Metal Structures

Design Project II

Floor girders – examples of calculation (part II)

IIIrd example of calculations – rigid joint

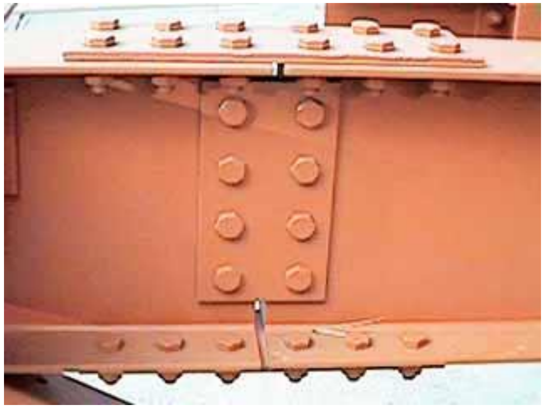

Photo: amsd.co.uk

Rigid joint, primary beam - primary beam, two transport members

New complex of data

HEA 650

Bending moment M_{Ed} = 727,8 kN m

Vertical force V_{Ed} = 162,2 kN

Axial force N_{Ed} = 0,0 kN

S235

f_y = 235 MPa

Analysis of bolted joint concerns few important questions:

- Initial assumptions about geometry of joit → #t / 4 – 5
- Distribution of loads in joint → #t / 6 – 11
- Initial analysis of bolts (category of joint, class of bolt, dimension, length, geometry) → #t / 12 – 27
- Distribution of extrenal actions between bolts → #t / 28 – 34
- Stiffness of joint (according assumption – rigid joint) → #t / 35
- Checking of resistances → #t / 36 – 79

Initial asumptions about geometry

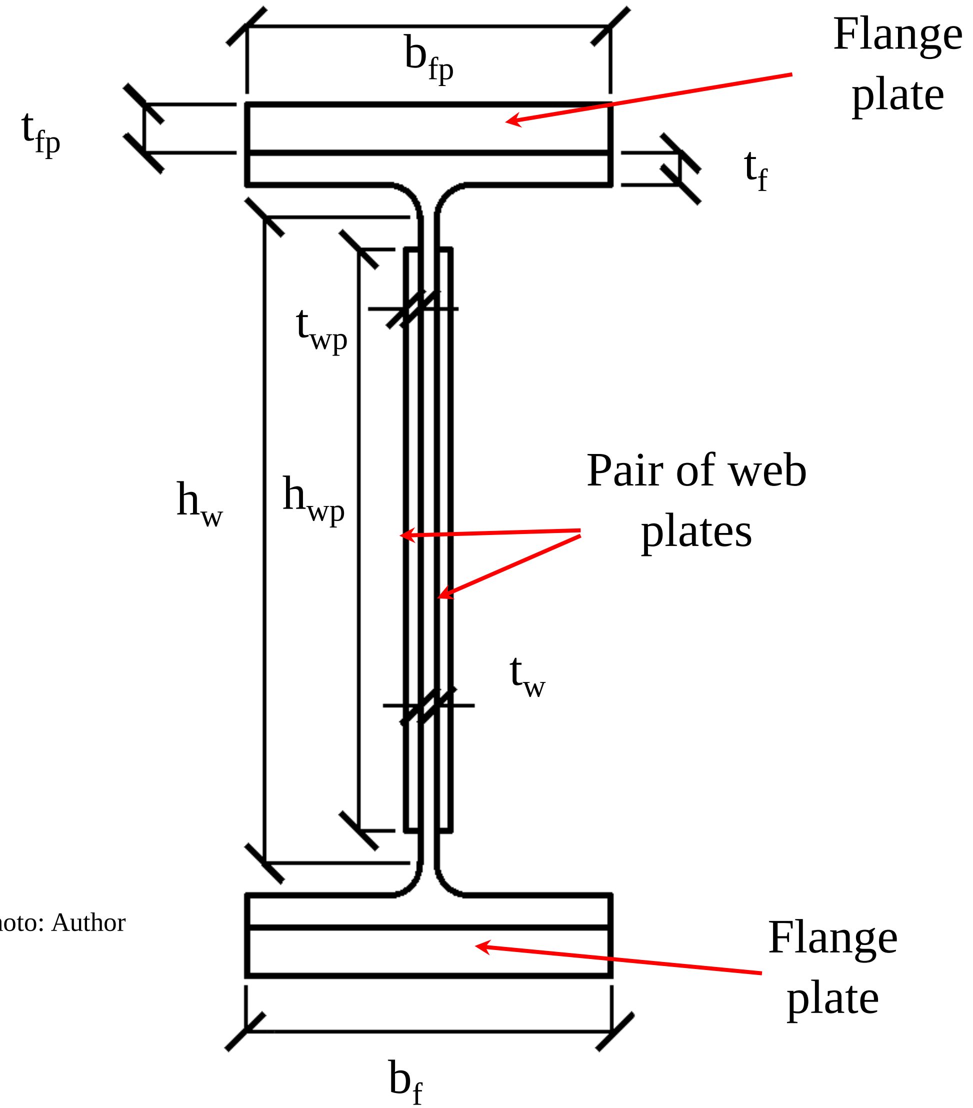

Photo: Author

Recommendation:

$b_{fp} = b_f$

$t_f \leq t_{fp} \leq 2t_f$

$t_{wp} \leq t_w \leq 2t_{wp}$

$t_{wp} \geq 8$ mm

$h_{wp} \approx 0{,}8\ h_w$

Initial checking of geometry:

$0{,}8\ J_{I,\ y} \leq J_{fp,\ y}$

$J_{fp,\ y} \geq 10\ J_{wp,\ y}$

HEA 650, geometry

I^{st} class of cross-section

$J_y = 175\ 200\ cm^4$

$h = 640\ mm$

$t_w = 13{,}5\ mm$

$h_w = 534\ mm$

$t_f = 26\ mm$

$b_f = 300\ mm$

$r = 27\ mm$

You must remember: **plates of some thickness are not produced or not recommended**:

...20, 21, 22, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46... [mm]

$b_{fp} = b_f = 300\ mm$

$t_f \leq t_{fp} \leq 2t_f \rightarrow 26 \leq t_{fp} \leq 52 \rightarrow t_{fp} = 30\ mm$

$t_{wp} \leq t_w \leq 2t_{wp} \rightarrow t_{wp} \leq 13{,}5 \leq 2t_{wp}$

$t_{wp} \geq 8\ mm$

$t_{wp} = 12\ mm$

$h_{wp} \approx 0{,}8\ h_w \rightarrow h_{wp} \approx 0427\ mm \rightarrow h_{wp} = 420\ mm$

$0{,}8\ J_{I,\ y} = 140\ 160\ cm^4 \leq J_{fp,\ y} = 202\ 000\ cm^4$ **OK**

$J_{fp,\ y} = 202\ 000\ cm^4 \geq 10\ J_{wp,\ y} = 148\ 176\ cm^4$ **OK**

Shear joint, distribution of cross-sectional forces

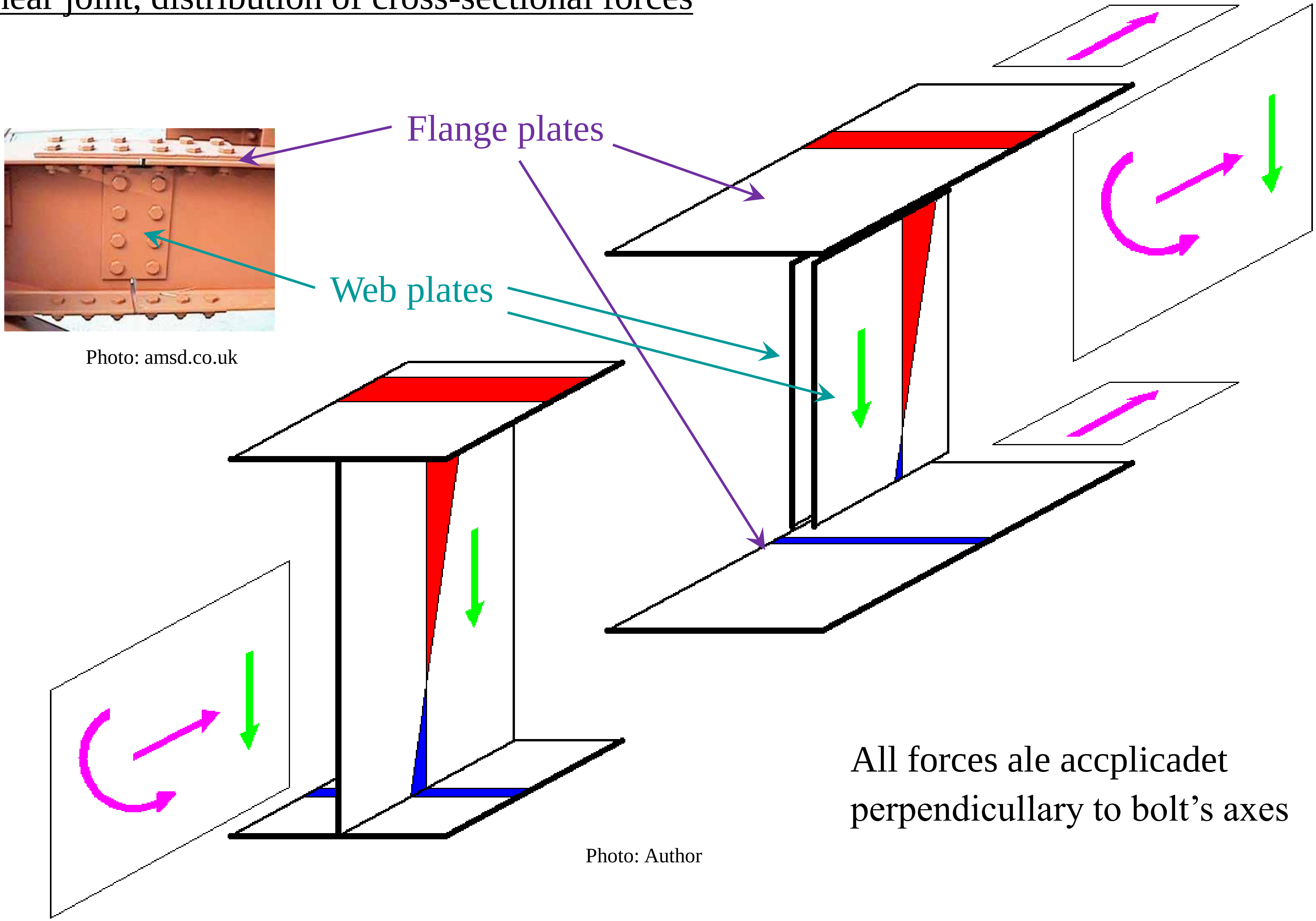

Photo: amsd.co.uk

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All forces ale accplicadet perpendicullary to bolt’s axes

Recommendation: in proportion to geometrical characteristics of flange (f) and web (w):

$M_{fp} = M_{Ed}\, J_{f,\,y} / J_{I,\,y}$

$M_{wp} = M_{Ed}\, J_{w,\,y} / J_{I,\,y}$

$N_{fp} = N_{Ed}\, A_f / A_I$

$N_{wp} = N_{Ed}\, A_w / A_I$

$V_{fp} = 0$

$V_{wp} = V_{Ed}$

$J_{f,\,y} \approx$ (Steiner's theorem only) $\approx$

$\approx 2\, b_f\, t_f\, (h / 2 - t_f / 2)^2 = 147\,028\ cm^4$

$J_{w,\,y} \approx J_{I,\,y} - J_{f,\,y} = 28\,172\ cm^4$

$M_{fp} = 610{,}770$ kNm

$M_{wp} = 117{,}030$ kNm

No external axial force:

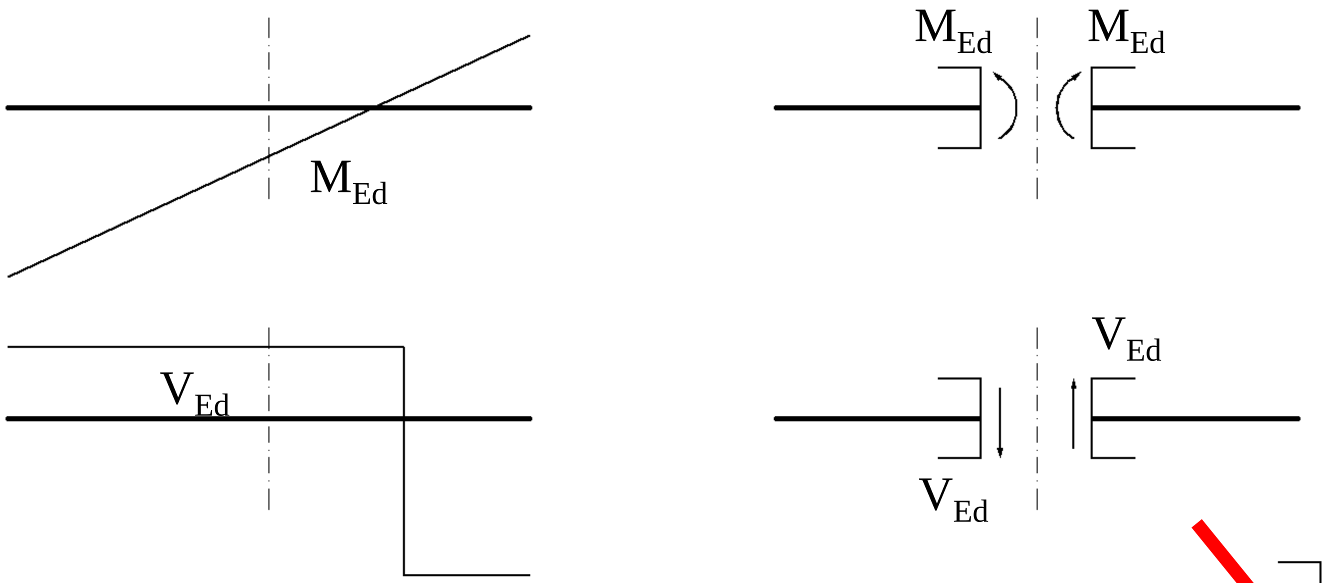
$N_{fp} = 0{,}0$ kN

$N_{wp} = 0{,}0$ kN

$V_{fp} = 0$

$V_{wp} = 162{,}200$ kN

These cross-sectional force act on both parts of joint in the same value



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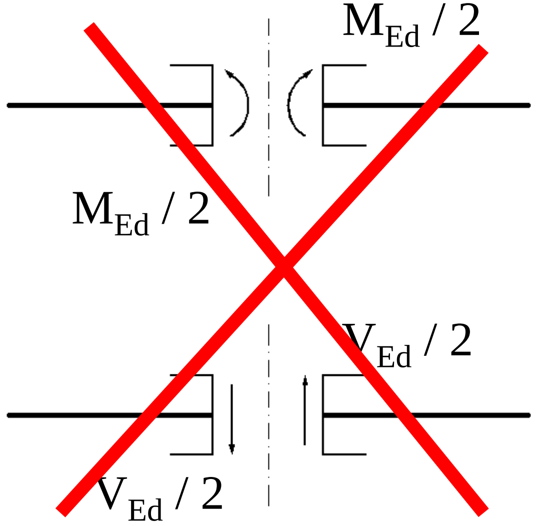


Common mistake: half of values on both patrs on joint

Recalculation from global forces to local forces in plates

Flange plate, in general case: part of global axial force (N_{fp} ; in analysed case = 0) +/- one of couple of forces from bending moment applicated to flange plate (M_{fp});

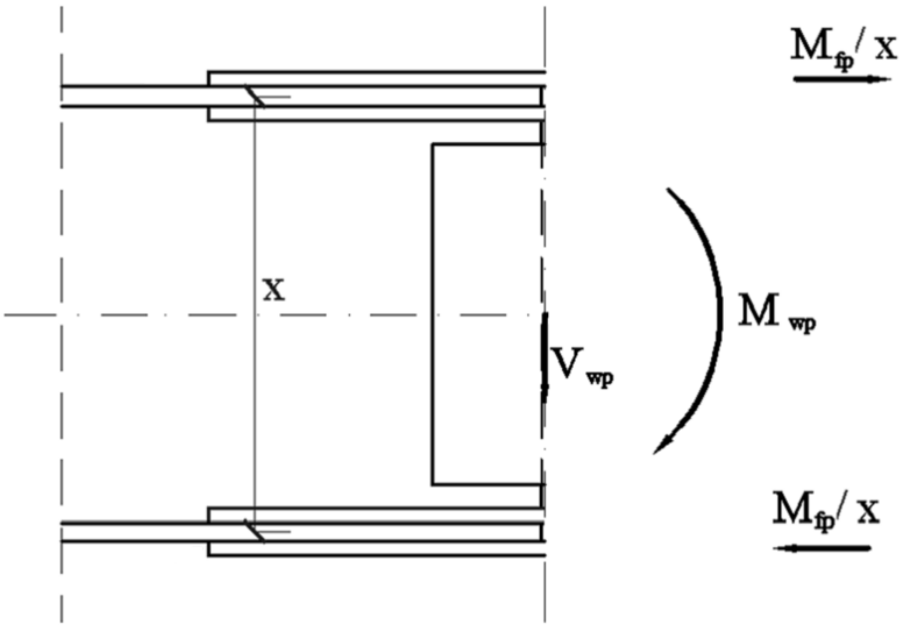


Photo: Author

$x = h - t_f / 2 - t_f / 2 = 588$ mm

$F_{fp} = | M_{fp} | / x = 1037{,}724$ kN

Web plate: part of axian force (N_{wp} ; in analysed case = 0) ; part of bending moment (M_{wp}); total external shear force ($V_{wp} = V_{Ed}$)

Initial checking resistance

Flange plate:

$$F_{fp} / [\ 0{,}8\ (0{,}5\ A_{fp})\ \ f_y\ ] \leq 1{,}0$$

Web plate:

$$\sigma = N_{wp} / (0{,}8\ A_{wp}) + M_{wp} / (0{,}8\ W_{wp,y})$$

$$\tau = V_{wp} / A_{wp}$$

$$[\sqrt{(\sigma^2 + 3\tau^2)}] / f_y \leq 1{,}0$$

0,5 $A_{fp} \rightarrow A_{fp}$ it is area of **both** flange plates (the same: $J_{f,\,y}$ means moment of inertia **both** flanges); here is analysed only **one** flange plate (more stressed);

0,8 $\rightarrow$ initial assumption about netto geometry of plates (cross-section without holes for bolts); phenomenon not important for shear force.

