Column bases in shear and normal force

Nol Gresnigt

Delft University of Technology, Civil Engineering and Geosciences, the Netherlands

Arie Romeijn

Delft University of Technology, Civil Engineering and Geosciences, the Netherlands

František Wald

Czech Technical University, Prague, Czech Republic

Martin Steenhuis †

Eindhoven University of Technology, Faculty of Architecture, Building and Planning, the Netherlands

Connections of steel columns to concrete foundations may be loaded by combinations of normal force, bending moment and shear force. Shear force will primarily be transmitted by friction between the base plate and the grout layer to the concrete foundation. If the compression force is small, or if tension force is present, as may occur in slender high rise structures like towers and masts, the friction will be small or absent. Then, the anchor bolts will be loaded by shear force and bending moment.

At the Stevin Laboratory of Delft University of Technology, experimental and theoretical research has been carried out on column bases loaded by combinations of shear force and tension force.

In the paper, the main results of this research programme are summarised. The test results are presented and the analytical model that was developed to describe the load deformation behaviour.

A comparison is made with the design rules as given by the Comité Euro-International du Béton (CEB, 1994 and 1996). Based on the research, design rules for this load case were proposed to the drafting panel for the revision of Eurocode 3 from ENV to EN status (Part 1.8: Design of Joints).

Key words: Base plates, shear and tension, Eurocode 3, analytical model, tests

1 Introduction

Horizontal shear force in column bases may be resisted by (see Figure 1):

(a)   friction between the base plate, grout and concrete footing,

(b)   shear and bending of the anchor bolts,

(c)   a special shear key, for example a block of I-stub or T-section or steel pad welded onto the bottom of the base plate,

(d)   direct contact, e.g. achieved by recessing the base plate into the concrete footing.

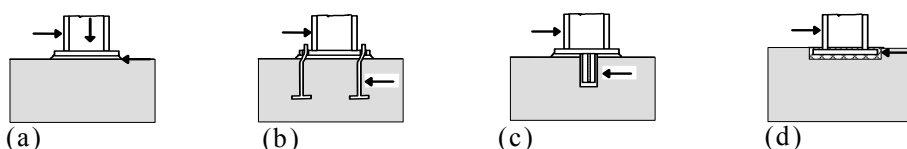(a)   (b)   (c)   (d)

Figure 1: Column bases loaded by horizontal shear force

In most cases, the shear force can be resisted through friction between the base plate and the grout. The friction depends on the compressive load and on the coefficient of friction. Pre-stressing the anchor bolts will increase the shear force transfer by friction.

Sometimes, for instance in slender buildings, it may happen that due to horizontal forces (wind loading) columns are loaded in tension. In such cases, the horizontal shear force usually cannot be transmitted through friction. If no other provisions are installed (e.g. shear studs), the anchor bolts will have to transmit these shear forces.

Because the grout does not have sufficient strength to resist bearing stresses between the bolt and the grout, considerable bending of the anchor bolts may occur, as is indicated in Figure 2. The main failure modes are rupture of the anchor bolts (local curvature of the bolt exceeds the ductility of the bolt material), crumbling of the grout, failure (splitting) of the concrete footing and pull-out of the anchor bolt.

Due to the horizontal displacement, not only shear and bending in the bolts will occur, but also the tensile force in the bolts will be increased due to second order effects. The horizontal component of the increasing tensile force gives an extra contribution to the shear resistance and stiffness. The increasing vertical component gives an extra contribution to the transfer of load by friction and increases resistance and stiffness as well. These factors explain the shape of the load deformation diagram as given in Figure 2. The increase of the load continues till fracture occurs in one of the components of the connection. If the connection is well designed and executed, such fracture will occur at

very large deformation (much larger than acceptable in serviceability and ultimate limit state).
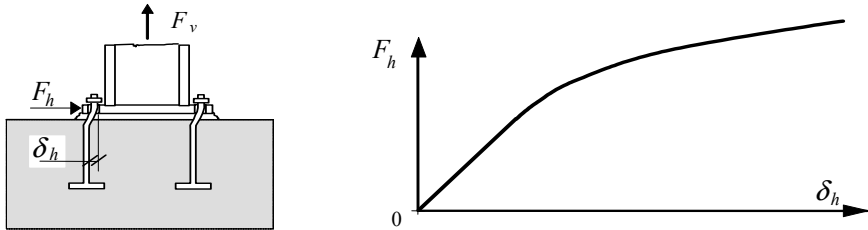

