded sections

Class	Part subject to compression	Part subject to bending and compression	
		Tip in compression	Tip in tension
Stress distribution in parts (compression positive)			
1	$c/t \le 9\varepsilon$	$c/t \le \dfrac{9\varepsilon}{\alpha}$	$c/t \le \dfrac{9\varepsilon}{\alpha\sqrt{\alpha}}$
2	$c/t \le 10\varepsilon$	$c/t \le \dfrac{10\varepsilon}{\alpha}$	$c/t \le \dfrac{10\varepsilon}{\alpha\sqrt{\alpha}}$
Stress distribution in parts (compression positive)			
3	$c/t \le 14\varepsilon$	$c/t \le 21\varepsilon\sqrt{k_\sigma}$ For k_σ see EN 1993-1-5	

$\varepsilon = \sqrt{235/f_y}$	f_y	235	275	355	420	460
	ε	1,00	0,92	0,81	0,75	0,71

Local buckling of plates

$$\sigma_{cr} = K \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2$$

where b is the width of the plate and t is its thickness.

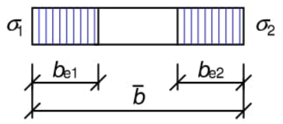
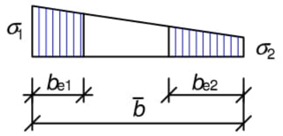
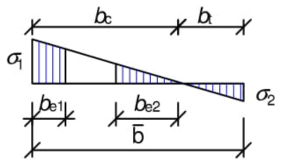
- For plates in uniform longitudinal compression:

  $K = 4$ for internal elements.

  $K = 0.43$ for outstand elements.

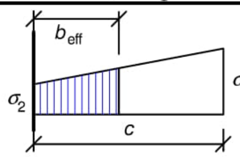
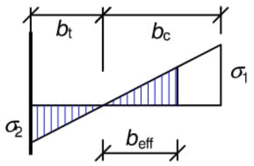
- For plates under in-plane bending (EN 1993-1-5): $K = k_\sigma$

Table 4.1: Internal compression elements

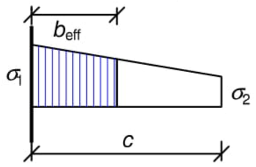
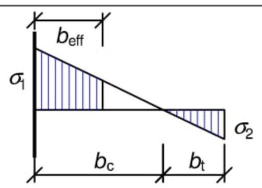
Stress distribution (compression positive)	Effective^{p} width b_{eff}
	$\underline{\psi = 1}$: $b_{eff} = \rho\ \bar{b}$ $b_{e1} = 0{,}5\ b_{eff}$ $\quad b_{e2} = 0{,}5\ b_{eff}$
	$\underline{1 > \psi \geq 0}$: $b_{eff} = \rho\ \bar{b}$ $b_{e1} = \dfrac{2}{5-\psi} b_{eff}$ $\quad b_{e2} = b_{eff} - b_{e1}$
	$\underline{\psi < 0}$: $b_{eff} = \rho\ b_c = \rho\ \bar{b} / (1-\psi)$ $b_{e1} = 0{,}4\ b_{eff}$ $\quad b_{e2} = 0{,}6\ b_{eff}$

$\psi = \sigma_2/\sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1	AC1 $-1 > \psi \geq -3$ AC1
Buckling factor k_σ	4,0	$8{,}2 / (1{,}05 + \psi)$	7,81	$7{,}81 - 6{,}29\psi + 9{,}78\psi^2$	23,9	$5{,}98\ (1 - \psi)^2$

Table 4.2: Outstand compression elements

Stress distribution (compression positive)	Effective^{p} width b_{eff}
	$\underline{1 > \psi \geq 0}$: $b_{eff} = \rho\ c$
	$\underline{\psi < 0}$: $b_{eff} = \rho\ b_c = \rho\ c / (1-\psi)$

$\psi = \sigma_2/\sigma_1$	1	0	-1	$1 \geq \psi \geq -3$
Buckling factor k_σ	0,43	0,57	0,85	$0{,}57 - 0{,}21\psi + 0{,}07\psi^2$