$A_{fp} = 180,0 \text{ cm}^2$

$F_{fp} / [\, 0,8\, (0,5\, A_{fp})\ f_y\,] = 0,613 \leq 1,0$ **OK**

$\sigma = M_{wp} / (0,8\, W_{wp,y})$

$\tau = V_{wp} / A_{wp}$

$W_{wp,y} = 705,6 \text{ cm}^3$

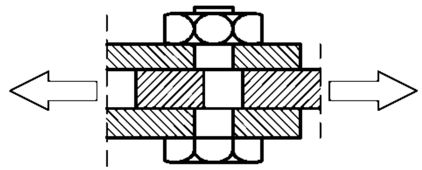
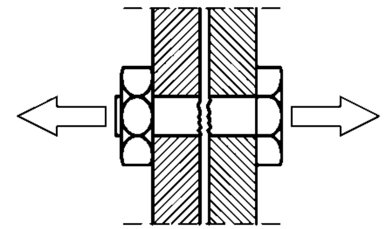
$A_{wp} = 100,8 \text{ cm}^2$

$\sigma = 207,323 \text{ MPa}$

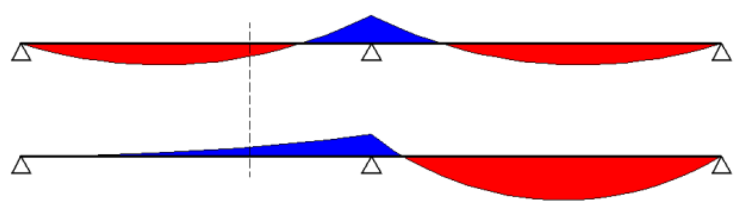
$\tau = 16,091 \text{ MPa}$

$[\sqrt{(\sigma^2 + 3\tau^2)}\,] / f_y = 0,890 \leq 1,0$ **OK**

Categories of bolted joints and loads

					
Categories of bolted joint	A	B	C	D	E
Types of loads	Static without changing the direction of the bending moments; aerodynamic	Static with changing the direction of the bending moments; aerodynamic	Dynamic	Static; aerodynamic	Dynamic
Types of bolts	„normal”	preloaded		„normal”	preloaded

Changing the direction of the bending moment: various combinations of loads



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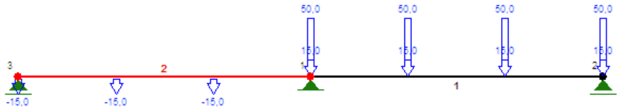
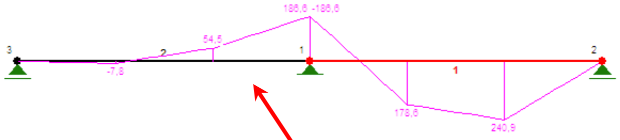
Loads are static only. Various combinations of actions: checking direction of bending moment.

It will be bolted joint category B.





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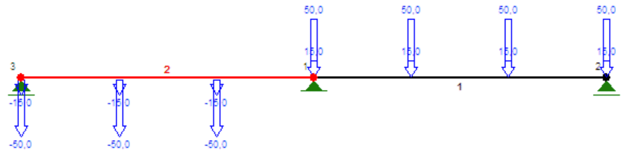
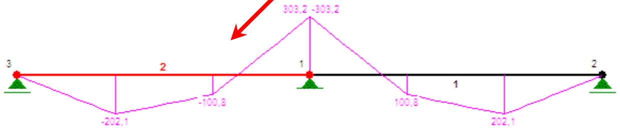
Checking direction of bending moment in joint

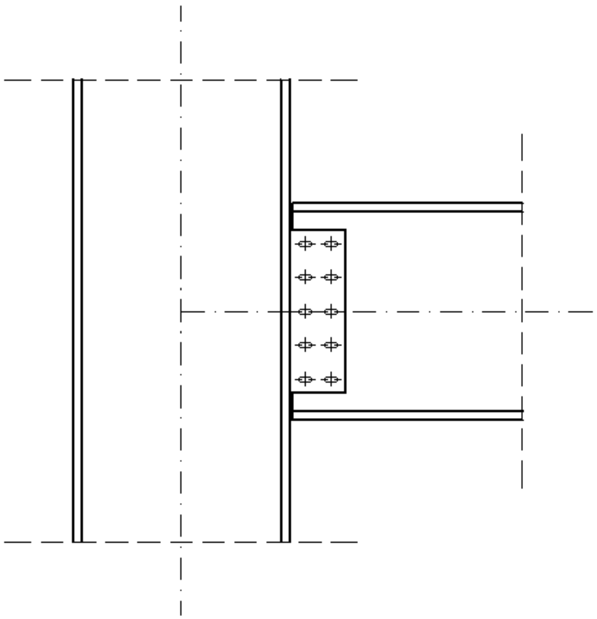




According to results of experiments, we can assume, that there are always pinned joints, if:

→ #14 / 42

- web only is supported;
- for bolts are applied slotted holes.



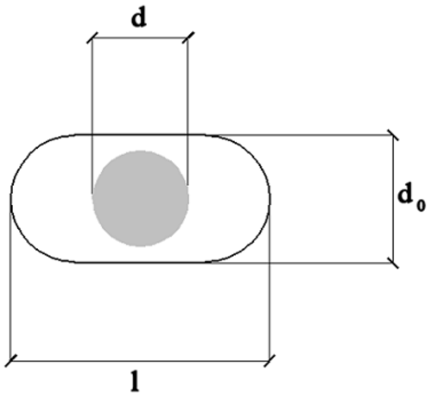


Photo: Author

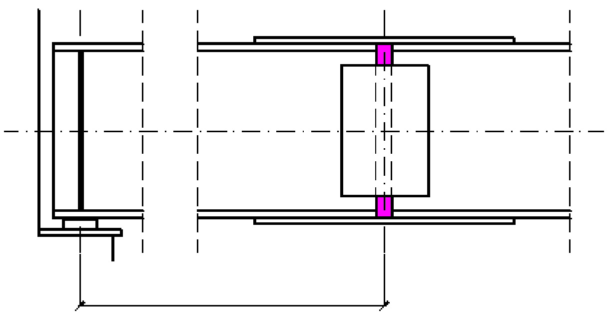
Photo: tekla-detailed-structural-fabrication.com

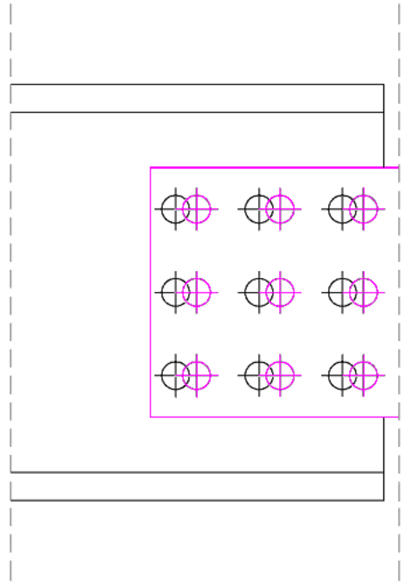
Of course, slotted holes can be used for compensation of imperfection during erection of structures. The technical solutions used at that time are heading towards the development of a rigid joint.

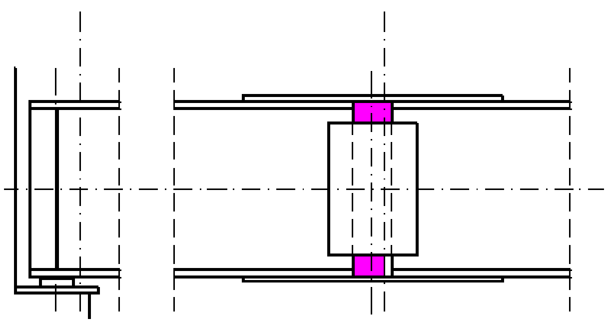
But other solutions allow to get an pinned joint with them.

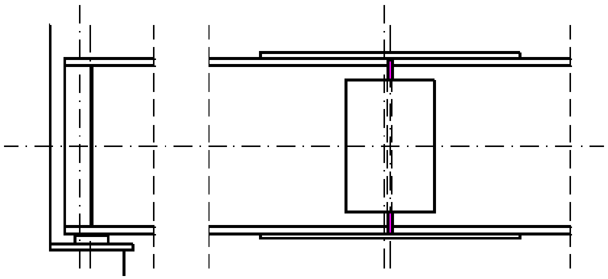
→ #14 / 43

Photo: Author









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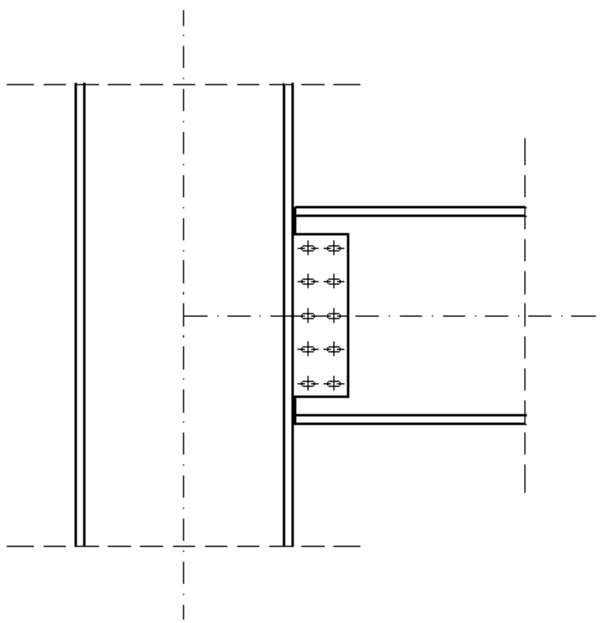
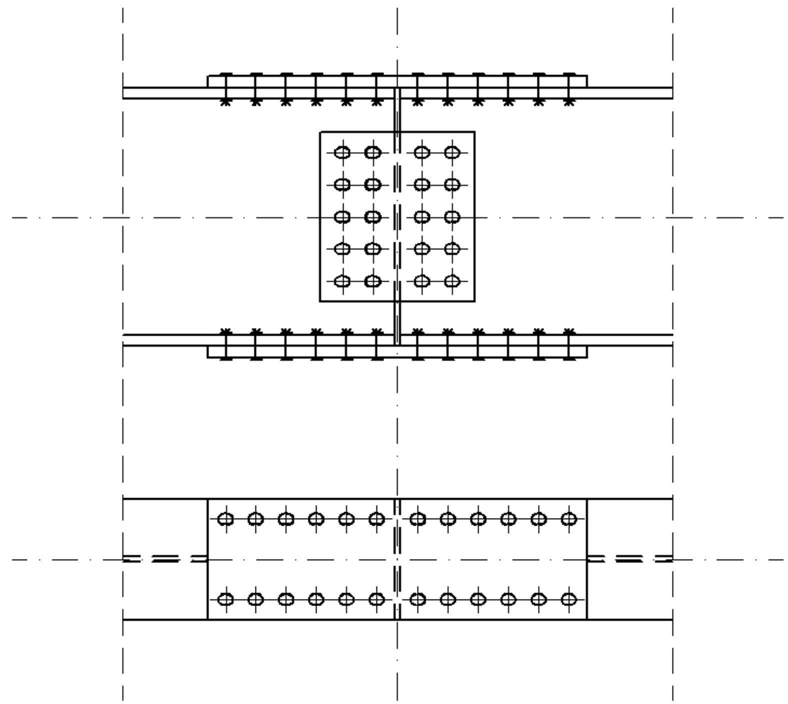
Previous part of calculation (Des #2 Ex #1):
slotted holes applicated to ensure **hinge joint**

At now:
slotted holes in **rigid joint** to avoind problems with imperfections.

Generally: slotted holes can make hinge joint (in bolteg joint **category A**), but after application additional specific technical solution (preloaded bolts, bolted joint **category B or C**) , joint will can be taken into consideration as rigid.





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→ #Des 2 examp 1 / 50

Differences between two diameters: d_0 - d = or l - d = [mm]

Bolts or pins:		M 12, M 14	M16, M 18, M 20, M 22	M 24	M 27, M 30 ...
Fit bolts		0			
Normal round holes		1 (0,5) 2	2 (1,5)		3 (2,5)
Oversize round holes		3	4	6	8
Short slotted holes	d_0	1 2	2		3
	l	4	6	8	10
Long slotted holes	d_0	1 2	2		3
	l	1,5 d			

EN 1090-2 tab 11

(mast, towers)

countersunk bolts

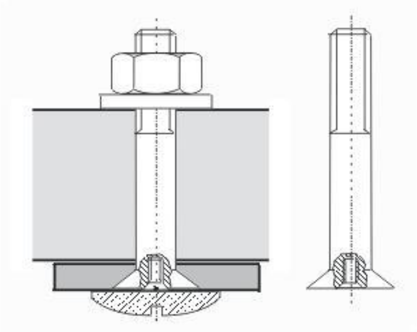


Photo: zeglarstwo.sail-ho.pl

Rivets - nominal hole diameter shall be specified individually in each design project

→ #Des 2 examp 1 / 43

Bolts:

Category	Class	Diameter
A, D	4.6, 4.8	d =16 mm
	5.6, 5.8, 6.8	d = 20 - 24 mm
	8.8, 10.9	d ≥ 24 mm
B	8.8, 10.9	d ≥ 24 mm
C, E		

Symbol:

M16 → d = 16mm

Class: X.Y

$X = f_{ub} / 100 \rightarrow f_{ub} = 100\, X$

$Y = 10\, f_{yb} / f_{ub} \rightarrow f_{yb} = 10\, X\, Y$

Class: 4.8

$f_{ub} = 400$ MPa

$f_{yb} = 320$ MPa

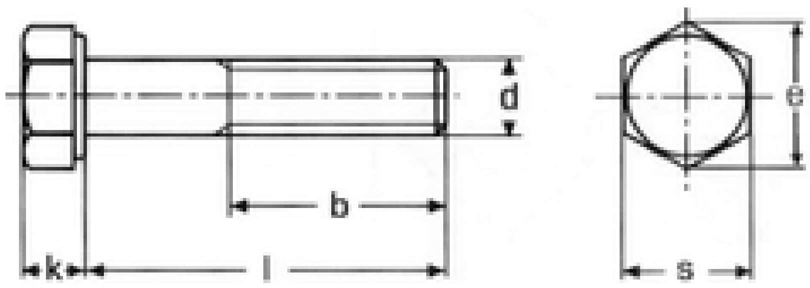


Photo: Author

Bolted joint category B means, that classes 8.8 and 10.9 are recommendend. There will be taken into consideration **class 8.8**.

f_{ub} = 800 MPa

f_{yb} = 640 MPa

For this class, diameter of bolt non smaller than 24 mm is recommended. There will be taken into consideration **bolt M24**

d = 24 mm

A = 4,52 cm^2 (unthreaded portion cross-section)

A_s = 3,53 cm^2 (threadet portion cross-section)

Long slotted holes (for avoiding of imperfections) will be applicated:

d_0 = d + 2 mm = 26 mm

l = 1,5 d = 36 mm

Ideal situation:

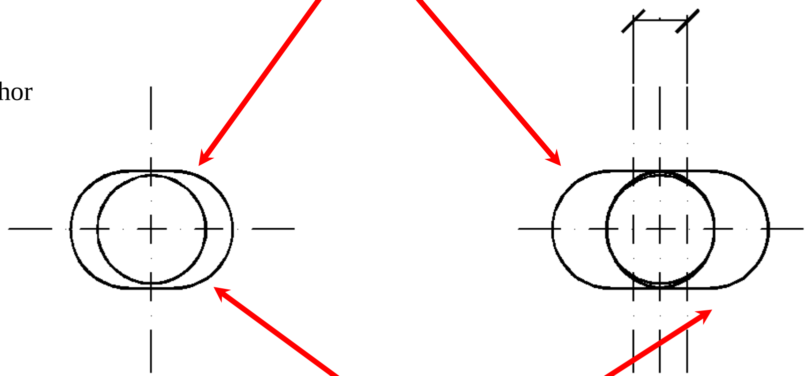
Real situation (impact of imprerfections):

Hole in „bottom element”

max 12 mm

Max distance between edges of holes in „top” and „bottom element” (plate and flange / web of beam)

Photo: Author

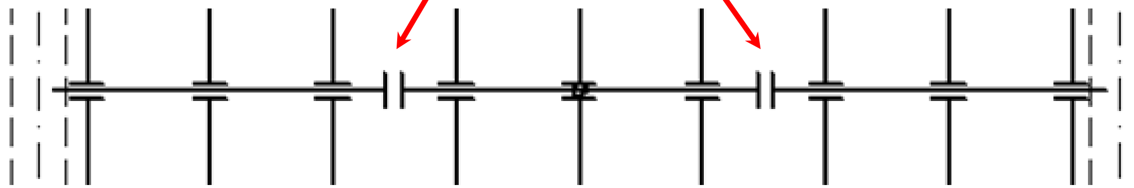


Edges of both holes in the same place

Hole in „top element”

Two joints for construction site, on each 12 mm reserve for imperfections → possibility of compensation of 24 mm imperfection (non-intetional shifts on supports).

Photo: Author



Verification of initial assumptions about bolt: M24, class 8.8 (recommendations):

$1{,}5\ t_{min} \leq d \leq 2{,}5\ t_{min}$

Category A, D: $\Sigma t \leq 5d$

Category B, C, E: $\Sigma t \leq 8d$

$f_{ub} > f_u$

Min. thickness of each elements connected by bolt

Flange - flange plate: $t_{min} = 26$ mm

$1{,}5\ t_{min} = 39\text{ mm} \leq d = 24 \leq 2{,}5\ t_{min} = 65\text{ mm}$

not satisfied

This is recommendation only, not Eurocore requirement. It is possible that it will not be satisfied.