Figure 2: Column base loaded by shear and tension force

The thickness of the grout layer has an important influence on the horizontal deformations. In the tests carried out by the Stevin Laboratory (Stevin, 1989), the deformations at rupture of the anchor bolts were between about 15 and 30 mm, whilst grout layers had a thickness of 15, 30 and 60 mm. The deformations have to be taken into account in the check of the serviceability limit state. Because of the rather large deformations that may occur, this check may govern the design. The size of the holes may have a considerable influence on the horizontal deformations, especially when oversized holes are applied. In such cases it may be useful to apply larger washers under the nuts, to be welded onto the base plate after erection, or to fill the hole by a two component resin. For the application of such resin, reference is made to the ECCS recommendations (1994) and EN 1993-1-8 (2006).

In the Stevin Laboratory (Stevin, 1989), a model for the load deformation behaviour of base plates loaded by combinations of normal force and shear has been developed, see section 2. Section 4 gives an overview of the tests carried out in Delft. For the design of fasteners, the CEB has published a Design Guide (CEB, 1996). The CEB model (the CEB design rules for "fixtures") has been compared with the Stevin Laboratory model and the tests. It appears that the CEB model gives very conservative results, especially when large tensile forces are present and / or the thickness of the grout layer is large. The main reason is that the CEB model does not take account of the positive influence of the grout layer (COST, 1999). In section 3 a summary of the CEB model is presented. In section 5 the test results are compared with the Stevin Laboratory model and the CEB model. Section 6 gives a summary of the design rules proposed for part 1.8 of EN 1993.

It is noted that in steel construction, usually only the steel part of the base plate connection is considered. In the CEB Design Guide much attention is paid to the concrete part. It is recommended to the steel designer to acquire knowledge about the requirements to the reinforced concrete. For detailed design guidance and the various failure modes that may occur in the concrete, reference is made to the CEB Design Guide (CEB, 1996).

For an interesting test series on anchor bolts, reference is made to the work of Nakashima (1998). He studied the mechanical properties of steel column base anchor bolts, particularly those parts of such anchor bolts which are exposed, i.e., not embedded in concrete footings. He studied the anchor bolts which are often subjected to combined stresses which are caused by tension, shear and in addition bending moments. Special attention is paid to the influence of the thread and other factors on the deformation capacity.

2   The Stevin Laboratory model

In most cases the shear force can be transmitted via friction between the base plate and the grout. The friction capacity depends on the normal force (compression) between the base plate and the grout and the friction coefficient. At increasing horizontal displacement the shear force increases till it reaches the friction capacity. At that point the friction resistance stays constant with increasing displacements, while the load transfer through the anchor bolts increases further. Because the grout does not have sufficient strength to resist the bearing stresses between the bolts and the grout, considerable bending of the anchor bolts may occur, as is indicated in Figures 2 and 3.

The test specimen shows the bending deformation of the anchor bolts, the crumbling of the grout and the final cracking of the concrete.

Figure 3: Test specimen loaded by shear force and tensile force (Stevin, 1989)

2.1 *Derivation of the analytical model*

In Figure 4, the deformations and some important measures are indicated. Figure 5 shows the schematisation of the deformations and the forces, which are taken into account in the analytical model. In the derivations, the following symbols are used:

$A_{b,s}$ =   tensile stress area of the anchor bolt

F_t =   applied tensile force

F_h =   applied shear force (horizontal force)