Stress distribution (compression positive)	Effective^{p} width b_{eff}
	$\underline{1 > \psi \geq 0}$: $b_{eff} = \rho\ c$
	$\underline{\psi < 0}$: $b_{eff} = \rho\ b_c = \rho\ c / (1-\psi)$

$\psi = \sigma_2/\sigma_1$	1	$1 > \psi > 0$	0	$0 > \psi > -1$	-1
Buckling factor k_σ	0,43	$0{,}578 / (\psi + 0{,}34)$	1,70	$1{,}7 - 5\psi + 17{,}1\psi^2$	23,8

- For plates in shear:

$$\tau_{cr} = K \frac{\pi^2 E}{12(1-\nu^2)} \left(\frac{t}{b}\right)^2$$

$$K = 5.34 + \frac{4}{(a/b)^2} \qquad \text{if a > b}$$

$$K = 5.34 + \frac{4}{(b/a)^2} \qquad \text{if b > a}$$

Effective widths

(EN 1993-1-5; Clause 4.4)

$$A_{c,eff} = \rho A_c \tag{4.1}$$

where ρ is the reduction factor for plate buckling.

(2) The reduction factor ρ may be taken as follows:

– internal compression elements:

$\rho = 1,0$ for AC1 $\bar{\lambda}_p \le 0,5 + \sqrt{0.085 - 0.055\psi}$ AC1

$$\rho = \frac{\bar{\lambda}_p - 0,055(3+\psi)}{\bar{\lambda}_p^2} \le 1,0 \quad \text{for AC1 } \bar{\lambda}_p > 0,5 + \sqrt{0.085 - 0.055\psi}\text{, AC1 AC1 } \textit{text deleted} \text{ AC1} \tag{4.2}$$

– outstand compression elements:

$\rho = 1,0$ for $\bar{\lambda}_p \le 0,748$

$$\rho = \frac{\bar{\lambda}_p - 0,188}{\bar{\lambda}_p^2} \le 1,0 \quad \text{for } \bar{\lambda}_p > 0,748 \tag{4.3}$$

where $\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr}}} = \frac{\bar{b}/t}{28,4\,\varepsilon\sqrt{k_\sigma}}$

Shear buckling

Shear buckling needs to be checked if: $\frac{h_w}{t_w} \ge 72\varepsilon$

where h_w is the web height, t_w is the web thickness and $\varepsilon = \sqrt{235/f_y}$ (with f_y in MPa).

$$V_{b,Rd} = \chi_w \frac{(f_y/\sqrt{3})h_w t_w}{\gamma_{M1}}$$

$$\lambda_w = 0.76\sqrt{\frac{f_y}{\tau_{cr}}}$$

Table 5.1: Contribution from the web χ_w to shear buckling resistance

	Rigid end post	Non-rigid end post
$\bar{\lambda}_w < 0{,}83/\eta$	η	η
$0{,}83/\eta \leq \bar{\lambda}_w < 1{,}08$	$0{,}83/\bar{\lambda}_w$	$0{,}83/\bar{\lambda}_w$
$\bar{\lambda}_w \geq 1{,}08$	$1{,}37/(0{,}7+\bar{\lambda}_w)$	$0{,}83/\bar{\lambda}_w$

Flange induced buckling

(EN 1993-1-5; Clause 8)

(1) To prevent the compression flange buckling in the plane of the web, the following criterion should be met:

$$\frac{h_w}{t_w} \leq k\,\frac{E}{f_{yf}}\sqrt{\frac{A_w}{A_{fc}}} \qquad (8.1)$$

where A_w is the cross section area of the web;

A_{fc} is the effective cross section area of the compression flange;

h_w is the depth of the web;

t_w is the thickness of the web.