$\Sigma t = 26 + 30 = 56\text{ mm} \leq 8d = 192\text{ mm}$

OK

Web - web plate: t_{min} 12 mm

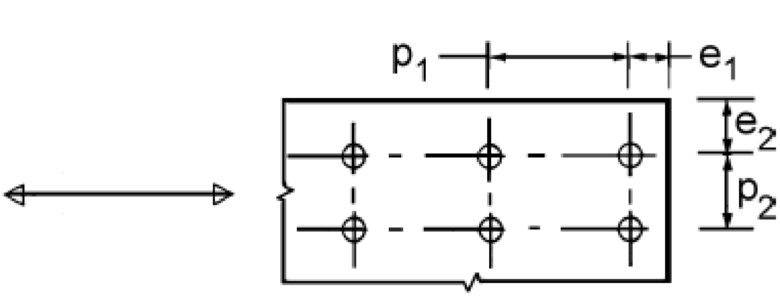
$1{,}5\ t_{min} = 18\text{ mm} \leq d = 24 \leq 2{,}5\ t_{min} = 30\text{ mm}$

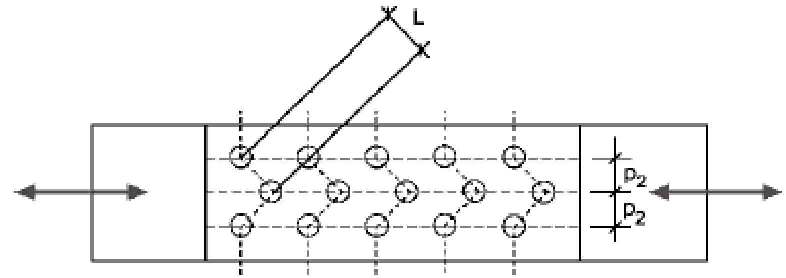
OK

$\Sigma t = 12 + 13{,}5 + 12 = 38\text{ mm} \leq 8d = 192\text{ mm}$

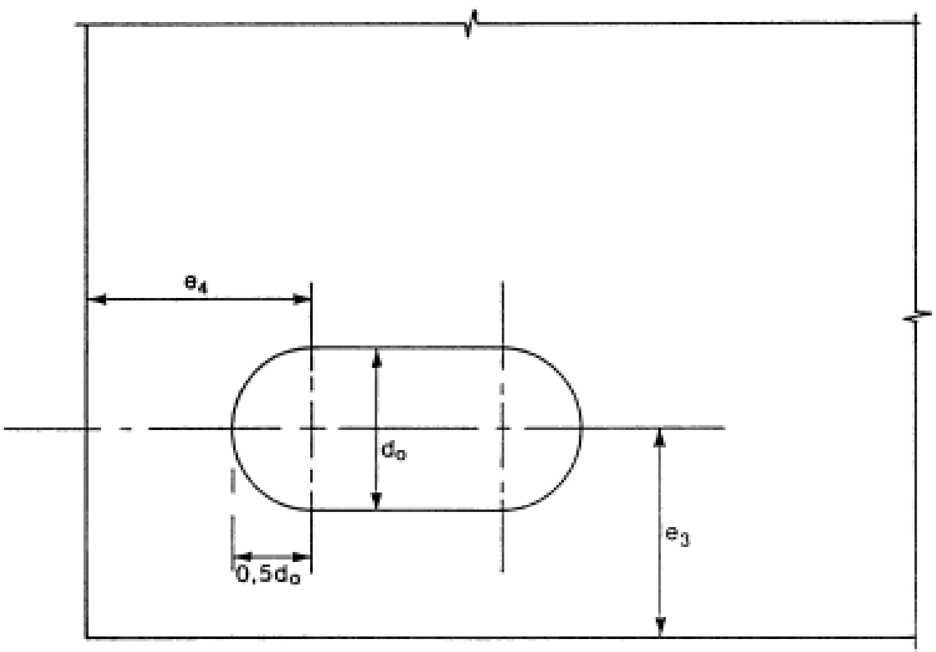
OK

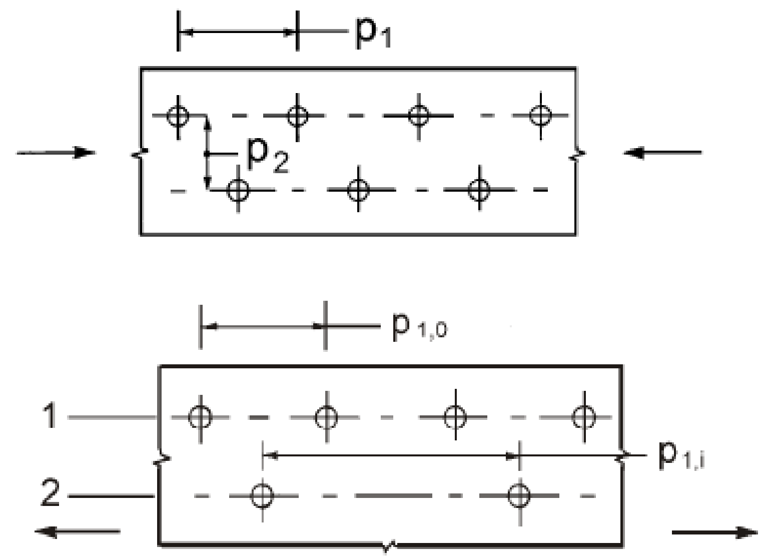
$f_{ub} = 800\text{ MPa} > f_u = 360\text{ MPa}$ **OK**





Distances according to EN 1993-1-8 fig. 3.1





EN 1993-1-8 tab 3.3

Dimensions	Minimum	Maximum		
		„Normal" steels		Stainless steels
		Steel exposed to the weather / corrosion influences	Not exposed	
e_1	$1{,}2\ d_0$	$4\ t_{e,\ min} + 40$ mm		max($8\ t_{e,\ min}$; 125 mm)
e_2	$1{,}2\ d_0$	$4\ t_{e,\ min} + 40$ mm		max($8\ t_{e,\ min}$; 125 mm)
e_3	$1{,}5\ d_0$			
e_4	$1{,}5\ d_0$			
p_1	$2{,}2\ d_0$	min($14\ t_{e,\ min}$; 200 mm)	min($14\ t_{e,\ min}$; 200 mm)	min($14\ t_{min}$; 175 mm)
$p_{1,0}$		min($14\ t_{e,\ min}$; 200 mm)		
$p_{1,i}$		min($14\ t_{e,\ min}$; 200 mm)		
p_2	$2{,}4\ d_0$ ($1{,}2\ d_0$ and $L \geq 2{,}4\ d_0$)	min($14\ t_{e,\ min}$; 200 mm)	min($14\ t_{e,\ min}$; 200 mm)	min($14\ t_{min}$; 175 mm)

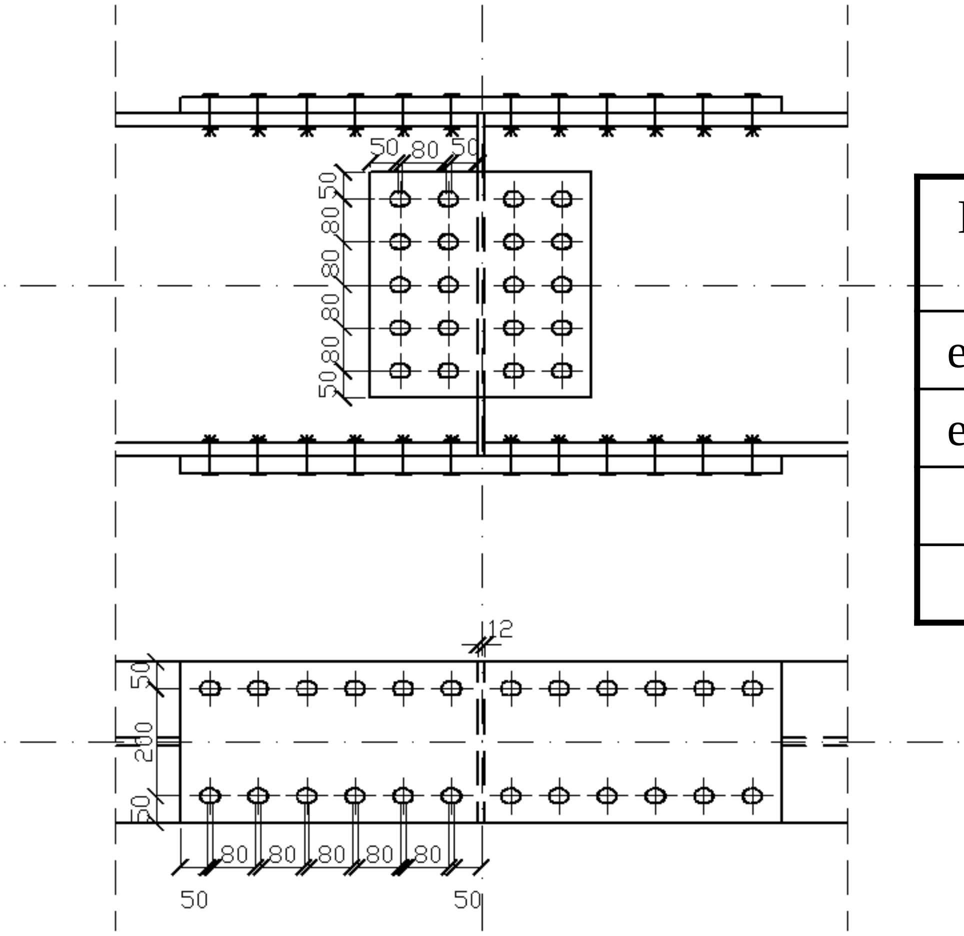


Photo: Author

Flange:

One direction of external force only

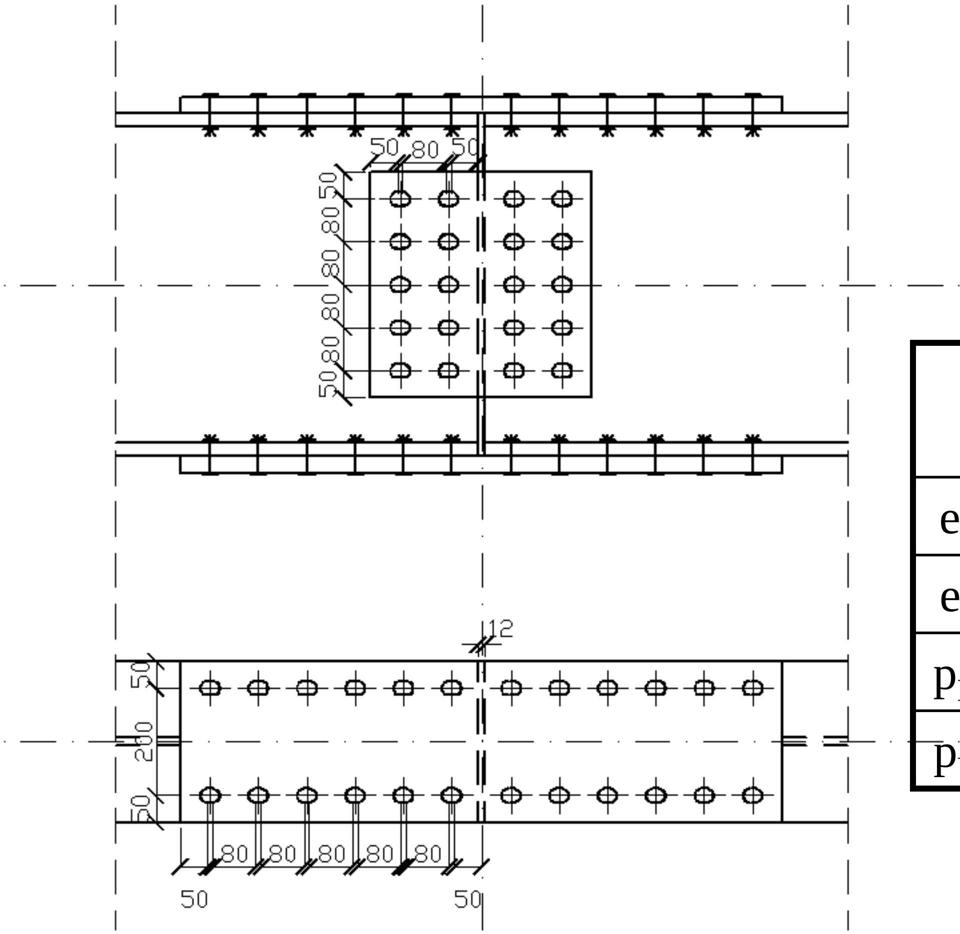
Dim.	min [mm]	max [mm]	real [mm]	Concl.
e_1 (e_4)	36	144	50	OK
e_2 (e_3)	36	144	50	OK
p_1	56	200	80	OK
p_2	62	200	200	OK

In case of compressive axial force:

$p_1 / t < 9\varepsilon$

ε (S235) = 1,0 ; t = 30 mm

80 / 30 = 2,667 < 9 OK



Web:

Two directions of external forces

Dim.	min [mm]	max [mm]	real [mm]	Concl.
e_H (e_1 ; e_4)	36	144	50	OK
e_V (e_2 ; e_3)	36	144	50	OK
p_H (p_1 ; p_2)	56	200	80	OK
p_V (p_2 ; p_2)	56	200	80	OK

Photo: Author

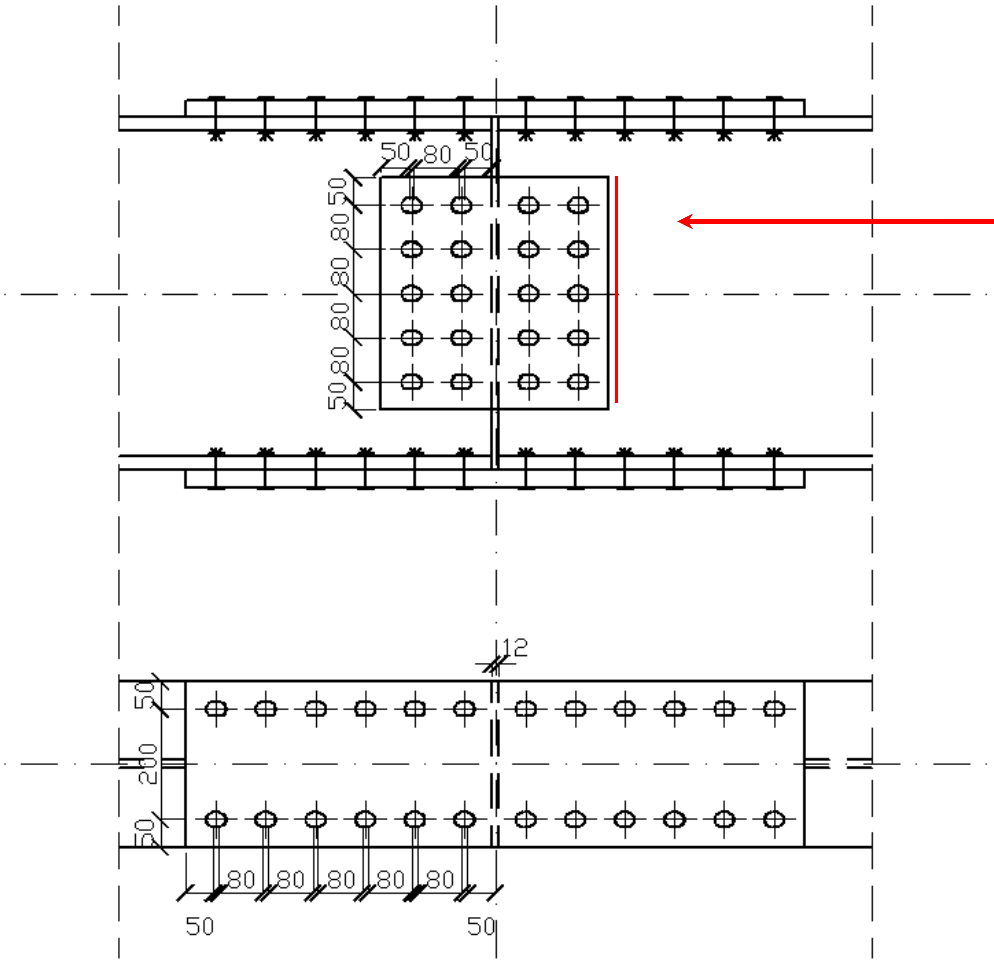


Photo: Author

Common mistake in student projects:

initially assumed height of web plate

$$h_{wp} \approx 0{,}8\ h_w$$

is different from the final adopted height

$$2 \cdot e + n \cdot p$$

It must be one and the same value:

$$h_{wp} \approx 0{,}8\ h_w \approx 420\ \text{mm}$$

$$50 + 4 \cdot 80 + 50 = 420\ \text{mm}$$

Additional limit: enough space on flange

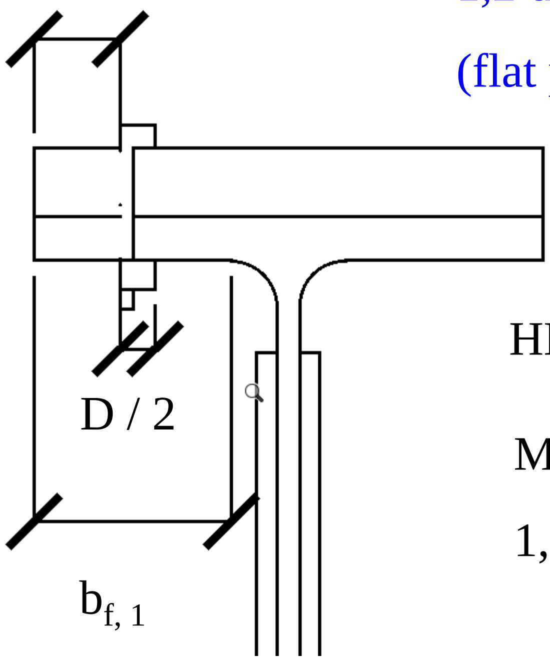


Photo: Author

$1{,}2\ d_0 + D / 2 + 5\ \text{mm} \leq b_{f,\,1}$

(flat part of flange)

HEA 650: $b_{f,\,1} = (300 - 2 \cdot 27 - 13{,}5) / 2 = 116\ \text{mm}$

M24: $1{,}2\ d_0 = 31{,}2\ \text{mm}$; $D / 2 = 20{,}8\ \text{mm}$

$1{,}2\ d_0 + D / 2 + 5\ \text{mm} = 57\ \text{mm} \leq b_{f,\,1}$ **OK**

Otherwise, we risk that nut will get stuck on rounded part between web and flange and we will not be able to tighten bolt.

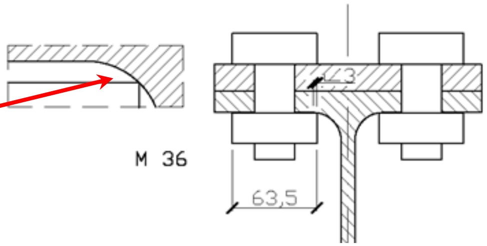
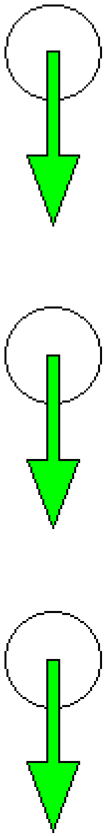


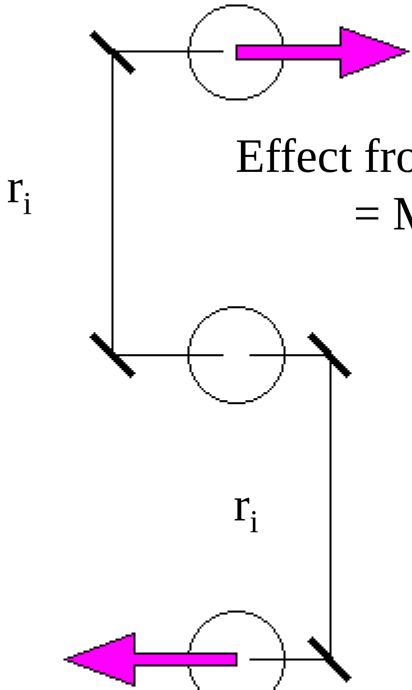
Photo: Author

Distribution of forces:

Effect from bending moment: always perpendicular to arm r between **center of bolts group** and analised bolt.