F_w =   friction force between base plate and grout

N_b =   normal force in the grout

F_a =   normal force in the anchor bolt

d_b =   diameter of the anchor bolt

δ_a =   elongation of the anchor bolt

δ_b =   compression of the grout layer

δ_h =   horizontal displacement of the base plate

v =   actual thickness of the grout layer

v_r =   thickness of the grout layer in the analytical model: $v_r = v + 0.5d_b$

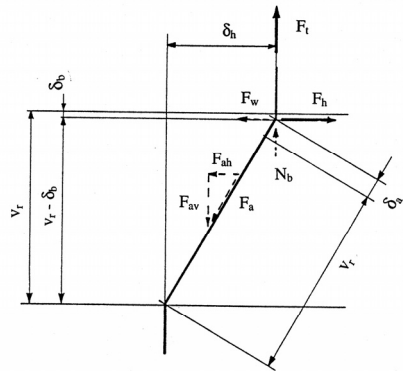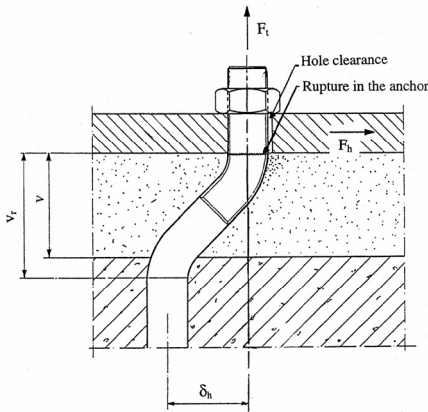   ($v_r = \ell$ as in the CEB model, see section 3)

Figure 4: *Deformation and some measurements of the anchor bolts*

Figure 5: *Schematisation of the deformations and forces in the analytical model*

Due to the horizontal displacement of the base plate, bending of the bolts will occur and the tensile force in the bolts (F_a) will increase. This causes an increase of the compression

force between the base plate and the grout, resulting in a larger friction force (F_w) between the grout and the base plate, see equations (2) and (3).

At rather small horizontal deformations (δ_h), the tensile force F_a in the bolt reaches the yield force $F_{yb} = A_s \cdot f_{yb}$. This means that the bending moments in the anchor bolts rapidly decrease and the horizontal component F_{ah} of F_a (Figure 5) rapidly increases. Because of the high tensile force in the bolts, the bending moment capacity in the bolts will be small. Therefore, in the analytical model the bending moments in the bolts are not taken into account. The bearing stresses of the grout-bolt contact are not taken into account either, because they are small compared to other forces. For the horizontal equilibrium it follows:

$$F_h = F_a \frac{\delta_h}{v_r + \delta_a} + F_w \tag{1}$$

$$F_w = f_w \left(F_a \frac{v_r - \delta_b}{v_r + \delta_a} - F_t \right) \tag{2}$$

In these equations f_w is the coefficient of friction between the grout and the base plate. For the deformation it follows:

$$\delta_h^2 = (v_r + \delta_a)^2 - (v_r - \delta_b)^2 \tag{3}$$

Because δ_h^2 is small compared with δ_h this can be simplified to:

$$\delta_h^2 = 2 \, v_r \, (\delta_a + \delta_b) \tag{4}$$

For the "elastic" part of the behaviour, δ_a and δ_b can be written as:

$$\delta_a = \frac{F_a \, v_r}{E \, A_{b,s}} \tag{5}$$

$$\delta_b = \frac{(F_a - F_t) \, v_r}{E_{grout} \, A_{grout}} \tag{6}$$

Because $E_{grout} \, A_{grout}$ is much greater than $E A_{b,s}$, δ_b will be small compared with δ_a. Therefore δ_b is not taken into account further. From the geometry it follows:

$$v_r + \delta_a = \sqrt{\delta_h^2 + v_r^2} \tag{7}$$

For (1), (2) and (4) can be written with (7):

$$F_h = F_a \frac{\delta_h}{\sqrt{\delta_h^2 + v_r^2}} + F_w \tag{8}$$

$$F_w = f_w \left(F_a \frac{v_r}{\sqrt{\delta_h^2 + v_r^2}} - F_t \right) \tag{9}$$

$$\delta_h = \sqrt{2\, v_r\, \delta_a} \tag{10}$$

For every δ_h the elongation δ_a can be calculated via (10), then with (5) the force F_a and with (8) and (9) the horizontal force F_h. The above equations are valid for $F_a \leq F_{a,y}$ where

$$F_{a,y} = A_s \cdot f_{y,b} \tag{11}$$

For $F_a = F_{a,y}$ it follows with (8), (9) and (11):

$$F_h = \frac{f_{y,b}\, A_{b,s}}{\sqrt{\delta_h^2 + v_r^2}}\,(\delta_h + f_w v_r) - f_w F_t \tag{12}$$

with

$$\delta_h = v_r \sqrt{\frac{2 f_{y,b}}{E}} \tag{13}$$

For the design value of the coefficient of friction $f_{w,d}$ the following values are proposed:

- sand-cement mortar: $f_{w,d} = 0{,}20$
- special grout (e.g. Pagel IV): $f_{w,d} = 0{,}30$