The value of the factor k should be taken as follows:

- plastic rotation utilized $k = 0{,}3$
- plastic moment resistance utilized $k = 0{,}4$
- elastic moment resistance utilized $k = 0{,}55$

Stiffener buckling

(EN 1993-1-5; Clause 4.5.3)

$$\alpha_c = \alpha + \frac{0.09}{i/e}$$

where:

$\alpha = 0.34$ for closed section stiffeners

$\alpha = 0.49$ for open section stiffeners

i = the radius of gyration of the effective column

e = max (e_1, e_2)

e_1 = the distance between the centroid of the stiffener and the centroid of the effective column

e_2 = the distance between the centre line of the stiffened plate and the centroid of the effective column

Moment-shear-axial force interaction

(EN 1993-1-3; Clause 8)

(1) For cross-sections subject to the combined action of an axial force N_{Ed}, a bending moment M_{Ed} and a shear force V_{Ed} no reduction due to shear force need not be done provided that $V_{Ed} \leq 0{,}5\ V_{w,Rd}$. If the shear force is larger than half of the shear force resistance then following equations should be satisfied:

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \left(1 - \frac{M_{f,Rd}}{M_{pl,Rd}}\right)\left(\frac{2V_{Ed}}{V_{w,Rd}} - 1\right)^2 \leq 1{,}0 \qquad \text{...(6.27)}$$

where:

N_{Rd} is the design resistance of a cross-section for uniform tension or compression given in 6.1.2 or 6.1.3;

$M_{y,Rd}$ is the design moment resistance of the cross-section given in 6.1.4;

$V_{w,Rd}$ is the design shear resistance of the web given in 6.1.5(1);

$M_{f,Rd}$ is the moment of resistance of a cross-section consisting of the effective area of flanges only, see EN 1993-1-5;

$M_{pl,Rd}$ is the plastic moment of resistance of the cross-section, see EN 1993-1-5.

DS5: Connections

Bolt size	Tensile Area
-	mm^2
M10	58.0
M12	84.3
M14	115
M16	157
M18	192
M20	245
M22	303
M24	353
M27	459
M30	561

Shear capacity of a bolt:

$$F_{V,Rd} = 0.6Af_{ub}/\gamma_{M2}$$

Tensile capacity of a bolt:

$$F_{t,Rd} = 0.9A_s f_{ub}/\gamma_{M2}$$

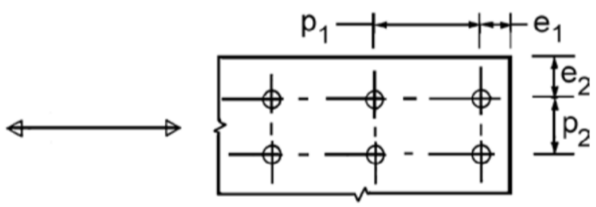
Bolt in tension and shear:

$$\frac{F_{V,Ed}}{F_{V,Rd}} + \frac{F_{t,Ed}}{1.4F_{t,Rd}} \leq 1.0$$

Table 18 — Values of the nominal minimum preloading force $F_{p,C}$ in [kN]

Property class	Bolt diameter in mm									
	12	**14**	**16**	**18**	**20**	**22**	**24**	**27**	**30**	**36**
8.8	47	65	88	108	137	170	198	257	314	458
10.9	59	81	110	134	172	212	247	321	393	572

Minimum end and edge distances, and bolt spacings:



$e_1 \geq 1.2\ d_0$

$e_2 \geq 1.2\ d_0$

$p_1 \geq 2.2\ d_0$

$p_2 \geq 2.4\ d_0$

Bolt tear-out:

$$F_{1,Rd} = 2at\frac{f_y}{\sqrt{3}}/\gamma_{M0}$$

t = ply thickness

A_{nt} = area in tension

A_{nV} = area in shear

Block tear-out in tension:

$$F_{eff,1,Rd} = \frac{f_u A_{nt}}{\gamma_{M2}} + \frac{f_y}{\sqrt{3}}\frac{A_{nV}}{\gamma_{M0}}$$

Block tear-out in shear:

$$F_{eff,2,Rd} = 0.5\frac{f_u A_{nt}}{\gamma_{M2}} + \frac{f_y}{\sqrt{3}}\frac{A_{nV}}{\gamma_{M0}}$$