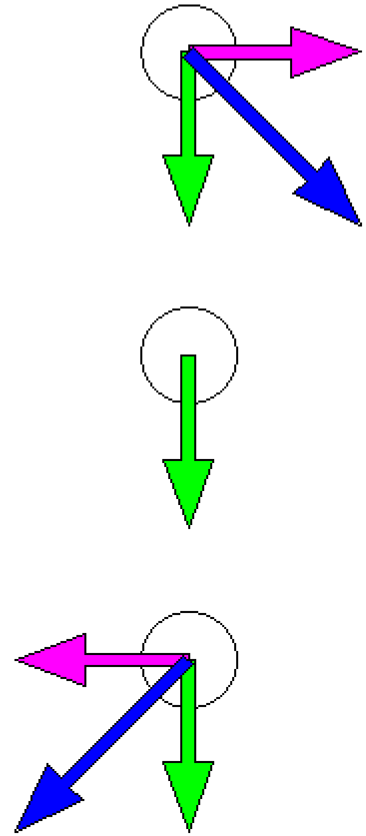
Photo: Author





Effect from bending moment =
$= M_{Ed} \cdot r_i / \Sigma [(r_i)^2]$

$\Sigma [(r_i)^2] \neq [\Sigma (r_i)]^2$



Resultants

Vertical force per one bolt =
= total force / number of bolts

→ Des #2 examp 1 / 55

Distribution of forces, flange

Force in bolt = Force in flange / number of bolts on one side of joint

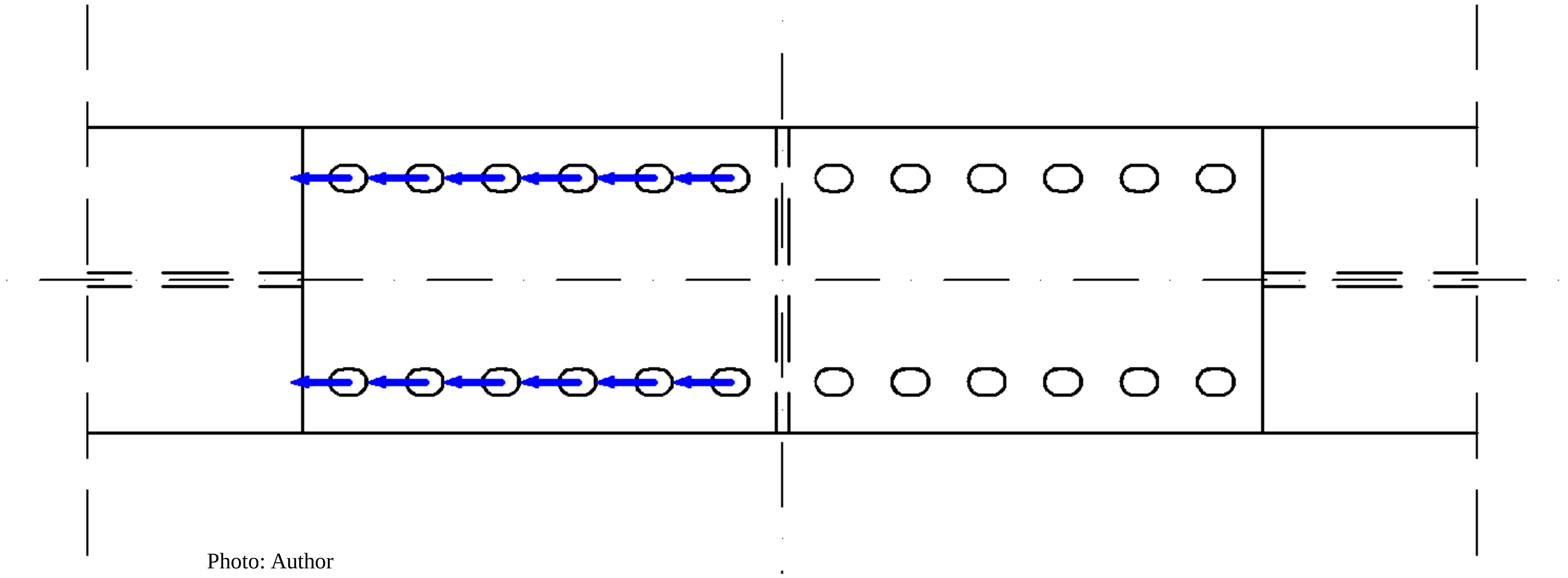


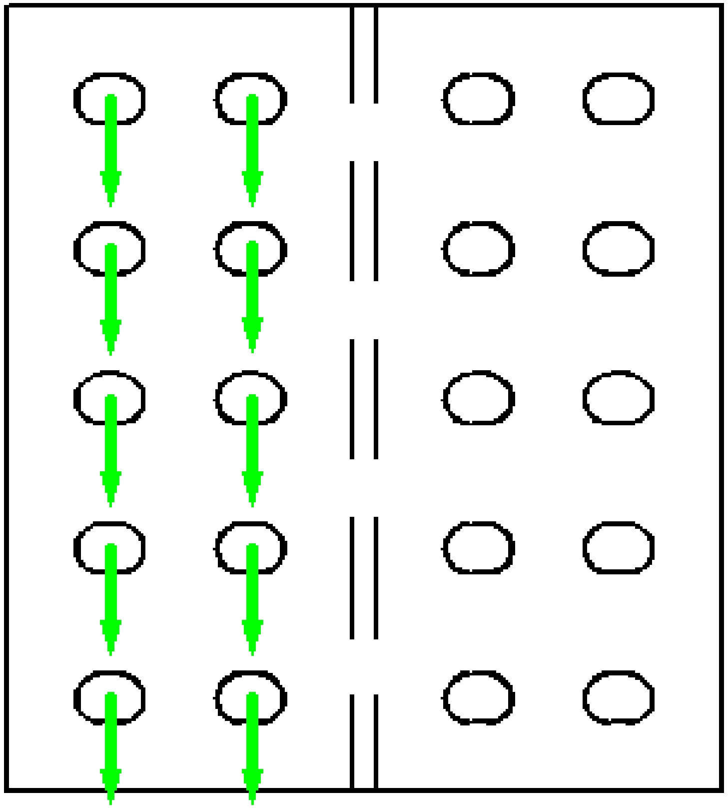
Photo: Author

$$F_{bf} = 1037{,}724\ kN / 12 = 86{,}477\ kN$$

Distribution of forces, web

First force in bolt = Shear force in web / number of bolts on one side of joint

Photo: Author



F_{bf} = 162,200 kN / 10 = 16,220 kN

Distribution of forces, web

Second force in bolt = $M_{Ed} \cdot r_i / \Sigma [(r_i)^2]$

$\Sigma [(r_i)^2] \neq [\Sigma (r_i)]^2$

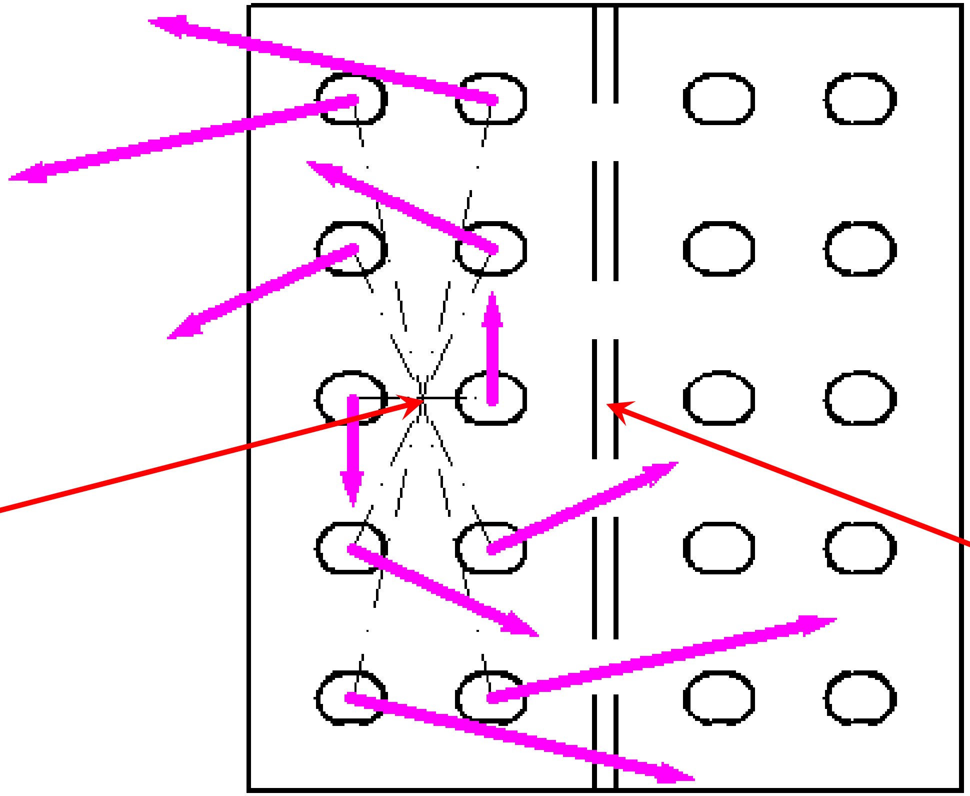


Photo: Author

Centre of gravity for **group of bolts on one side of joint**

Common mistake in student projects:

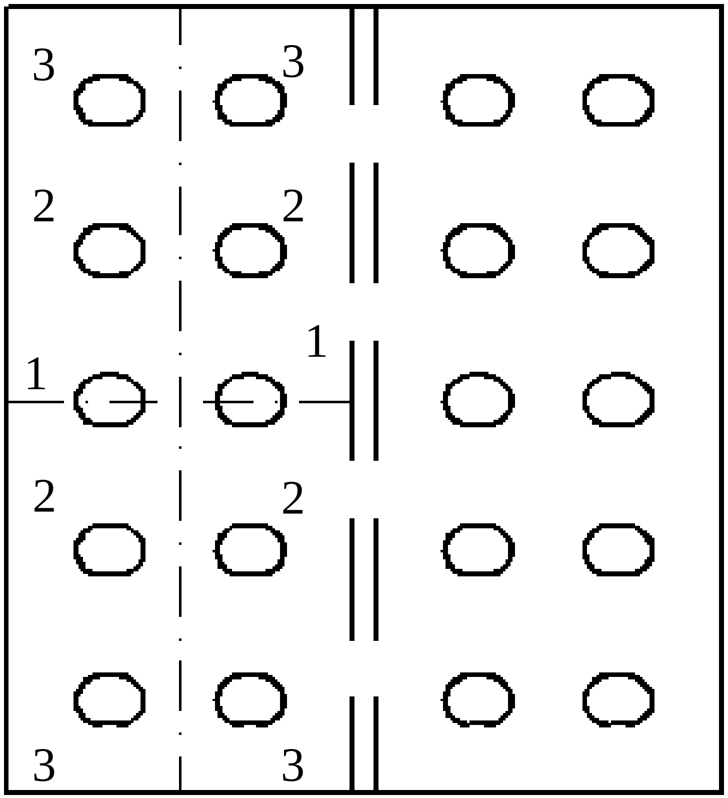
Centre of gravity of total joint, not group of bolts, is taken into consideration

Effect of bending moment is in proportion to length of arm and perpendicular to arm

Distribution of forces, web

Because of horizontal and vertical axes of symmetry, only three bolts will be analysed

Photo: Author



$r_1 = 37{,}5 \text{ mm} = 0{,}0375 \text{ m}$

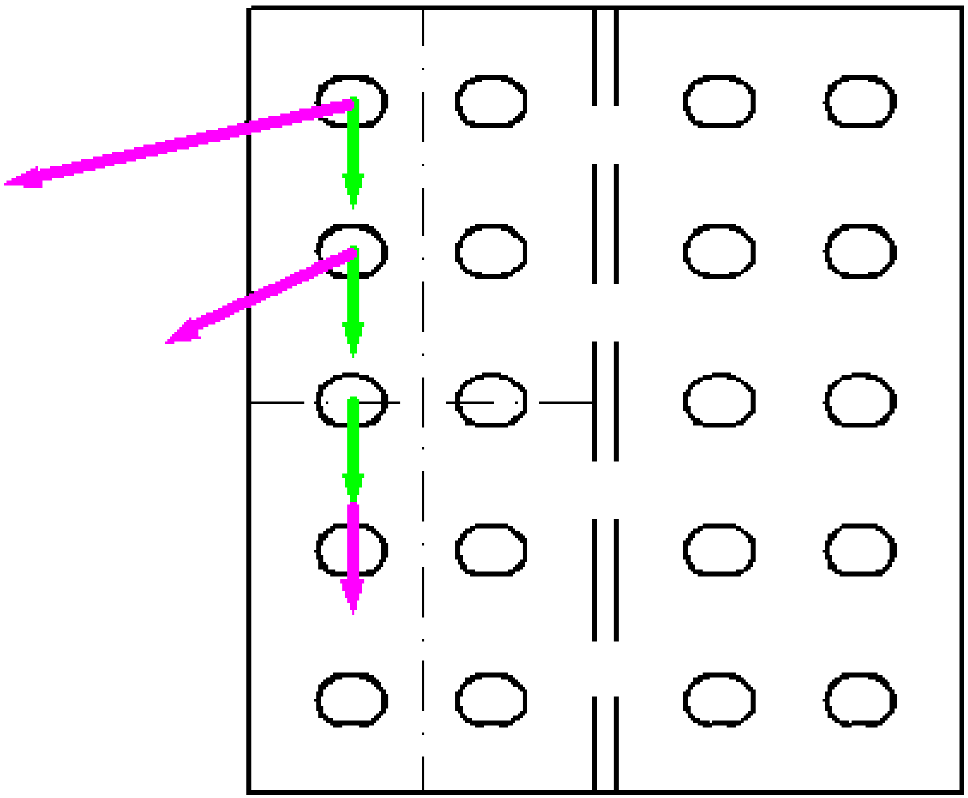
$r_2 = 88{,}4 \text{ mm} = 0{,}0884 \text{ m}$

$r_3 = 164{,}3 \text{ mm} = 0{,}1643 \text{ m}$

$\Sigma\, [(r_i)^2] = 2\,(r_1)^2 + 4\,(r_2)^2 + 4\,(r_3)^2 = 0{,}142 \text{ m}^2$

Distribution of forces, web

Photo: Author



Common effect from shear force and bending moment (example for three bolts).

For each bolt: sum of these forces will be converted into two components, horizontal and vertical.

Distribution of forces, web

Bolt	Part from shear force (vertical) [kN]	Vertical part ftom bending moment [kN]	Horizontal part ftom bending moment [kN]	Σ V [kN]	Σ H [kN]	Product [kN]
1	16,220	30,906	0,000	47,126	0,000	47,126
2	16,220	30,906	65,975	47,126	65,975	81,077
3	16,220	30,906	131,835	47,126	131,835	140,005

Stiffness of joint

According to #15 / 69-70, shear bolted joint with bolts category B or C, can be treated as rigid joint. This means, that real behaviou of joint is the same as in initial assumption (rigid joint). Each formulas from Eurocode can be applicated without any changes, that would result from behavior of semi-rigid joint.

Resistance of bolted joint cathegory B: six mechanisms of destruction:

Shear resistance

Photo: ceprofs.civil.tamu.edu

Bearing resistance

(local deformation of plate)

Photo: ascelibrary.org

Block tearing (total destruction of plate)

Photo: quora.com

Netto area (other type of total destruction of plate)

Photo: quora.com

Slip-resistant (too small friction between elements)

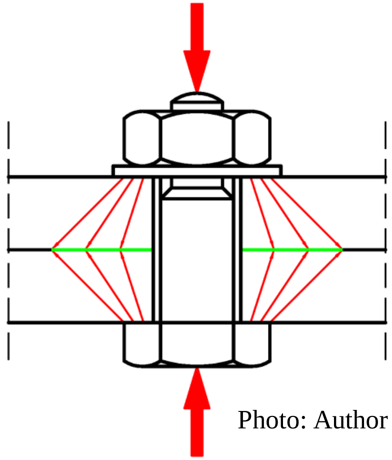


Photo: Author

Punching resistance (local destruction of plate)

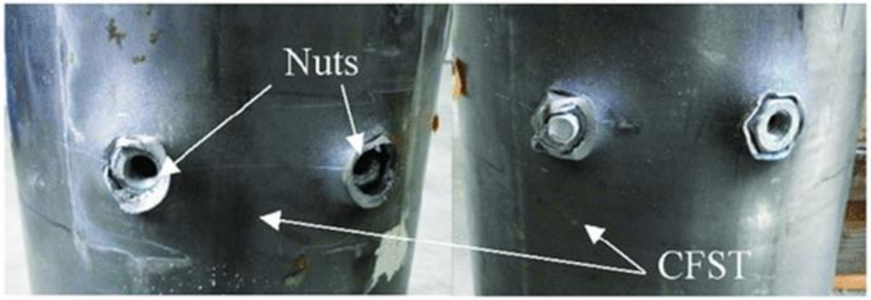


Photo: Moment Resisting Connection with Curved Endplates: Behaviour Study, A. Mudrow & all

Loads:

Shear resistance

Photo: ceprofs.civil.tamu.edu

Total force applicated to one bolt:

Flange bolt: 86,477 kN

Web bolt :

First bolt: 47,126 kN

Second bolt: 81,077 kN

Third bolt: 140,005 kN

Bearing resistance

Photo: ascelibrary.org

Two perpendicular force, separately in the first and second directions:

Flange plate (one direction ol load only): 86,477 kN

Web plate:

Around first bolt: 47,126 kN ; 0,000 kN

Around second bolt: 47,126 kN ; 65,975 kN

Around third bolt: 47,124 kN ; 131,835 kN

Loads:

Slip-resistant:

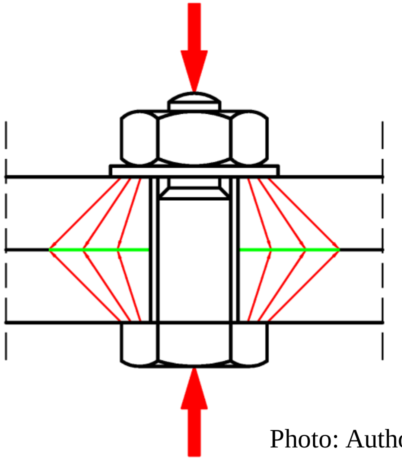


Photo: Author

Punching resistance

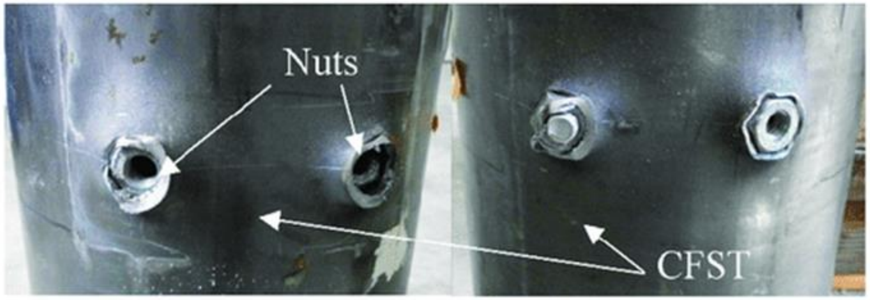


Photo: Moment Resisting Connection with Curved Endplates: Behaviour Study, A. Mudrow & all

Total force applicated to one bolt, but for category B **in characteristic values**:

Flange bolt: 57,985 kN

Web bolt :

First bolt: 32,234 kN

Second bolt: 55,457 kN

Third bolt: 95,763 kN

Caracteristic values → #t / 39

Value of preloading force needed to obtain friction (results from resistance in case of slip-resist)

For category B **in characteristic values**:

Cross-sectional forces comes from loads:

$g_k = 3,53\ kN / m^2$

$g_d = 1,35 \cdot 3,53 = 4,776\ kN / m^2$

$q_k = 10,00\ kN / m^2$

$q_d = 1,5 \cdot 10,00 = 15,00\ kN / m^2$

$g_k + q_k = 13,53$

$g_d + q_d = 19,776$

$k / d = 13,53 / 19,776 = 0,684$

Cross-sectional forces in characteristic values could be taken as 68,4% of its design values.