2.2 *Comparison with one of the tests*

To demonstrate the analytical model, one of the test results is calculated, namely DT6 in (Stevin, 1989), see Figure 6. In this test, a tensile force $F_t = 141$ kN was kept constant in the column, while the horizontal force F_h was increased. Figure 7 gives the test result together with the result of the analytical model. With equations (13) and (12) it follows:

$$\delta_h = v_r \sqrt{\frac{2 f_{y,b}}{E}} = 40 \sqrt{\frac{2 \cdot 861}{210000}} = 3{,}6 \text{ mm}$$

$$F_h = \frac{f_{y,b} A_{b,s}}{\sqrt{\delta_h^2 + v_r^2}}(\delta_h + f_w v_r) - f_w F_t = \frac{861 \cdot 245}{\sqrt{3{,}6^2 + 40^2}}(3{,}6 + 0{,}20 \cdot 40) \cdot 2 - 0{,}20 \cdot 141 = 94 \text{ kN}$$

A linear relationship is assumed until the value of δ_h equals δ_h according to equation (13) and F_a equals $A_s f_{y,b}$. This part of the load deformation curve is called the elastic stage, see Figure 7. For larger values of δ_h the load deformation curve is called the plastic stage. E.g. for $\delta_h = 15$ mm, it follows with equation (12): $F_h = 227 - 28 = 199$ kN.

In the test, failure occurred in the anchor bolts (rupture) at the edge of the base plate, due to local high bending strains. The value $F_{v,Rd} = 105$ kN in Figure 7 is explained in the next section.

Figure 6: Set-up of test DT6
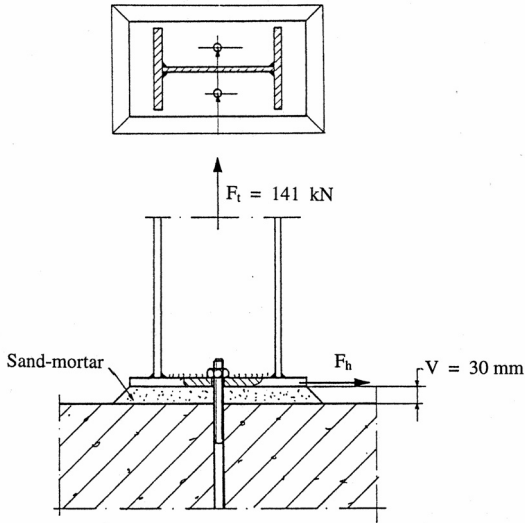
- 2 anchor bolts M20, grade 8.8
- $F_{u,b}$ = 1076 N/mm² (measured tensile strength of the bolt material)
- $f_{y;b}$ = 861 N/mm² (assumed as $0.8\, f_{u,b}$)
- $\varepsilon_{u,b}$ = 12% (measured rupture strain of the bolt material)
- A_s = 245 mm²
- grout = sand-cement mortar
- v = 30 mm
- $v_r = 30 + 0.5 \cdot 20 = 40$ mm
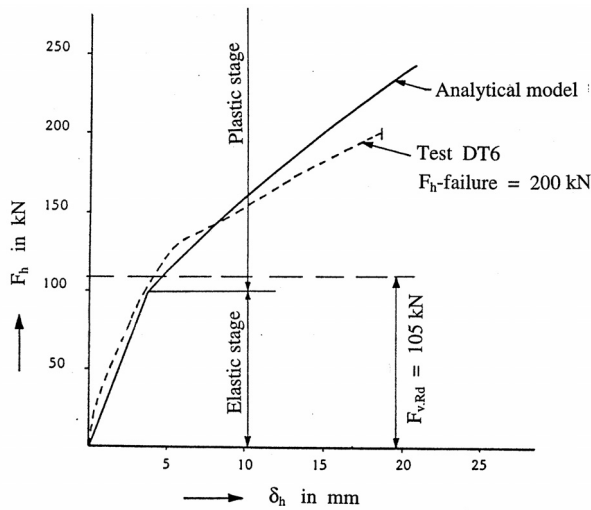

Figure 7: Comparison of the analytical model with result of test DT6

2.3   Ultimate design strength

The ultimate strength is a function of the strength of the various parts in the column base and the ductility of the anchor bolts. A greater ductility allows a greater horizontal displacement and thus a greater F_{ah} (Figure 5) and consequently a greater F_h.