Bolt bearing:

$$F_{b,Rd} = \frac{k_1 \propto_b f_u dt}{\gamma_{M2}}$$

where α_b is the smallest of α_d ; $\frac{f_{ub}}{f_u}$ or 1,0;

in the direction of load transfer:

- for end bolts: $\alpha_d = \frac{e_1}{3d_0}$; for inner bolts: $\alpha_d = \frac{p_1}{3d_0} - \frac{1}{4}$

perpendicular to the direction of load transfer:

AC2 - for edge bolts: k_1 is the smallest of $2,8\frac{e_2}{d_0} - 1,7, 1,4\frac{p_2}{d_0} - 1,7$ and 2,5 AC2

- for inner bolts: k_1 is the smallest of $1,4\frac{p_2}{d_0} - 1,7$ or 2,5

Punching shear:

$$B_{p,Rd} = 0.6\pi d_m t_p f_u / \gamma_{M2}$$

t_p = thickness of the plate under the head/nut

d_m = average diameter of the head/nut

Bolt slip load:

$$F_{s,Rd} = \frac{n\mu F_{p,C}}{\gamma_{M3,ser}}$$

n = number of friction planes

$F_{p,C}$ = bolt pre-load

μ = friction coefficient (see below)

$\gamma_{M3,ser}$ = 1.10

Classifications that may be assumed for friction surfaces

Surface treatment	Class	Slip factor (μ)
Surfaces blasted with shot or grit with loose rust removed, not pitted	A	0.50
Surfaces hot-dip galvanized and flash (sweep) blasted and with alkali-zinc silicate paint with a nominal thickness of 60 μm	B	0.40
Surfaces blasted with shot or grit; a) coated with alkali-zinc silicate paint with a nominal thickness of 60 μm+ b) thermally sprayed with aluminium or zinc or a combination of both to a nominal thickness not exceeding 80 μm	B	0.40
Surfaces hot-dip galvanized and flash (sweep) blasted	C	0.35
Surfaces cleaned by wire brush or flame cleaning, with loose rust removed	C	0.30
Surfaces as rolled	D	0.20

Reduction factor for long bolted connections ($L_j > 15d$, where d is the bolt diameter):

$$\beta_{L,f} = 1 - \frac{L_j - 15d}{200d} \qquad 0.75 \leq \beta_{L,f} \leq 1.0$$

Reduction factor for shear lag in eccentrically connected angles (EN 1993-1-8 Clause 3.10.3):

Pitch	p_1	$\leq 2{,}5\ d_o$	$\geq 5{,}0\ d_o$
2 bolts	β_2	0,4	0,7
3 bolts or more	β_3	0,5	0,7

Bolt group subject to moment:

$$F_i = kr_i \qquad\qquad k = \frac{M}{\sum r_i^2}$$

M = applied moment

r_i = distance from the bolt to the centre of rotation of the bolt group

F_i = bolt shear force

Design of welds:

$$\sqrt{\sigma_x^2 + 3\left(\tau_y^2 + \tau_z^2\right)} \leq \frac{f_u}{\beta_w \gamma_{M2}} \qquad \text{and} \qquad \sigma_x \leq 0.9\frac{f_u}{\gamma_{M2}}$$

f_u = ultimate tensile strength of the weaker connected part

β_w = 0.9 for S355; 0.85 for S275

Reduction factor for long welds:

- if $l_w \geq 150a$: $\beta_{Lw,1} = 1.2 - \frac{0.2l_w}{150a}$ $\quad \beta_{Lw,1} \leq 1.0$
- if $l_w \geq 1.7$ m in stiffeners of plate girders: $\beta_{Lw,2} = 1.1 - \frac{l_w}{17}$ (l_w in m)