Loads:

Netto area

Photo: quora.com

Similar phenomena. The only difference is shape of break line and type of load (straight or almost-straight line and many loads for netto area; straight or broken line and one force for block tearing)

Block tearing

Photo: quora.com

In both cases total loads, applicated to member

Member	Netto area	Block tearing (phenomenon calculated for one direction of force only)
Flange plate	1037,724 kN	
Web plate	117,030 kNm and 162,200 kN	Many various loads, not taking into consideration
I-beam	727,800 kNm and 162,200 kN	

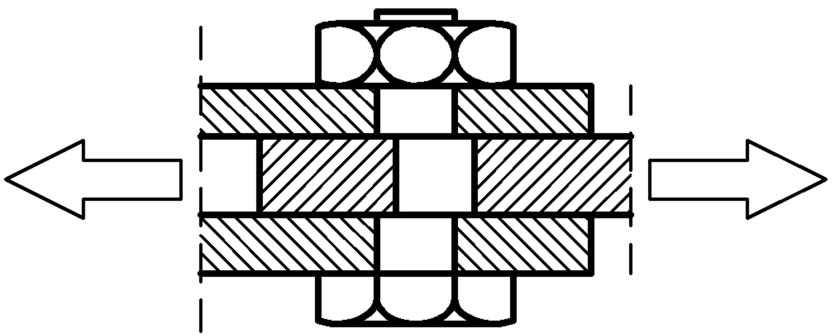
Shear resistance: destruction of shank of bolt

$F_{V,Rd} = n \, \alpha_v \, f_{ub} \, A_b / \gamma_{M2}$ EN 1993-1-8 tab 3.4

$\gamma_{M2} = 1{,}25$

→ Des #2 examp 1 / 66

Photo: Author



A_b - area of unthreaded portion of bolt A, or threaded portion of bolt A_s

n - numer of shear planes (in analised case n = 1, between web of IPE 300 and vertical stiffener)

α_V :

$A_b = A_s$		$A_b = A$
4.6 5.6 8.8	4.8 5.8 6.8 10.9	
0,6	0,5	0,6

EN 1993-1-8 tab. 3.4

Recommendation type of bolt for category B: type HV with a thread along part of shank length according to EN 14 399-4

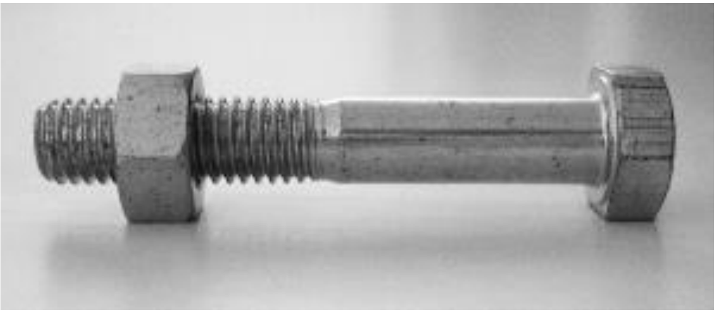


Photo: wikipedia

Photo: fxaball.co.uk

Categories B: two washers, under cup and nut

Flange-flange plate: two possible bolt positions, "up" and "down".

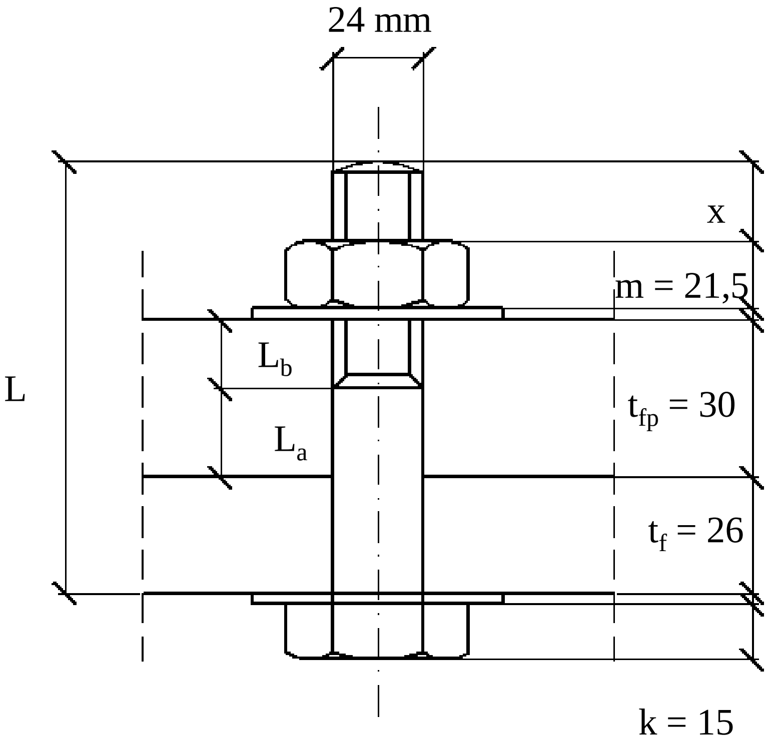
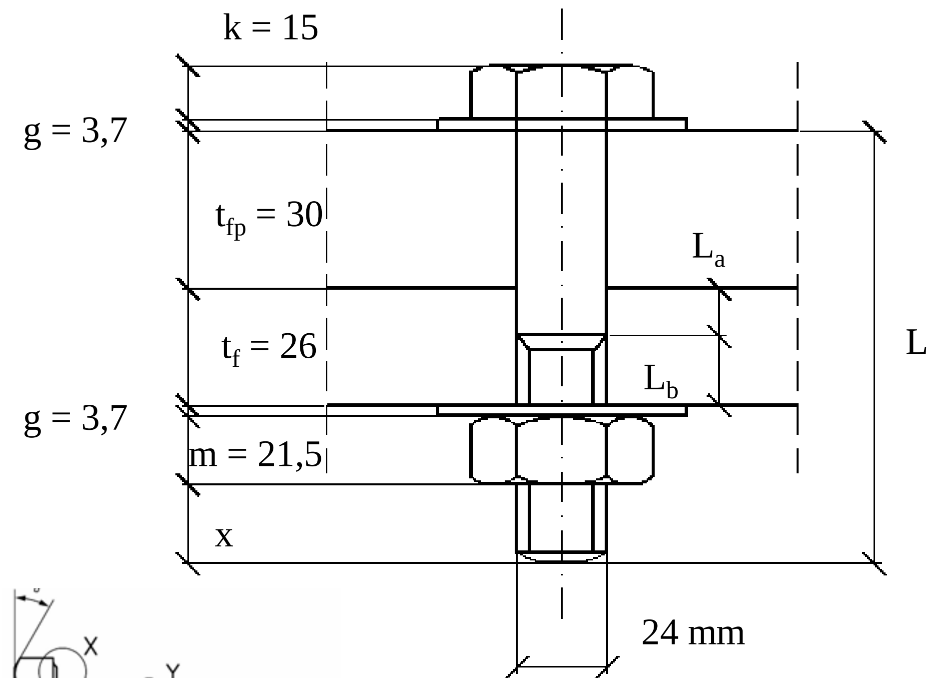


Photo: Author



$$4P = 12\text{ mm} \leq x \leq d = 24\text{ mm}$$

$$L_a \geq 2/3 \max (t_{fp} \;\; ; \;\; t_f) = 20\text{ mm}$$

$$L_b \geq 4P = 12\text{ mm}$$

$$L = x + m + g + t_f + t_{fp} + g = 97 - 109$$

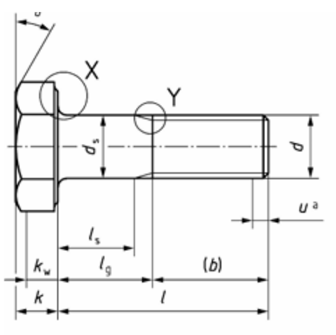


Photo: EN 14 399-4 fig. 1

$$l_s \geq \max (t_f + 2/3\, t_{fp} \;\; ; \;\; 2/3\, t_f + t_{fp}) = 48\text{ mm}$$

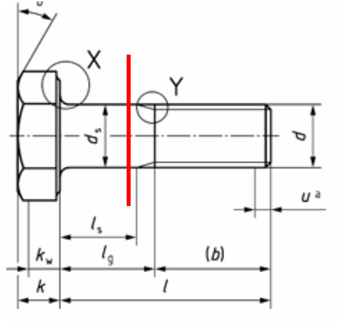


Photo: EN 14 399-4 fig. 1

Photo: EN 14 399-4 tab. 1

Thread (d)			M12		M16		M20		M22		M24		M27		M30		M36	
l			l_s and l_g [c]															
			l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g
nom.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
35	33,75	36,25	6,75	12														
85	83,25	86,75	56,75	62	51	57	44,5	52	43,5	51	37	46	35	44	30,5	41	21	33
90	88,25	91,75	61,75	67	56	62	49,5	57	48,5	56	42	51	40	49	35,5	46	26	38
95	93,25	96,75	66,75	72	61	67	54,5	62	53,5	61	47	56	45	54	40,5	51	31	43
100	98,25	101,75			66	72	59,5	67	58,5	66	52	61	50	59	45,5	56	36	48
105	103,25	106,75			71	77	64,5	72	63,5	71	57	66	55	64	50,5	61	41	53

Shear plane goes through unthreated part of bolt. $A = 4{,}52\ cm^2$

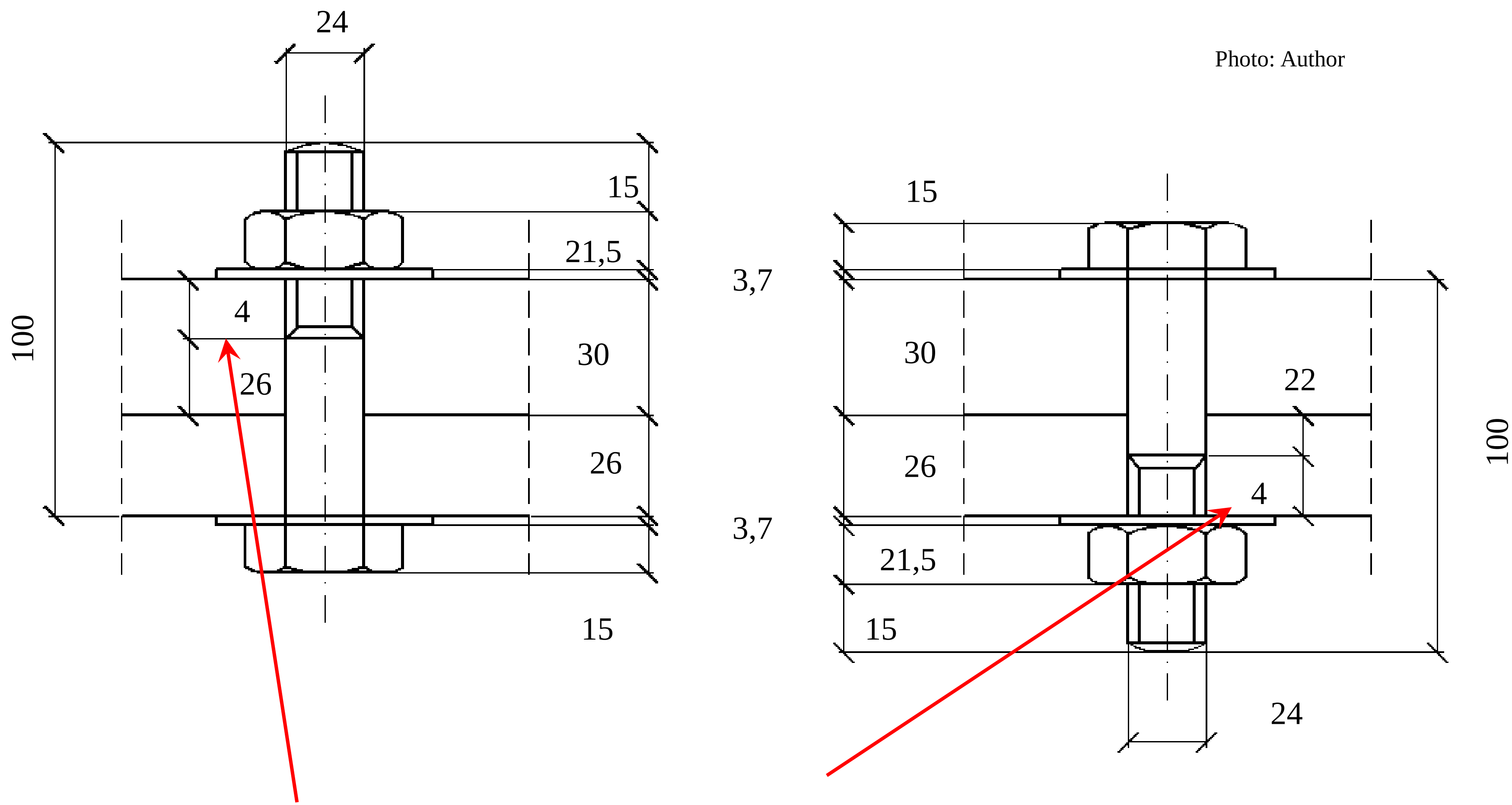


Photo: Author

Does not meet recommendation > 4P = 12 mm, but the rest is correct; accepted.

Web - web plate: one possible bolt positions

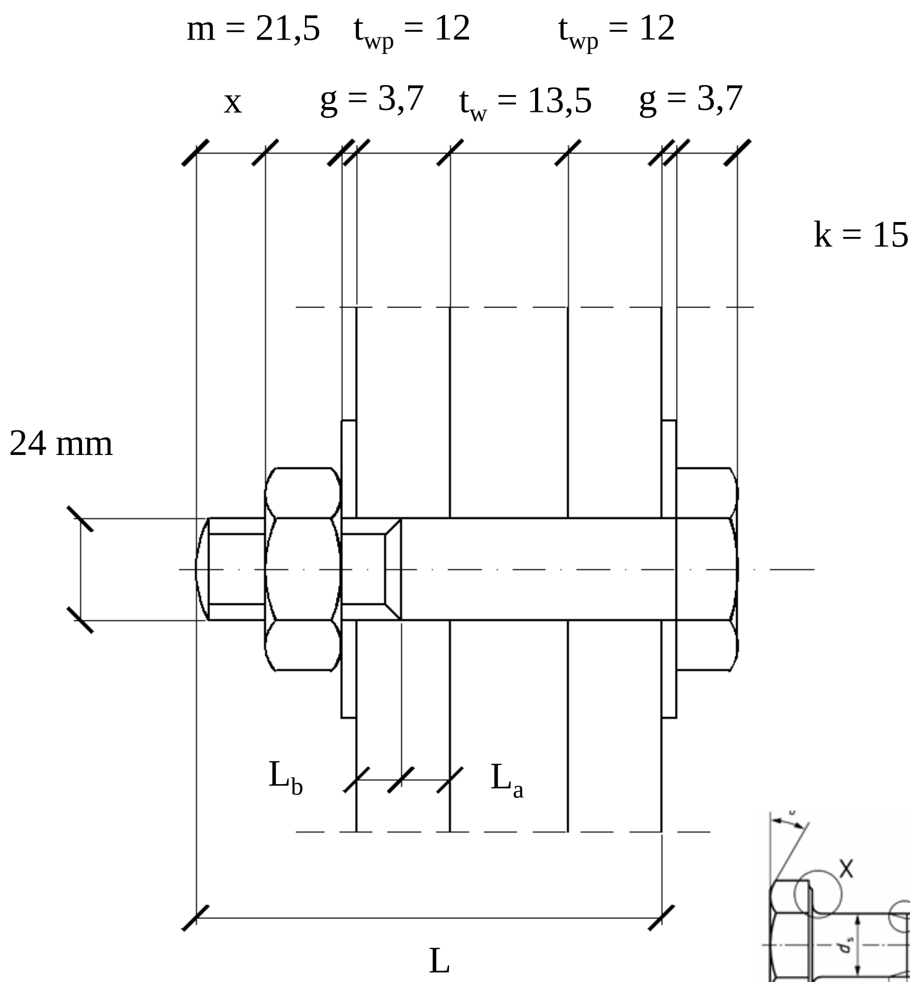


Photo: Author

$$4P = 12 \text{ mm} \leq x \leq d = 24 \text{ mm}$$

$$L_a \geq 2/3\ t_{wp} = 8 \text{ mm}$$

$$L_b \geq 4P = 12 \text{ mm}$$

$$L = x + m + g + t_{wp} + t_w + t_{wp} + g = 78 - 90$$

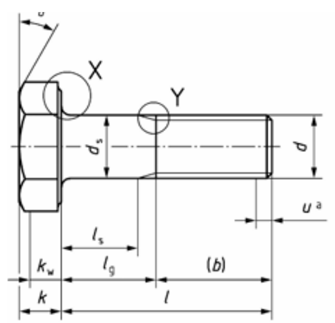


Photo: EN 14 399-4 fig. 1

$$l_s \geq 2/3\ t_{wp} + t_w + t_{wp} = 34$$

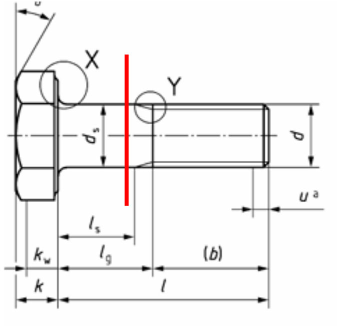


Photo: EN 14 399-4 fig. 1

Photo: EN 14 399-4 tab. 1

Thread (d)			M12		M16		M20		M22		M24		M27		M30		M36	
l			l_s and l_g															
			l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g	l_s	l_g
nom.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.	min.	max.
75	73,5	76,5	46,75	52	41	47	34,5	42	33,5	41	27	36	25	34	20,5	31		
80	78,5	81,5	51,75	57	46	52	39,5	47	38,5	46	32	41	30	39	25,5	36		
85	83,25	86,75	56,75	62	51	57	44,5	52	43,5	51	37	46	35	44	30,5	41	21	33
90	88,25	91,75	61,75	67	56	62	49,5	57	48,5	56	42	51	40	49	35,5	46	26	38

Shear plane goes through unthreated part of bolt. A = 4,52 cm^2

Web - web plate: one possible bolt positions

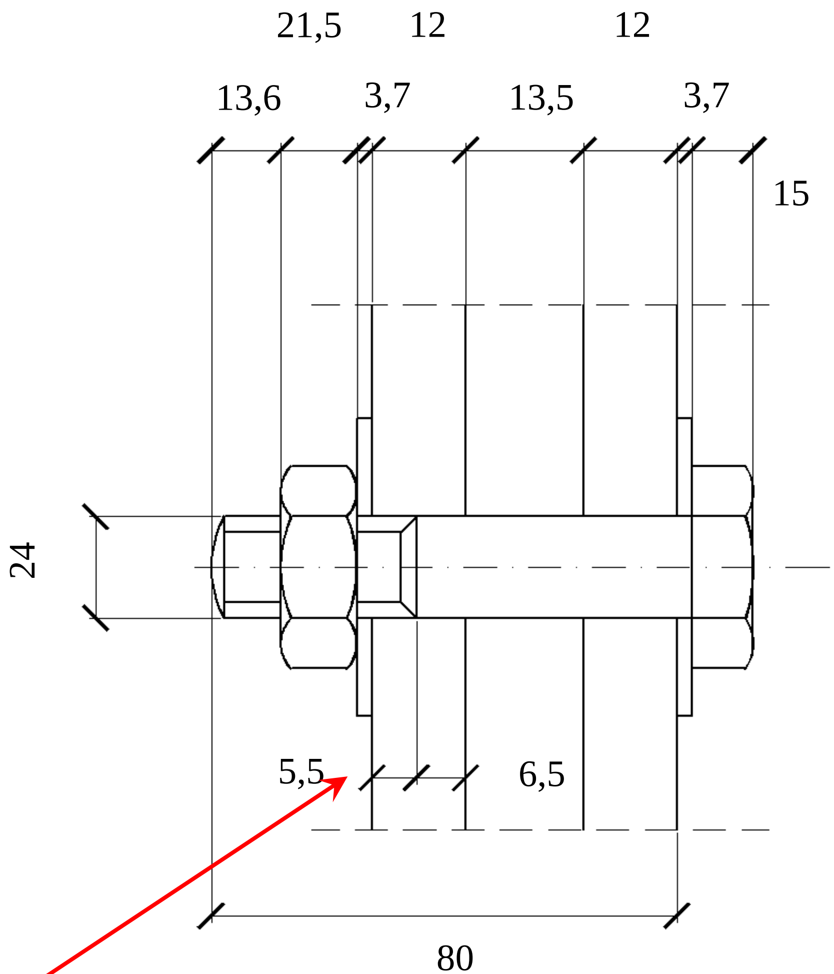


Photo: Author

Does not meet recommendation > 4P = 12 mm, but the rest is correct; accepted.