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It can also be noted that δ_h should be limited, both at serviceability and at ultimate limit state.

To predict the ultimate strength (if governed by the anchor bolt), a relation is needed between the local strain in the bolt and the horizontal deformation. Furthermore, the strain capacity (ductility) of the various anchor materials must be known.

In the tests, it appeared, as could be expected, that 4.6 grade anchor bolts were much more ductile than the 8.8 grade bolts. A difference in ductility can also be found in the requirements in the relevant product standards.

It is not easy to establish a reliable model to determine the strains in the anchor bolts and to find reliable data for the bending strain capacity of various anchor bolt materials. Therefore, a simplified method is proposed for the shear resistance of 4.6 and 8.8 grade anchor bolts. This simplified method is adopted in the Dutch Standard (NEN 6770, 1990):

$$\text{4.6 anchors:} \quad F_{v.Rd} = \frac{0{,}375\, f_{u,b} \cdot A_{b,s}}{\gamma_{Mb}} \tag{14}$$

$$\text{8.8 anchors:} \quad F_{v.Rd} = \frac{0{,}25\, f_{u,b} \cdot A_{b,s}}{\gamma_{Mb}} \tag{15}$$

with $\gamma_{Mb} = 1{,}25$.

Differences in ductility cause differences in ultimate strength, see Fig 7. This is the reason for the different factors in (14) and (15). Note that the resistance functions (14) and (15) are similar to the "normal" Eurocode 3 functions for bolts loaded in shear:

$$\text{4.6 and 8.8 bolts:} \quad F_{v.Rd} = \frac{0{,}60\, f_{u,b} \cdot A_{b,s}}{\gamma_{Mb}} \tag{16}$$

After checking the design resistance, the horizontal displacements should be checked for the serviceability limit state and for the ultimate limit state.

3 The CEB Design Guide model

In the CEB Design Guide (CEB, 1996), the load transfer from a fixture (e.g. base plate) into the concrete is covered. The CEB Design Guide covers many types of anchors and possible failure modes of the concrete. The design of the fixture (e.g. the base plate) must be performed according to the appropriate code of practice. In case of steel fixtures, a steel construction code is used.

Background information can be found in a separate CEB state of the art report: "Fastenings to concrete and masonry structures" (CEB, 1994). It reviews the behaviour of fastenings in concrete and masonry for the entire range of loading types (including monotonic, sustained, fatigue, seismic and impact loading), as well as the influence of environmental effects, based on experimental results.

For the transfer of shear forces, two methods are considered, namely:

- Friction between the fixture (e.g. base plate) and the grout or concrete,
- Shear/bending of the anchors.

3.1 *Friction between base plate and grout/concrete*

In section 4.1 of the CEB Guide it is stated that when a bending moment and/or a compression force is acting on a fixture, a friction force may develop, which for simplicity may conservatively be neglected in the design of the anchorage. If it is to be taken into account, then the design value of this friction force $V_{Rd,f}$ may be taken as:

$$V_{RD,f} = V_{Rk,f} / \gamma_{Mf} = \mu \cdot C_{Sd} / \gamma_{Mf} \qquad (17)$$

with

$V_{Rk,f}$	=	characteristic shear force
$V_{Rd,f}$	=	design shear force
μ	=	coefficient of friction
C_{Sd}	=	compression force under the fixture due to design actions
γ_{Mf}	=	1,5 (ultimate limit state)
γ_{Mf}	=	1,3 (limit state of fatigue)
γ_{Mf}	=	1,0 (serviceability 1imit state)

In general, the coefficient of friction between a fixture and concrete may be taken as $\mu = 0,4$. The friction force $V_{Rd,f}$ should be neglected if the thickness of grout beneath the fixture is thicker than 3 mm (e.g. in case of levelling nuts) and for anchorages close to an edge.

In conclusion, it can be stated that for "normal column bases", according to the CEB Guide, load transfer through friction should be neglected because in normal steel constructions the thickness of the grout is always more than 3 mm.

3.2 *Shear/bending of anchor bolts*

For the resistance of anchor bolts, two cases are considered, namely *(b)* and *(c)*:

(b)   *Shear loads without lever arm*

Shear loads acting on anchors may be assumed to act without a lever arm if both of the following conditions are fulfilled.

(1)   The fixture must be made of metal and in the area of the anchorage be fixed directly to the concrete without an intermediate layer or with a levelling layer of mortar with a thickness ≤ 3 mm.