  $0.6 \leq \beta_{Lw,2} \leq 1.0$

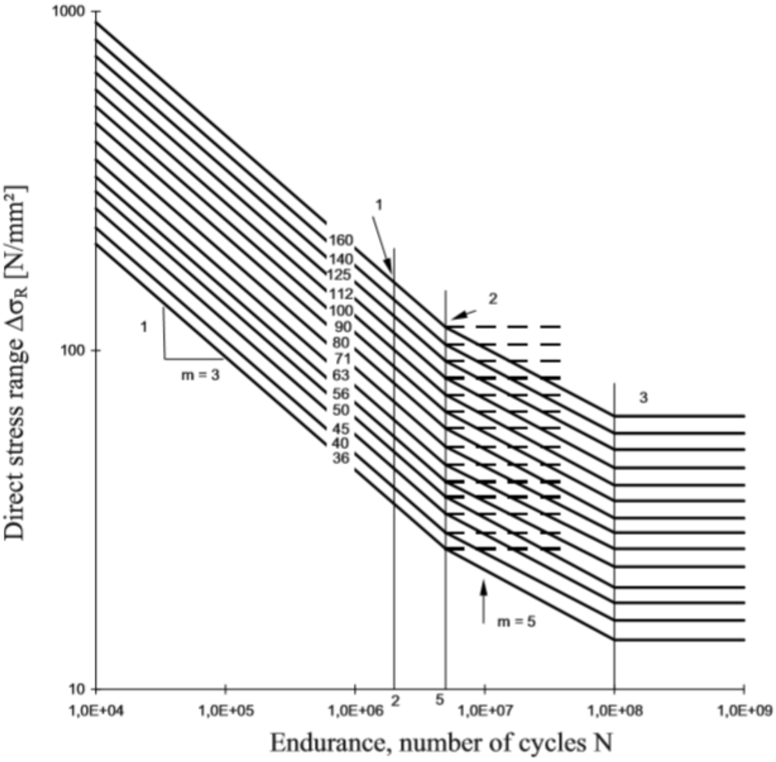
where a is the throat thickness of the weld.