d/l	M 12	M 16	M 20	M 22	M 24	M 27	M 30	M 36
30	48							
35	52							
40	56	105						
45	59	113	180					
50	64	121	194	249				
55	68	129	207	264				
60	72	137	219	279	353			
65	77	145	232	294	371			
70	81	153	244	309	389	519		
75	86	157	257	324	407	542	695	
80	90	165	269	339	425	564	723	
85	95	173	282	354	443	587	751	1186
90	99	181	288	363	449	609	779	1226
95	104	189	301	378	467	632	807	1266
100		197	313	393	485	645	832	1303
105		205	326	408	503	666	860	1343
110		213	338	423	521	687	888	1383
115		221	351	438	539	708	916	1423

Photo: euro-met.pl

Web – web plate unit mass 425 kg / 1000 pcs

Flange – flange plate unit mass 485 kg / 1000 pcs

Flange (n = 1, between flange plate and flange):

$F_{V,Rd} = n\ \alpha_v\ f_{ub}\ A_b\ /\ \gamma_{M2} = 1 \cdot 0{,}6 \cdot 800\ \text{MPa} \cdot 4{,}52\ \text{cm}^2\ /\ 1{,}25 = 173{,}568\ \text{kN}$

Web (n = 2, between „left" web plate and web + between web and „right" web plate):

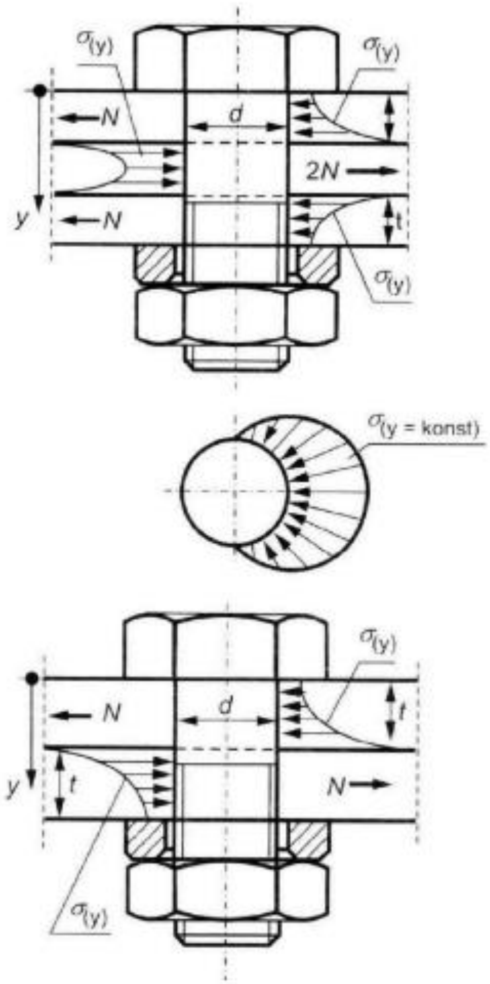
$F_{V,Rd} = n\ \alpha_v\ f_{ub}\ A_b\ /\ \gamma_{M2} = 2 \cdot 0{,}6 \cdot 800\ \text{MPa} \cdot 4{,}52\ \text{cm}^2\ /\ 1{,}25 = 347{,}136\ \text{kN}$

Flange:

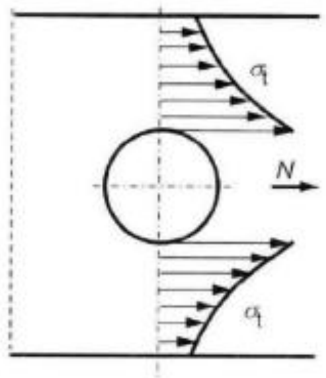
86,477 / 173,568 = 0,498 < 1,0 **OK**

Web (the most effort):

140,005 / 347,136 = 0,403 < 1,0 **OK**



Bearing resistance



Deformation or destruction of plates as the effect of contact with shank of bolt.

Photo: A. Biegus, Projektowanie konstrukcji stalowych według Eurokodów, Politechnika Wrocławska

→ Des #2 examp 1 / 68

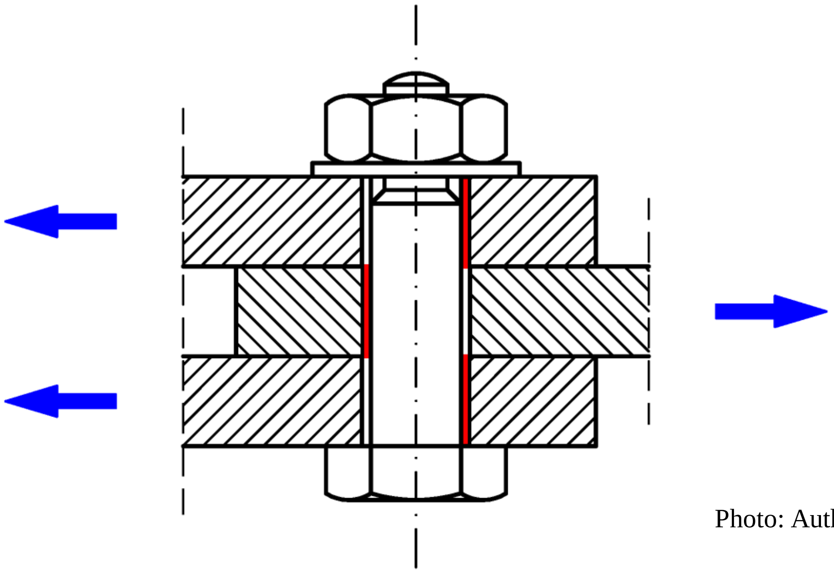


Photo: Author

→ Des #2 examp 1 / 70

$$F_{b,Rd} = \beta_b \, k_1 \, \alpha_b \, f_u \, d \, t_{min} / \gamma_{M2}$$

EN 1993-1-8 tab 3.4, red part is given in bottom part of table.

β_b – parameter of shape of hole → Des#2Ex#1 / 71

k_1 – parameter for phenomenons in direction perpendicular ⊥ to force → Des#2Ex#1 / 72

α_b – parameter for phenomenons in direction parallel ‖ to force → Des#2Ex#1 / 71, 72

f_u – ultimate strength of plate

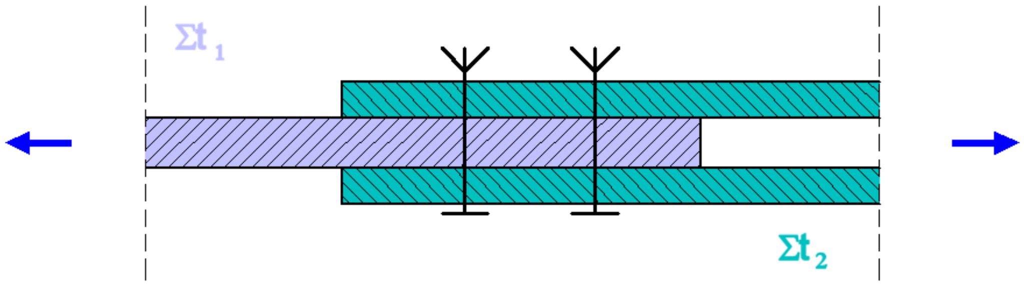
d – dimension of bolt

t_{min} – minimum total thickness of plate → Des#2Ex#1 / 71

γ_{M2} = 1,25

$\alpha_b = \min(\alpha_d ;\; f_{ub} / f_u ;\; 1{,}0)$

$t_{min} = \min(\Sigma t_1 ;\; \Sigma t_2)$



→ Des #2 examp 1 / 71

Photo: Author

Intentionally: no resistance, allowing free movement along hole's axis. This allows beam to rotate, as in an ideal hinge. **After bolt has moved**, it may possibly come into contact with plate. Then coefficient can be assumed as for overized round hole (to avoid damage of plate).

	β_b	
Fit bolts Normal round holes	1,0	
Oversized round holes	0,8	
Slotted holes	0,6	

EN 1993-1-8 tab 3.4

k_1 – parameter for phenomenons in direction perpendicular to force ⊥

α_b – parameter for phenomenons in direction parallel to force ‖

$$\alpha_b = \min(\alpha_d \;;\; f_{ub} / f_u \;;\; 1{,}0)$$

→ Des #2 examp 1 / 72

EN 1993-1-8 tab 3.4

d_0 – diameter of hole

	k_1 ⊥ Direction perpendicular to force
Inner	$\min(1{,}4\, p_2 / d_0 - 1{,}7 \;;\; 2{,}5)$
Edge	$\min(2{,}8\, e_2 / d_0 - 1{,}7 \;;\; 2{,}5)$

	α_d ‖ Direction parallel to force
Inner	$p_1 / 3d_0 - 0{,}25$
End	$e_1 / 3d_0$

Index 1 and 2 in symbols e_1 e_2 p_1 p_2 - there are no horizontal H and vertical V directions, but always paralell (1) ‖ and perpendicular (2) ⊥ to direction of force:

→ Des #2 examp 1 / 73

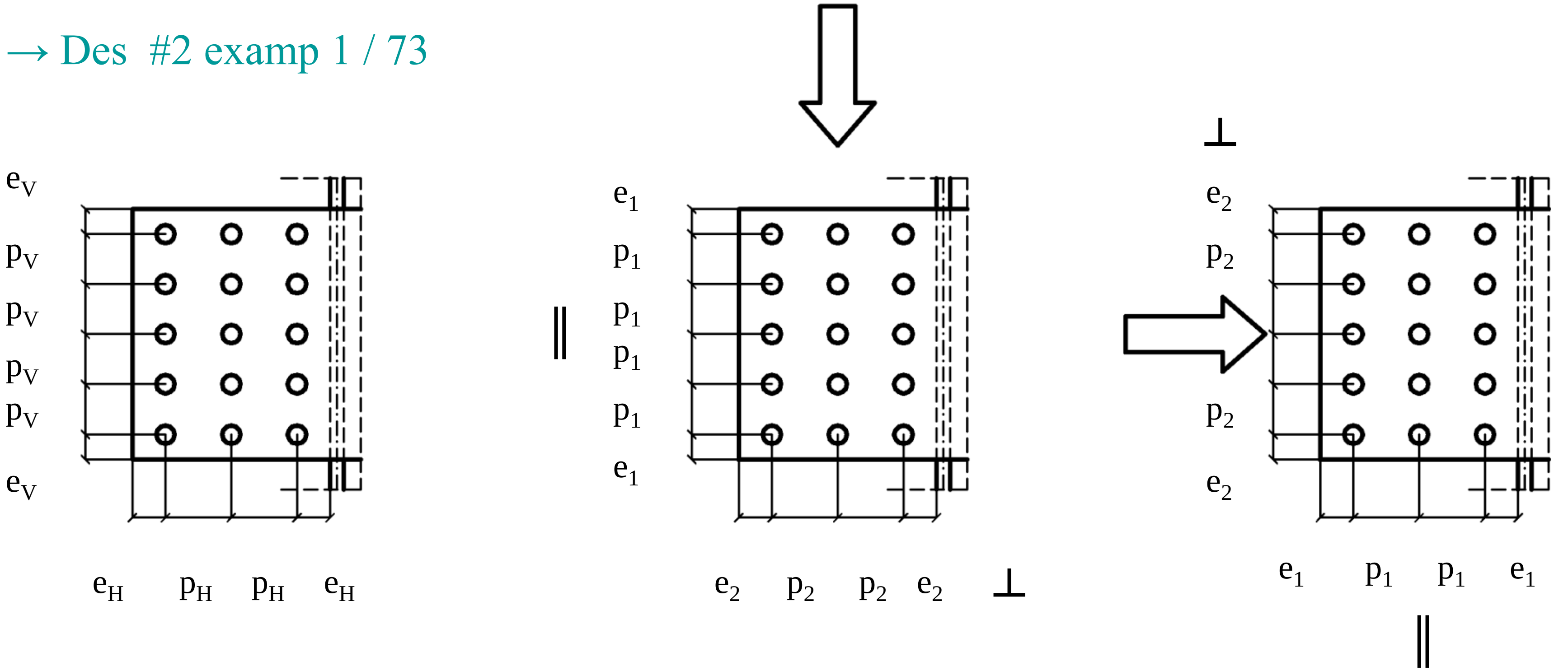
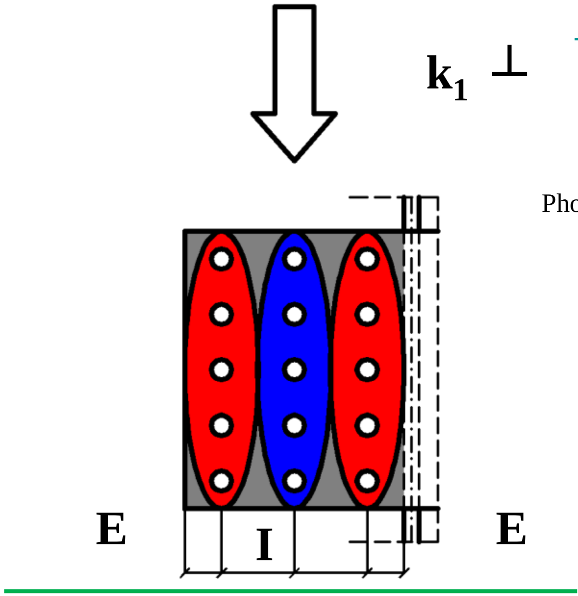


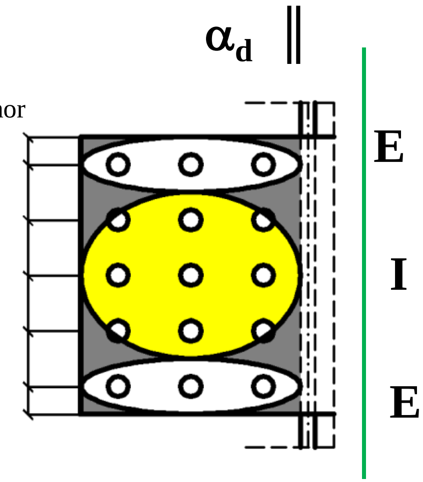
Photo: Author

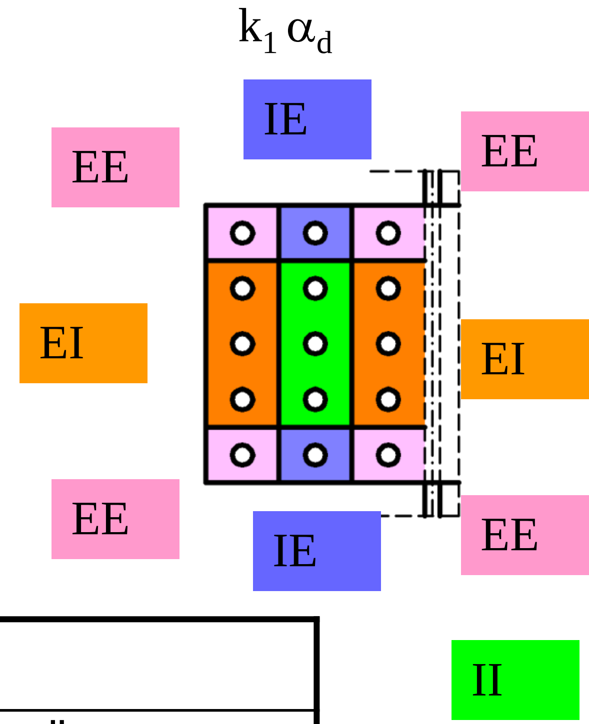
	$k_1 \perp$	Notice
Inner	min(1,4 p_2 / d_0 - 1,7 ; 2,5)	Neighboring bolts on **both sides** ⊥ **to force**
Edge	min(2,8 e_2 / d_0 - 1,7 ; 2,5)	Neighboring bolts on **one side only**



→ Des #2 examp 1 / 74

Photo: Author



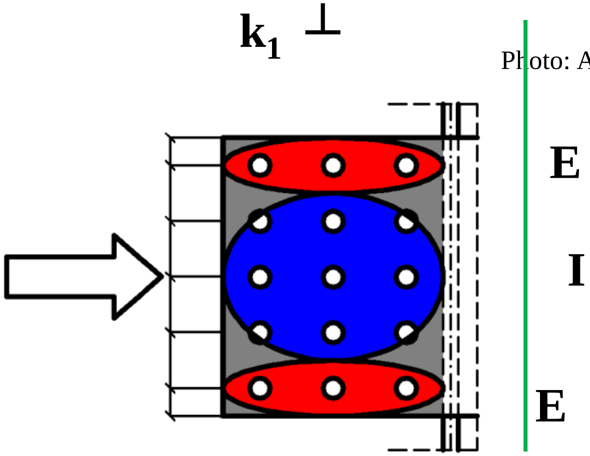


	α_d ∥	Notice
Inner	p_1 / 3d_0 - 0,25	Neighboring bolts on **both sides** ∥ **to force**
End	e_1 / 3d_0	Neighboring bolts on **one side only**

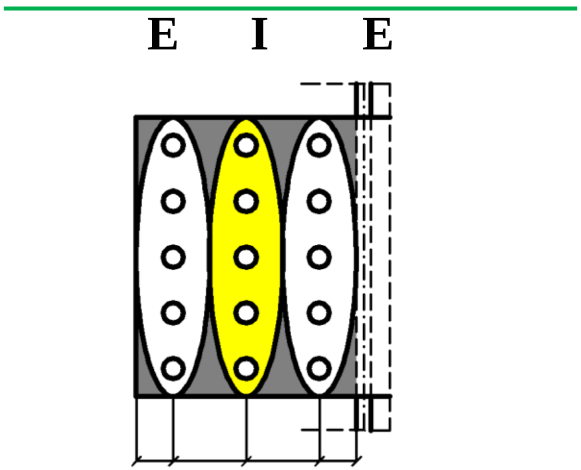
	$k_1 \perp$	Notice
Inner	min(1,4 p_2 / d_0 - 1,7 ; 2,5)	Neighboring bolts on **both sides** ⊥ **to force**
Edge	min(2,8 e_2 / d_0 - 1,7 ; 2,5)	Neighboring bolts on **one side only**

→ Des #2 examp 1 / 75

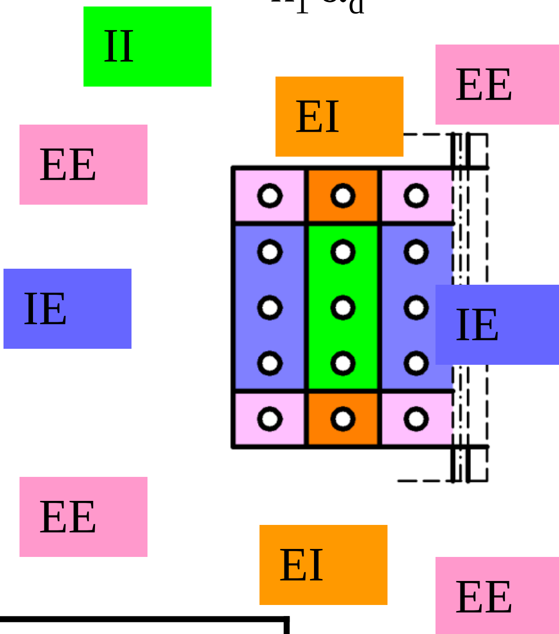
k_1 ⊥



α_d ∥



$k_1 \alpha_d$



	α_d ∥	Notice
Inner	p_1 / 3d_0 - 0,25	Neighboring bolts on **both sides** ∥ **to force**
End	e_1 / 3d_0	Neighboring bolts on **one side only**