(2)   The fixture must be adjacent to the anchor over its entire thickness.

(c)   *Shear loads with lever arm*

If the conditions (1) and (2) of the preceding section *(b)* are not fulfilled, the length ℓ

of the lever arm is calculated according to equation (18):

$$\ell = a_3 + e_1 \tag{18}$$

with

e_l =   distance between shear load and concrete surface

a_3 =   0,5 d for post-installed and cast-in-place anchors (Figure 8)

a_3 =   0 if a washer and a nut are directly clamped to the concrete surface

d =   nominal diameter of the anchor bolt or thread diameter (Figure 8)

The design moment acting on the anchor is calculated according to equation (19):

$$M_{Sd} = V_{Sd} \cdot \frac{\ell}{\alpha_M} \tag{19}$$

The value of α_M depends on the degree of restraint at the side of the fixture. No restraint ($\alpha_M = 1,0$) should be assumed if the fixture can rotate freely. Full restraint ($\alpha_M = 2,0$) may be assumed only if the fixture cannot rotate (see Figure 8b) and the hole is smaller than 1,2d.
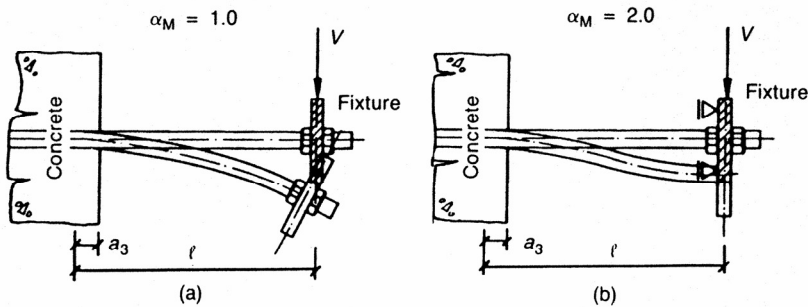

Figure 8: *Examples of fastenings (a) without and (b) with full restrain of the anchor at the side of the fixture (Figure 27 in the CEB Design Guide)*

3.3 *Plastic analysis*

In section 4.2.2 of the CEB Guide it is stated that in a plastic analysis it is assumed that significant redistribution of anchor tension and shear forces will occur in a group of anchor bolts. Therefore, plastic analysis is acceptable only when the failure is governed by ductile steel failure of the anchors. To ensure this failure mode, the CEB Guide gives several conditions that should be met:

(1)   The arrangement of the anchors. It is assumed that base plates meet these conditions.

(2)   The ultimate strength of a fastening as governed by concrete failure, should exceed its strength as governed by steel failure (equation (20)):

$$R_{d,c} \geq 1.25 \, R_{d,s} \cdot f_{uk} / f_{yk} \tag{20}$$

with

$R_{d,c}$ =   design concrete capacity of the fastening (concrete cone, splitting or pull out failure (tension loading) or concrete pry-out or edge failure (shear loading),

$R_{d,s}$ =   design steel capacity of the fastening,

f_{uk} =   the characteristic ultimate tensile strength (nominal value),

f_{yk} =   the characteristic yield strength or proof strength respectively (nominal value).

Equation (20) should be checked for tension, shear and combined tension and shear forces.

(3)   The nominal steel strength of the anchors should not exceed f_{uk} = 800 MPa. The ratio of nominal steel yield strength to nominal ultimate strength should not exceed f_{yk}/f_{uk} = 0,8, while the rupture elongation (measured over a length equal to 5d) should be at least 12%.

(4)   Anchors that incorporate a reduced section (e.g. a threaded part) should satisfy the following conditions:

(a)   For anchors loaded in tension, the tensile strength N_{uk} of the reduced section should either be greater than 1.1 times the yield strength N_{yk} of the unreduced section, or the stressed length of the reduced section should be ≥ 5d (d = anchor diameter outside the reduced section).

(b)   For anchors loaded in shear or which are to redistribute shear forces, the beginning of the reduced section should either be ≥ 5d below the concrete

surface or in the case of threaded anchors the threaded part should extend $\geq$ 2d into the concrete.

(c) For anchors loaded in combined tension and shear, the conditions (a) and (b) above should be met.

(5) The steel fixture should be embedded in the concrete or fastened to the concrete without an intermediate layer or with a layer of mortar with a thickness ≤ 3 mm.