S-N curves: $N_r(\Delta\sigma_r)^m = K$

N_r = number of cycles causing failure

$\Delta\sigma_r$ = amplitude of the stress cycle

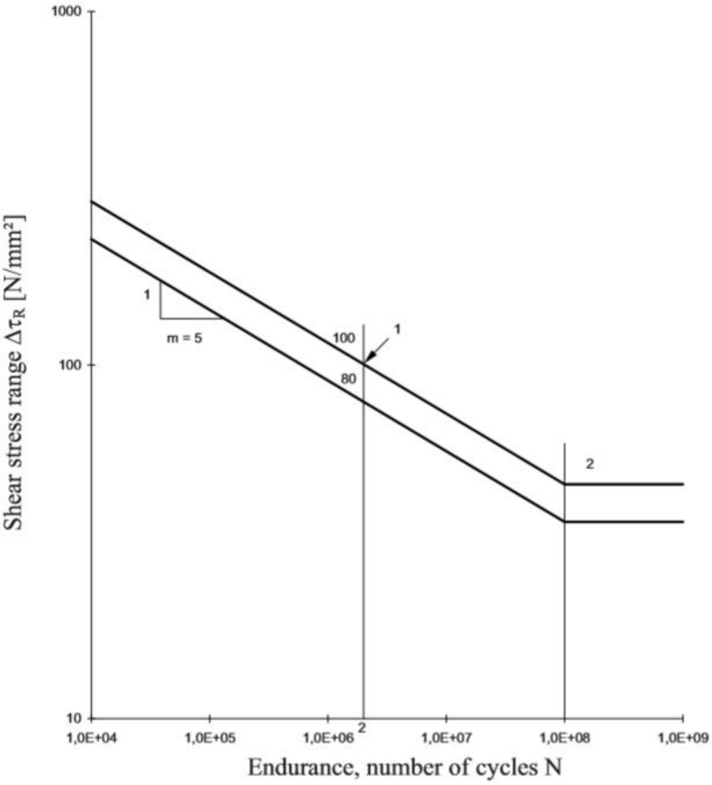
K, m = constants



1 *Detail category $\Delta\sigma_C$*

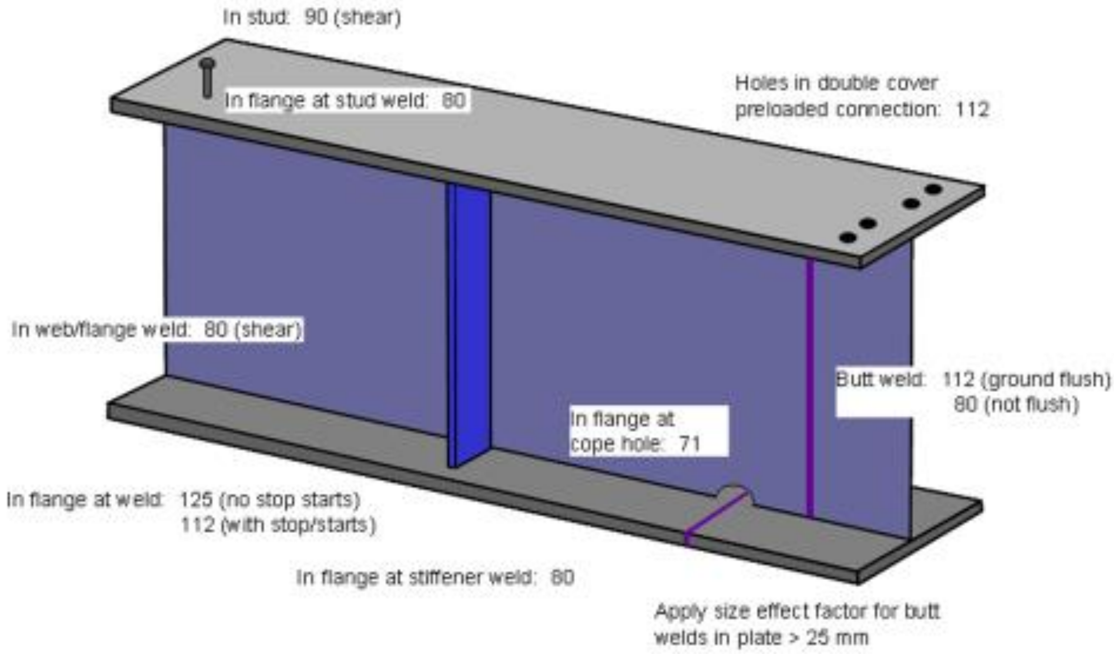
2 *Constant amplitude fatigue limit $\Delta\sigma_D$*

3 *Cut-off limit $\Delta\sigma_L$*



1 *Detail category $\Delta\tau_C$*

2 *Cut-off limit $\Delta\tau_L$*



Typical fatigue details in plate girders.

Palmgren-Miner rule:
$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} + \cdots \frac{n_i}{N_i} + \cdots \leq 1$$

n_i = number of applied cycles with amplitude $\Delta\sigma_i$

N_i = number of cycles with amplitude $\Delta\sigma_i$ causing failure

DS6: Composite beams

Headed shear studs:

- standard sizes are 13 mm, 16 mm, 19 mm, 22 mm, 25 mm.
- shear capacity is the lesser of:

$$P_{Rd} = \frac{0.8 f_u (\pi d^2/4)}{\gamma_V}$$

$$P_{Rd} = \frac{0.29 d^2 \, (f_{ck} E_{cm})^{0.5}}{\gamma_V}$$

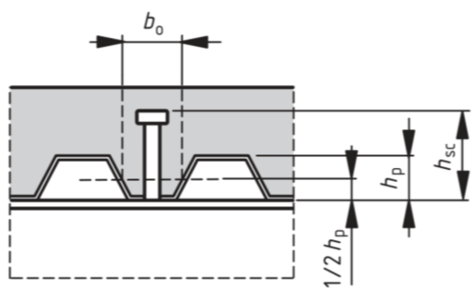
where:

f_u = ultimate tensile strength of the steel
d = diameter of the stud
f_{ck} = concrete compressive strength
E_{cm} = elastic modulus of the concrete
γ_V = 1.25