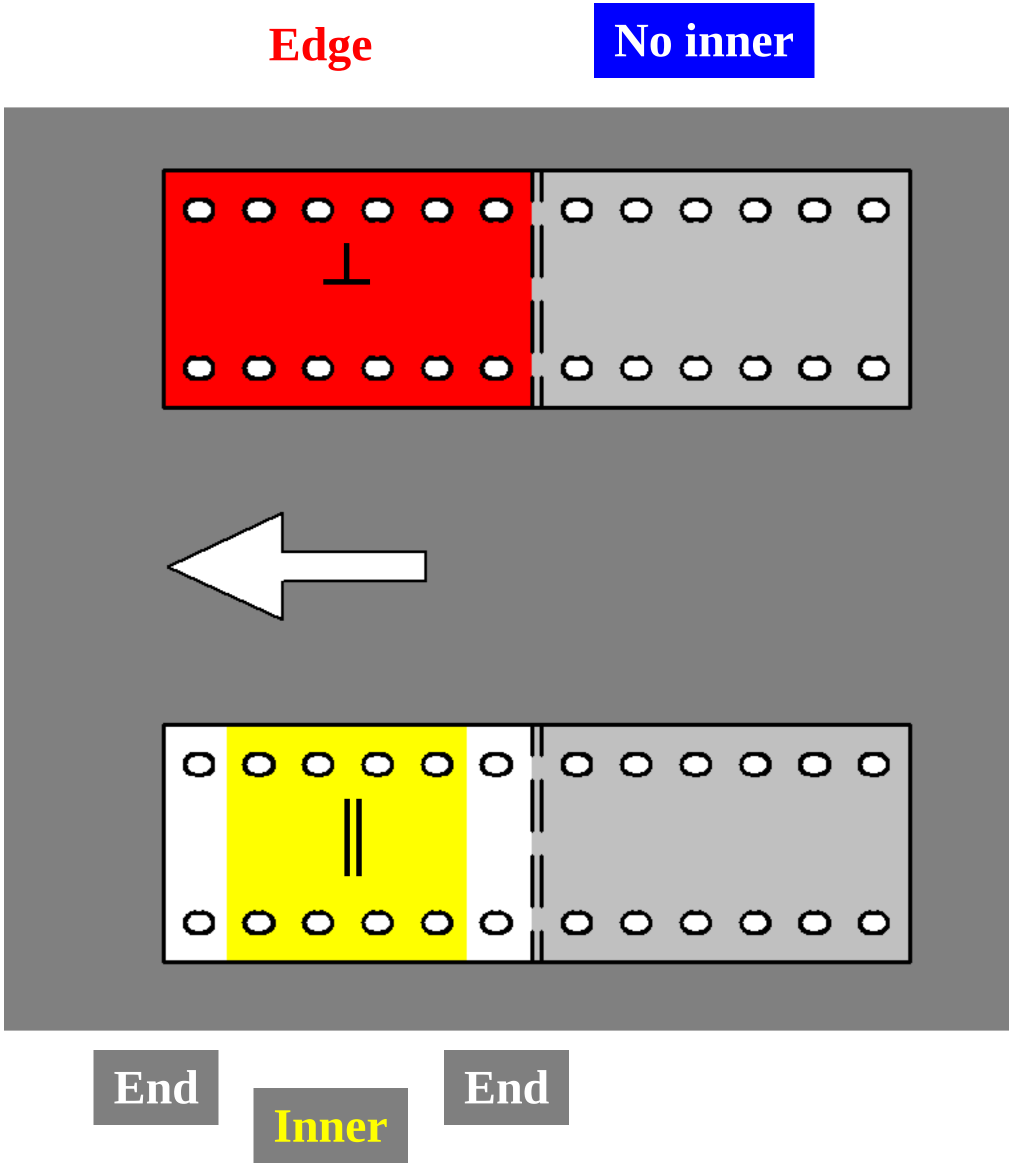


Photo: Author

	k_1 ⊥ Direction perpendicular to force
Inner	min (1,4 p_2 / d_0 - 1,7 ; 2,5)
Edge	min (2,8 e_2 / d_0 - 1,7 ; 2,5)

d_0 = (slotted hole: l) = 36 mm

	α_d ∥ Direction parallel to force
Inner	p_1 / 3d_0 - 0,25
End	e_1 / 3d_0

d_0 = 26 mm

Photo: Author

	$k_1 \perp$
Inner	
Edge	2,189

$f_{ub} / f_u = 800 / 360 = 2,222$

	α_d ‖	$\alpha_b = \min(\alpha_d ;\ f_{ub} / f_u ; 1,0)$ ‖
Inner	0,765	0,765
End	0,641	0,641

 $\beta_b = 0,8$

End **Edge**

$F_{b,Rd} = \beta_b\, k_1\, \alpha_b\, f_u\, d\, t_{min} / \gamma_{M2} = 0,8 \cdot 2,189 \cdot 0,641 \cdot 800\ \text{MPa} \cdot 24\ \text{mm} \cdot 26\ \text{mm} / 1,25 =$

$= 448,289\ \text{kN}$

$86,477 / 448,289 = 0,193 < 1,0$ **OK**

Inner **Edge**

$F_{b,Rd} = \beta_b\, k_1\, \alpha_b\, f_u\, d\, t_{min} / \gamma_{M2} = 0,8 \cdot 2,189 \cdot 0,765 \cdot 800\ \text{MPa} \cdot 24\ \text{mm} \cdot 26\ \text{mm} / 1,25 =$

$= 535,019\ \text{kN}$

$86,477 / 535,019 = 0,162 < 1,0$ **OK**

Edge

Inner

Edge

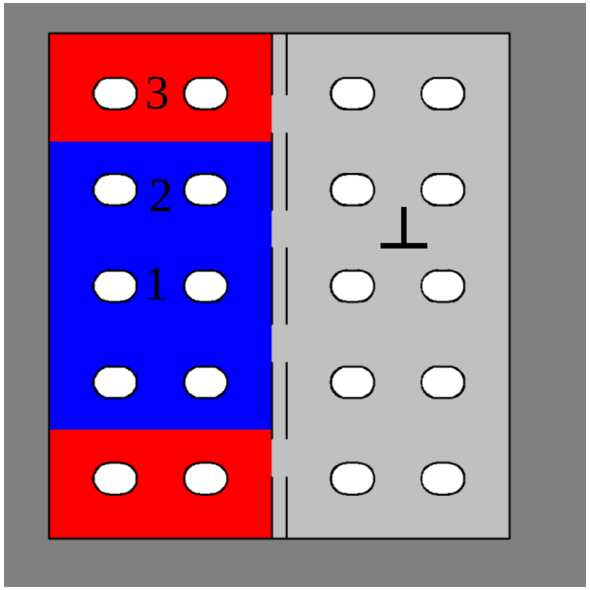
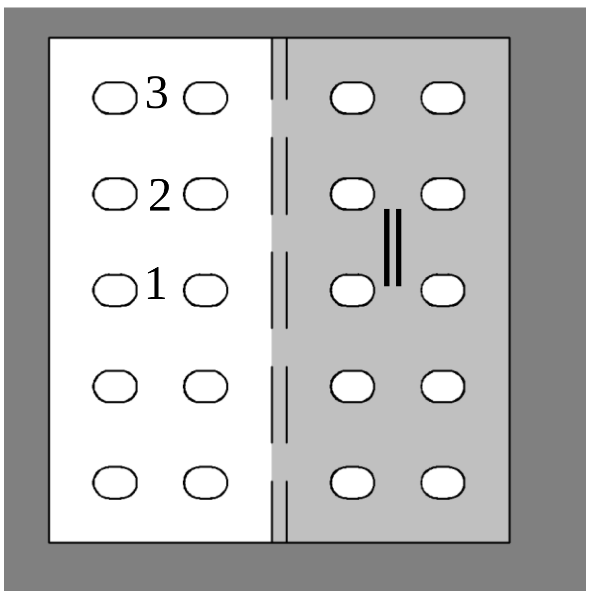


Photo: Author

	k_1 ⊥ Direction perpendicular to force
Inner	min (1,4 p_2 / d_0 - 1,7 ; 2,5)
Edge	min (2,8 e_2 / d_0 - 1,7 ; 2,5)

d_0 = 26 mm



End

No inner

	α_d ∥ Direction parallel to force
Inner	p_1 / 3d_0 - 0,25
End	e_1 / 3d_0

d_0 = (slotted hole: l) = 36 mm

Photo: Author

	$k_1 \perp$
Inner	2,500
Edge	2,500

$f_{ub} / f_u = 800 / 360 = 2,222$

	$\alpha_d \parallel$	$\alpha_b = \min(\alpha_d ; f_{ub} / f_u ; 1,0) \parallel$
Inner		
End	0,463	0,463

$\beta_b = 0,8$

Resistances for horizontal forces:

End **Edge** 3

$F_{b,Rd} = \beta_b k_1 \alpha_b f_u d t_{min} / \gamma_{M2} = 0,8 \cdot 2,500 \cdot 0,463 \cdot 800 \text{ MPa} \cdot 24 \text{ mm} \cdot 13,5 \text{ mm} / 1,25 =$

$= 192,015 \text{ kN}$

End **Inner** 2 1

$F_{b,Rd} = \beta_b k_1 \alpha_b f_u d t_{min} / \gamma_{M2} = 0,8 \cdot 2,500 \cdot 0,463 \cdot 800 \text{ MPa} \cdot 24 \text{ mm} \cdot 13,5 \text{ mm} / 1,25 =$

$= 192,015 \text{ kN}$

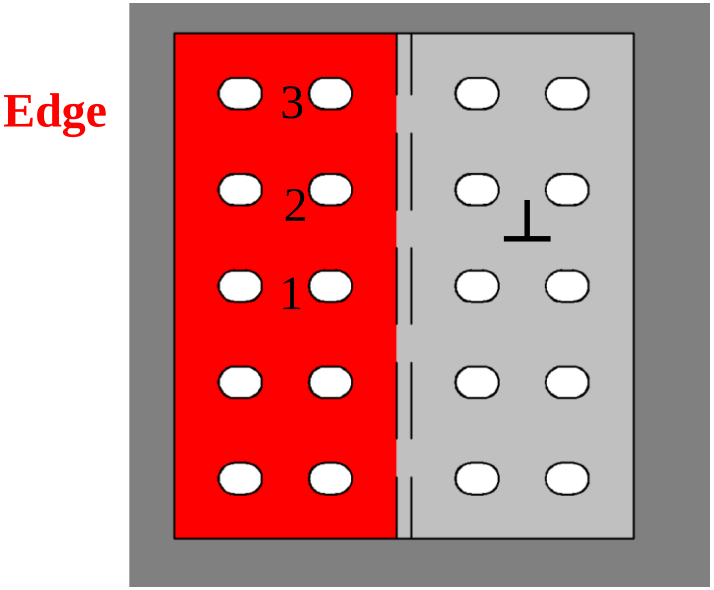
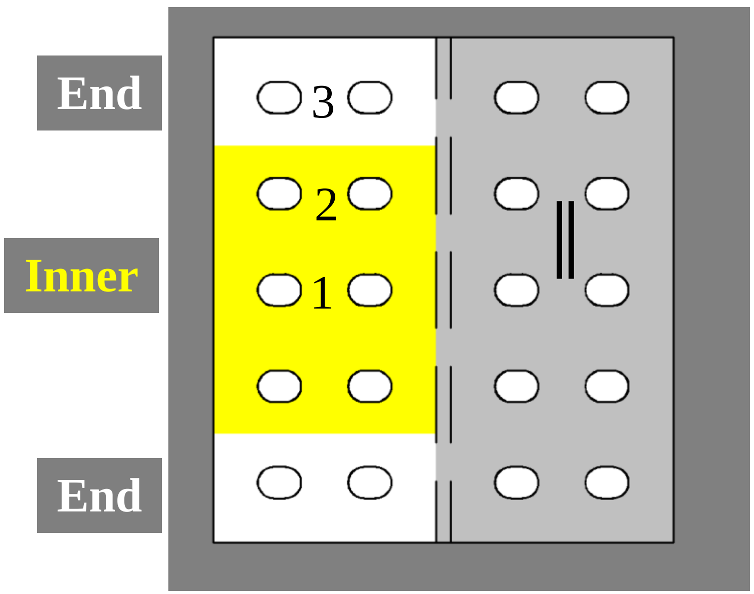


Photo: Author

No inner

	$k_1 \perp$ Direction perpendicular to force
Inner	min (1,4 p_2 / d_0 - 1,7 ; 2,5)
Edge	min (2,8 e_2 / d_0 - 1,7 ; 2,5)

d_0 = (slotted hole: l) = 36 mm



	$\alpha_d \parallel$ Direction parallel to force
Inner	p_1 / $3d_0$ - 0,25
End	e_1 / $3d_0$

d_0 = 26 mm

	$k_1 \perp$
Inner	
Edge	2,189

$f_{ub} / f_u = 800 / 360 = 2,222$

Photo: Author

	$\alpha_d \parallel$	$\alpha_b = \min (\alpha_d ;\ f_{ub} / f_u ; 1,0) \parallel$
Inner	0,776	0,776
End	0,641	0,641

$\beta_b = 0,6$

Resistances for vertical forces:

End **Edge** 3

$F_{b,Rd} = \beta_b\, k_1\, \alpha_b\, f_u\, d\, t_{min} / \gamma_{M2} = 0,6 \cdot 2,189 \cdot 0,641 \cdot 800 \text{ MPa} \cdot 24 \text{ mm} \cdot 13,5 \text{ mm} / 1,25 =$

$= 174,574 \text{ kN}$

Inner **Edge** 2 1

$F_{b,Rd} = \beta_b\, k_1\, \alpha_b\, f_u\, d\, t_{min} / \gamma_{M2} = 0,6 \cdot 2,189 \cdot 0,776 \cdot 800 \text{ MPa} \cdot 24 \text{ mm} \cdot 13,5 \text{ mm} / 1,25 =$

$= 211,341 \text{ kN}$

Web, checking resistance:

Bolt	Force H	Force V	Resistance H	Resistance V	E / R H	E / R V
1	0,000	47,126	192,015	174,574	0,000	0,270
2	65,975	47,126	192,015	174,574	0,343	0,270
3	131,835	47,126	192,015	211,341	0,687	0,223

Corner bolt: max values of loads (from bending moment), probably min resistance (because of small e)

Everything's all right.

In case of problems, it is recommended to add another column of bolts. Then, calculation must be made once again since slide #19.

Slip-resistant: preloaded bolts; initial non-zero value of axial tensile force in shank (as a effect of tight twistening of hex nut) → non-zero value of compressive force between plates → friction between plates. Destruction: value of load bigger than friction.

$F_{s,Rd} = k_s\ n\ \mu\ F_{p,C} / \gamma_{M3}$ EN 1993-1-8 p.3.9.1

$\gamma_{M3} = 1{,}25$

$F_{p,C}$ → #t / 66

k_s EN 1993-1-8 tab 3.6 (→ #t / 66)

μ EN 1993-1-8 tab 3.7 (→ #t / 67)

(Class of surface ≠ category of joint)

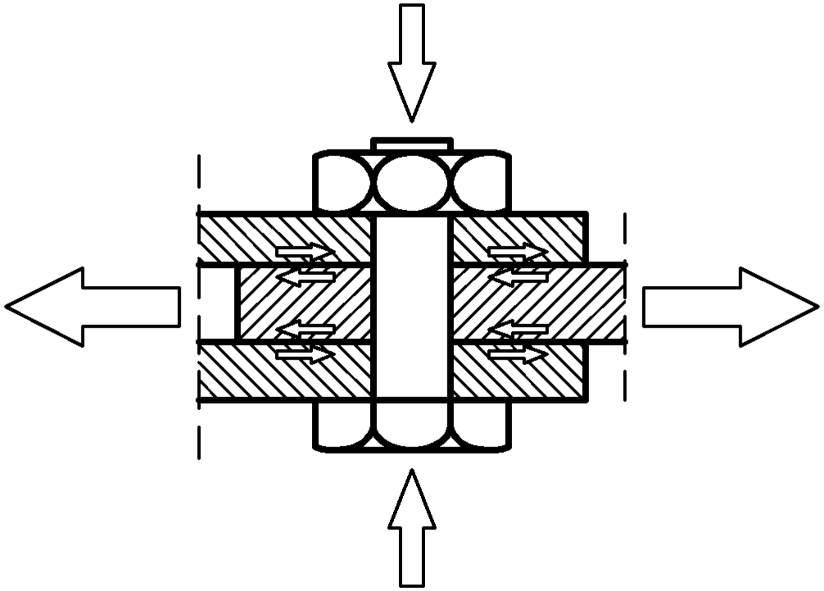


Photo: Author

$F_{p,C} = 0{,}7\, f_{ub}\, A_s / \gamma_{M7} = 0{,}636\, f_{ub}\, A_s = 88\%$ tensile force resistance $= 0{,}720\, f_{ub}\, A_s$

$\gamma_{M7} = 1{,}1$

EN 1993-1-8 (3.7)

Type of holes		Force	k_s
Round	Fit		1,0
	Normal		1,0
	Oversized		0,85
Slotted	Short		0,76
			0,85
	Long		0,63
			0,70

EN 1993-1-8 tab. 3.6

Photo: Author

EN 1993-1-8 tab. 3.7

EN 1090-2 tab 18

Class of friction surfaces	Friction coefficent μ	Surface treatement
A	0,5	Surface blasted with shot or girt with loose rust removed, not pitted;
B	0,4	Surfaces blasted with shot or girt: ◆ spray-metallized with a aluminum or zinc based product; ◆ with alkali-zinc silicate paint with a thickness of 50 μm to 80 μm;
C	0,3	Surfaces cleaned by wire-brushing or flame cleaning, with loose rust removed;
D	0,2	Surfaces as rolled;

Flange

$F_{s,Rd} = k_s \, n \, \mu \, F_{p,C} / \gamma_{M3}$

$\gamma_{M3} = 1{,}25$

k_s for long slotted holes = 0,63

μ taken into consideration 0,5 (class of surface A)

$F_{p,C} = 0{,}7 \, f_{ub} \, A_s = 197{,}680$ kN

$F_{s,Rd} = k_s \, n \, \mu \, F_{p,C} / \gamma_{M3} = 49{,}815$ kN

Bolted cathegory B:

load calculated for **characteristic value**

$F_{b,k} = 57{,}985$ kN

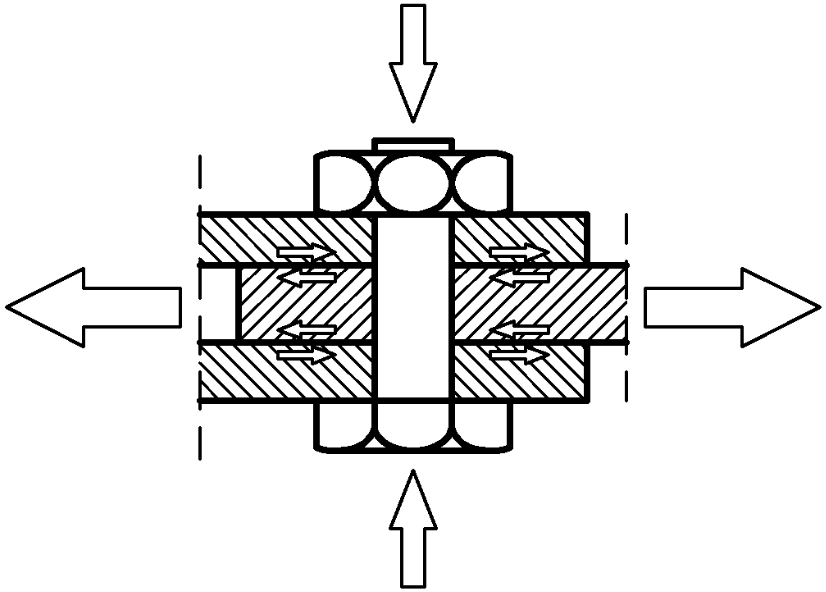
E/ R = 57,985 / 49,815 = 1,164 > 1,0   WRONG

More bolts must be applicated: 12 · 1,164 = 14 bolts

At now, force in bolt = (57,985 · 12) / 14 = 49,701 kN

E/ R = 49,701 / 49,815 = 0,998 < 1,0   OK

Photo: Author



Full information about bolts in flange; verification of shear resistance

Formula for resistance of bolt under shear force is:

$$F_{v,Rd,\,total} = \mathbf{n}\ \beta_{12\text{-}14}\ \beta_{Lf}\ \beta_{p}\ \boldsymbol{\alpha_V}\ \mathbf{f_{ub}}\ \mathbf{A_{(s)}}\ /\ \boldsymbol{\gamma_{M2}}$$

Part taken into consideration (→ #t / 50)

$\beta_{12\text{-}14}$ – important for M12, M14 only

β_p – important for various cross-sections of two I-beams on lest and right side of joins

β_{Lf} – impact of length of joint

At now, when total number of bolts in flange / flange plate is known (effect of checking resistance for shear force and slip-resistant), impact of length for shear force resistance must be analysed.

Condition 1: $\sqrt{[(\sigma_\perp)^2 + 3(\tau_\parallel{}^2 + \tau_\perp{}^2)]} \leq b_{LW}\, f_u / (\beta_w \gamma_{M2})$

Condition 2: $\sigma_\perp \leq 0{,}9\, b_{LW}\, f_u / \gamma_{M2}$

→ #17 / 69

Values of β_{LW} for different types and lengths of welds:

Length of weld:	0 - ∞		
Between flange and web in welded I-beam	1,0		
Length of weld:	L < 1,700 m	1,700 m < L < 8,500 m	L > 8,500 m
Between transverse stiffeners and plates in welded I-beam	1,0	1,1 - L / 17	0,6
Length of weld:	L < 150 a	150 a < L < 900 a	L > 900 a
All other cases	1,0	1,2 - 0,2 L / (150 a)	0,0

EN 1993-1-8 (4.9), (4.10)

In full analogy to welds: long joints for bolted joint:

Photo: EN 1993-1-8 fig. 3.7

EN 1993-1-8 3.8

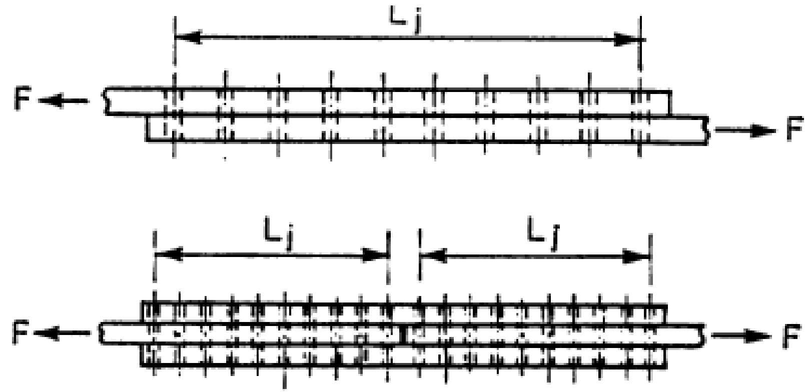
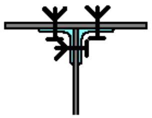


Photo: Author



b_{Lf} :

	$L_j \leq 15\ d$	$15\ d \leq L_j \leq 65\ d$	$L_j \geq 65\ d$
Uniform distribution of force transfer over the length of the joint (flange-web)	1,00		
All other cases	1,00	$1 - (L_j - 15\ d) / (200\ d)$	0,75

7 pairs of bolts:

Photo: EN 1993-1-8 fig. 3.7

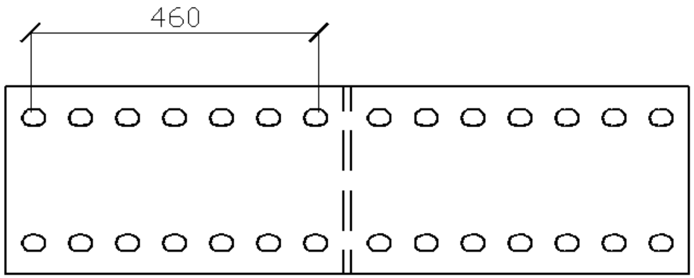
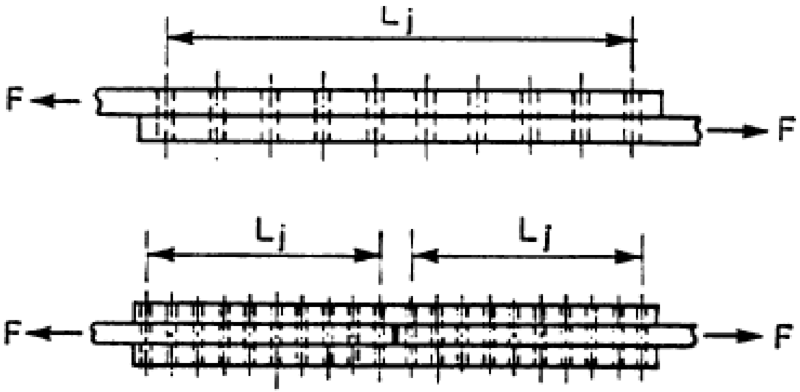


Photo: Author



$$15\ d = 360\ mm < L_j = 460\ mm < 65\ d = 1\ 560\ mm$$

$$b_{Lf} = 1 - (L_j - 15\ d) / (200\ d) = 0{,}979$$

Resistance for shear force is not 173,568 kN (→ #t / 50),

but 0,979 · 173,568 kN = 169,923 kN

86,477 / 169,923 = 0,509 < 1,0 **OK**

Web

$F_{s,Rd} = k_s\ n\ \mu\ F_{p,C} / \gamma_{M3}$

$\gamma_{M3} = 1,25$

k_s min for long slotted holes = 0,63

μ taken into consideration 0,5 (class of surface A)

$F_{p,C} = 0,7\ f_{ub}\ A_s = 197,680$ kN

$F_{s,Rd} = k_s\ n\ \mu\ F_{p,C} / \gamma_{M3} = 99,631$ kN

Bolted cathegory B:

load calculated for **characteristic value**

max product = 95,763 kN

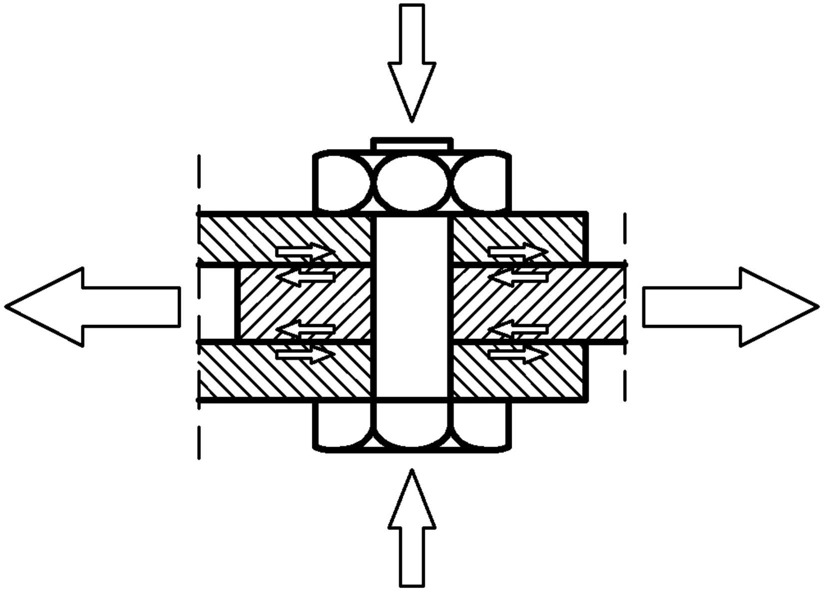


Photo: Author

E/ R = 95,763 / 99,631 = 0,961 < 1,0 OK

Punching resistance: as a effect of axial force in bolt (from preloading or load), cap or nut is punched through the plate.

$B_{p,Rd} = 0{,}6\ \pi\ d_m\ t_p\ f_u / \gamma_{M2}$

$d_m = (D + s) / 2$

EN 1993-1-8 tab 3.4

$\gamma_{M2} = 1{,}25$

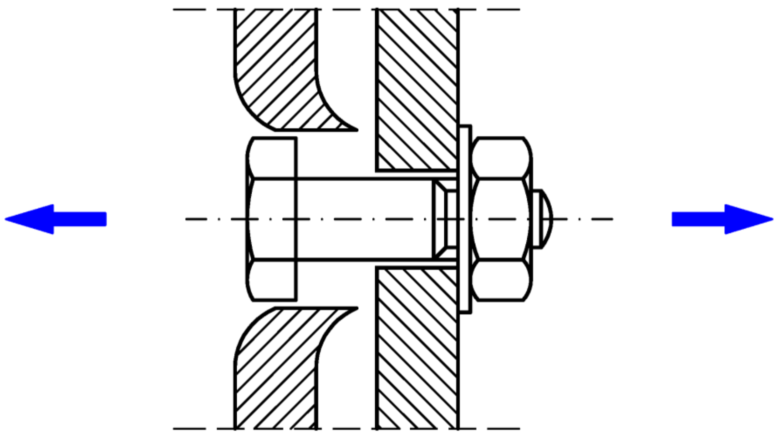


Photo: Author

Load: preloaded force, **the same for web and flange**: $F_{p,C} = 0{,}7\ f_{ub}\ A_s = 197{,}680$ kN

The lowest resistance: for web plate, $t_p = 12$ mm

$B_{p,Rd} = 238{,}716$ kN

$E / R = 197{,}690 / 238{,}716 = 0{,}828 < 1{,}0$ OK

Block tearing (total destruction of plate)

Photo: quora.com

Netto area (other type of total destruction of plate)

Photo: quora.com

Member	Netto area	Block tearing
Flange plate	1037,724 kN	
Web plate	117,030 kNm and 162,200 kN	Many various loads, not checking
I-beam	727,800 kNm and 162,200 kN	

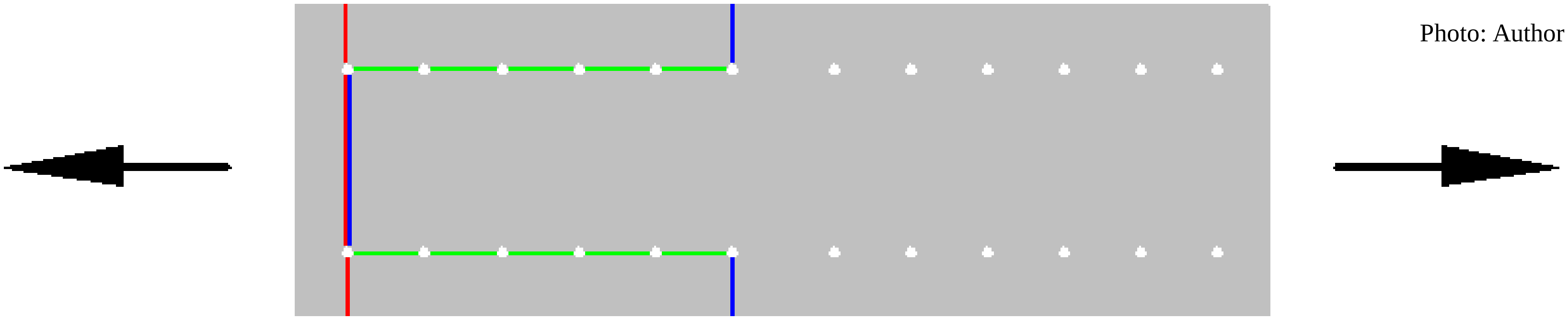


Photo: Author

Flange plate, axial force only. According to #Des 2 Ex1 / 83 we should calculate block tearing (tension part and shear part), but the smallest area is for red cross-section for netto area effect. Netto resistance for tensile axial force:

$$N_{u,Rd} = \min [0{,}9 A_{net} f_u / \gamma_{M2} \quad ; \quad A f_y / \gamma_{M0}]$$

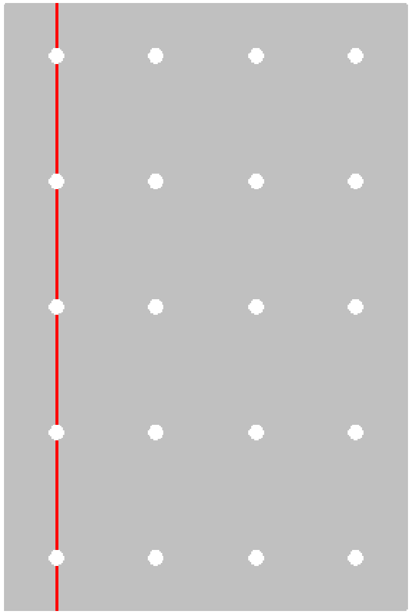


Photo: Author

Web plate, bending moment, shear force and, optionally, axial force.

$$\sigma(N_{fp}) = N_{fp} / A_{netto}$$

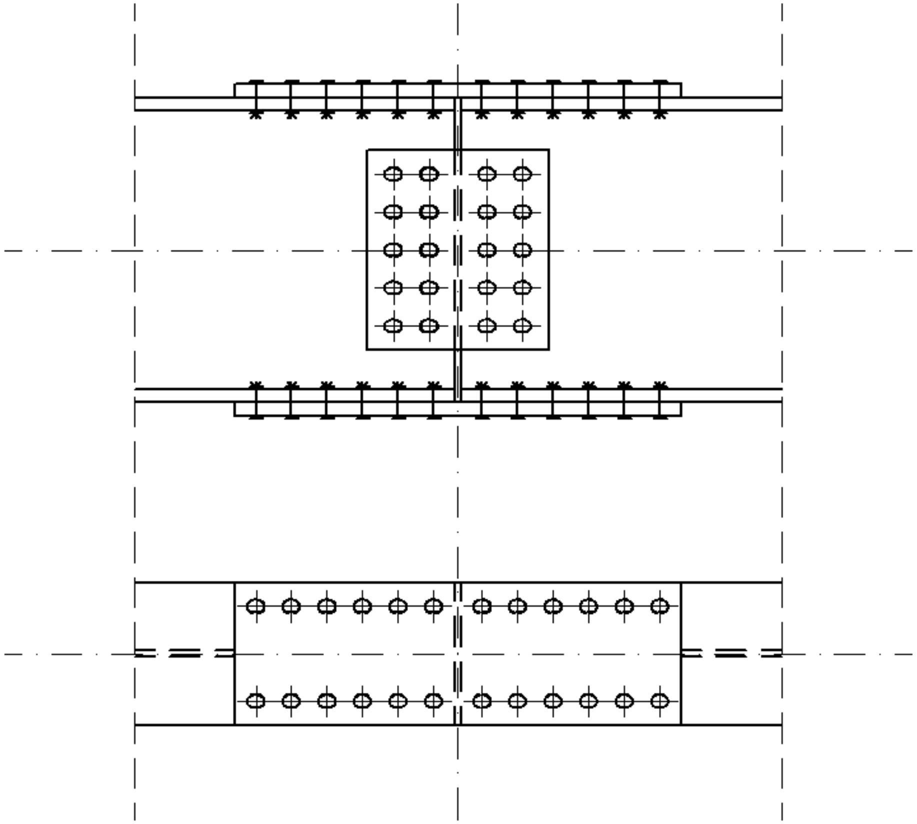
$$\sigma(M_{fp}) = M_{fp} / W_{netto}$$

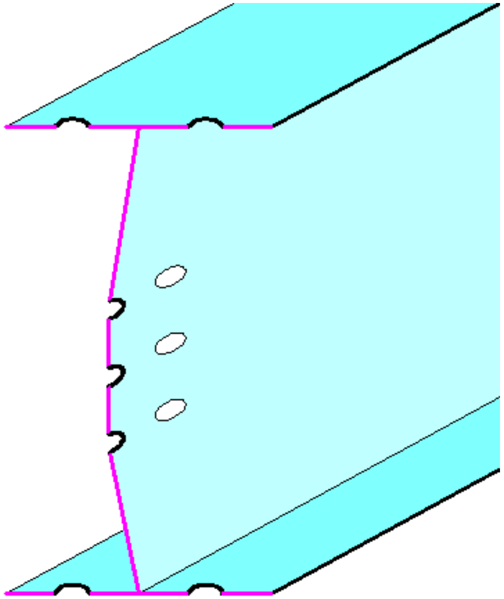
$$\tau(V_{fp}) = V_{fp} / A_{total}$$

$$\sqrt{\{ [\sigma(N_{fp}) + \sigma(M_{fp})]^2 + 3[\tau(V_{fp})]^2\}} \leq f_y$$

Web, flange - uniform cross-section, not two separate part. We should analysed destruction of whole netto cross-section.

Photo: Author





$$\sigma(M_{fp}) = M_{Ed} / W_{netto}$$

$$\tau(V_{fp}) = V_{Ed} / (h_w\ t_w)$$

$$\sqrt{\{ [\sigma(M_{fp})]^2 + 3[t(V_{fp})]^2\}} \leq f_y$$

Flange plate: $N_{u,Rd} = \min [\ 0{,}9\ A_{net}\ f_u / \gamma_{M2}\ \ ;\ \ A\ f_y / \gamma_{M0}]$

$A_{net} = 74{,}40\ cm^2 \quad A = 90\ cm^2 \quad f_y = 235\ MPa \quad f_u = 360\ Mpa$

$N_{u,Rd} = \min\ (2\ 142{,}720\ kN\ \ ;\ \ 2\ 115{,}000\ kN) = 2\ 115{,}000\ kN$

$E / R = 1\ 037{,}721 / 2\ 115{,}000 = 0{,}491 < 1$ **OK**

Element	Force [kN]	Bending moment [kNm]	A_V [cm^2]	W [cm^3]	σ [MPa]	τ [MPa]	σ_{eq} [MPa]	σ_{eq} / f_y
Web plate	162,200	117,030	100,80	515,429	227,577	16,091	229,454	**0,976**
HEA 650	162,200	727,800	86,40	4 594,696	158,400	18,773	161,703	**0,688**

A_V – total

W – netto

Thank you for attention

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