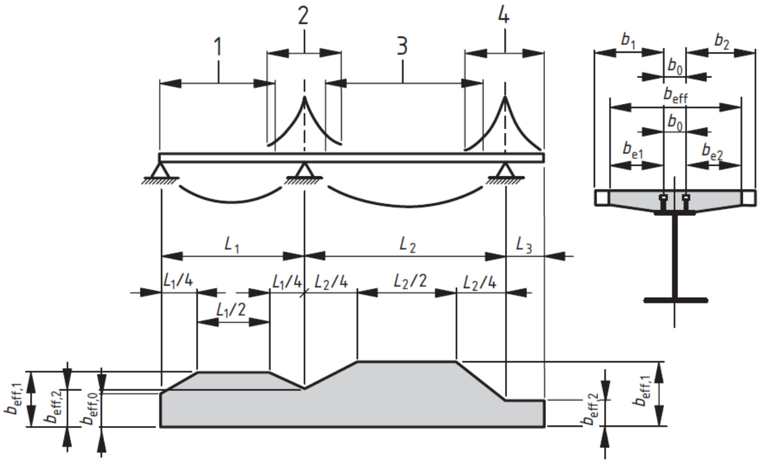
- Reduction factor for studs on steel decking:

$$k_t = \frac{0.7}{\sqrt{n_r}} \frac{b_0}{h_p} \left(\frac{h_{sc}}{h_p} - 1 \right)$$

n_r = number of studs per rib



Effective width of the concrete slab:



$$b_{eff} = L_e/4 + b_0$$

Key

1 $L_e = 0{,}85 L_1$ for $b_{eff,1}$
2 $L_e = 0{,}25(L_1 + L_2)$ for $b_{eff,2}$
3 $L_e = 0{,}70 L_2$ for $b_{eff,1}$
4 $L_e = 2 L_3$ for $b_{eff,2}$

Modular ratio: $n = 2n_0 \qquad n_0 = E_a/E_{cm}$

where E_a is the elastic modulus of steel and E_{cm} is the elastic modulus of the concrete:

Strength classes for concrete															Analytical relation / Explanation
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90	
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105	
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98	$f_{cm} = f_{ck}+8$(MPa)
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0	$f_{ctm}=0,30\times f_{ck}^{(2/3)}$ ≤C50/60 $f_{ctm}=2,12\cdot\ln(1+(f_{cm}/10))$ > C50/60
$f_{ctk,0,05}$ (MPa)	1,1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5	$f_{ctk;0,05} = 0,7\times f_{ctm}$ 5% fractile
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6	$f_{ctk;0,95} = 1,3\times f_{ctm}$ 95% fractile
E_{cm} (GPa)	27	29	30	31	33	34	35	36	37	38	39	41	42	44	$E_{cm} = 22[(f_{cm})/10]^{0,3}$ (f_{cm} in MPa)
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8	see Figure 3.2 $\varepsilon_{c1}(^0/_{00}) = 0,7\ f_{cm}^{0,31} < 2.8$
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8	see Figure 3.2 for $f_{ck} \geq 50$ Mpa $\varepsilon_{cu1}(^0/_{00})=2,8+27[(98-f_{cm})/100]^4$
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2, 5	2,6	see Figure 3.3 for $f_{ck} \geq 50$ Mpa $\varepsilon_{c2}(^0/_{00})=2,0+0,085(f_{ck}-50)^{0,53}$
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	see Figure 3.3 for $f_{ck} \geq 50$ Mpa $\varepsilon_{cu2}(^0/_{00})=2,6+35[(90-f_{ck})/100]^4$
n	2,0									1,75	1,6	1,45	1,4	1,4	for $f_{ck} \geq 50$ Mpa $n=1,4+23,4[(90-f_{ck})/100]^4$
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3	see Figure 3.4 for $f_{ck} \geq 50$ Mpa $\varepsilon_{c3}(^0/_{00})=1,75+0,55[(f_{ck}-50)/40]$
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6	see Figure 3.4 for $f_{ck} \geq 50$ Mpa $\varepsilon_{cu3}(^0/_{00})=2,6+35[(90-f_{ck})/100]^4$