(6) The diameter of the clearance hole in the fixture should be $\leq 1,2d$ (the bolt is assumed to bear against the fixture).

From the above equations, especially equation (20), it follows that according to the CEB Design Guide plastic design is only allowed for base plates without grout layer or with a grout layer not thicker than 3 mm. For usual base plate construction this means that according to the CEB Design Guide, plastic design is not allowed.

In equation (20) the relation between the required design concrete capacity of the fastening and the design steel capacity of the fastening is given. It appears that for e.g. 8.8 anchors it gives:

$$R_{d,c} \geq 1{,}56\, R_{d,s} \tag{21}$$

In the Stevin Laboratory design model it is assumed that measures are taken to ensure that failure of the concrete will not occur before failure of the base plate or anchor. The above requirements seem adequate to ensure this prerequisite.

3.4 Resistance functions for the shear load

In section 9.3.1 of the CEB Design Guide (1994), the following required verifications are given in the case of shear loading (elastic design approach):

- Steel failure, shear load without lever arm ($V_{Rd,s}$)
- Steel failure, shear load with lever arm ($V_{Rd,sm}$)
- Concrete pry-out failure ($V_{Rd,cp}$)
- Concrete edge failure ($V_{Rd,c}$)

For the design values $V_{Rd,s}$ and $V_{Rd,sm}$ the following equations are given:

$$V_{Rd,s} = \frac{V_{Rk.s}}{\gamma_{Ms}} \qquad \text{with} \qquad V_{Rk,s} = k_2 \cdot A_s \cdot f_{yk} \tag{22}$$

$$V_{Rd,sm} = \frac{V_{Rk.sm}}{\gamma_{Ms}} \qquad \text{with} \qquad V_{Rk.sm} = \frac{\alpha_M \cdot M_{Rk,s}}{\ell} \tag{23}$$

with

$$k_2 \quad = \quad 0{,}6 \tag{24}$$

A_s = stressed cross-section of the anchor in the shear plane

$M_{Rk,s}$ = $M_{Rk,s}^0 (1 - N_{Sd} / N_{Rd,s})$ (25)

$M_{Rk,s}^0$ = characteristic bending resistance of individual anchor $M_{Rk,s}^0 = 1{,}5\,W_{e\ell} f_{uk}$ (26)

$N_{Rd,s}$ = $N_{Rk,s} / \gamma_{Ms}$ (27)

$N_{Rk,s}$ = $A_s \cdot f_{y,k}$ (28)

γ_{Ms} = 1,20 if $f_{uk} \leq 800$ MPa and $f_{yk} / f_{uk} \leq 0{,}8$ (29)

γ_{Ms} = 1,50 if $f_{uk} \geq 800$ MPa or $f_{yk} / f_{uk} \geq 0{,}8$ (30)

N_{Sd} = applied normal force

α_M = factor depending on the support conditions, see Figure 8

ℓ = length of lever arm

Type of grout:
- Special grout Pagel IV
- Sand - cement mortar 2:1
- No grout

Thickness of grout:
- 15 mm
- 30 mm
- 60 mm

Anchor bolt:
- M20 - 4.6
- M20 – 8.8

Anchoring length:
- 250 mm with a bend at the end of the bar
- 600 mm with anchor plate

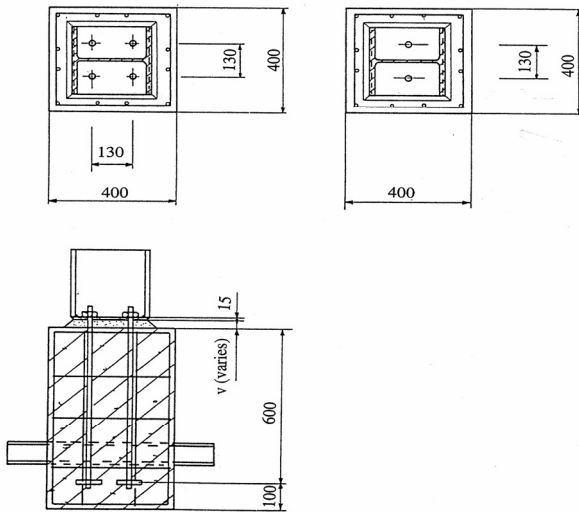Concrete reinforcement:
- with reinforcement
- without reinforcement

Figure 9: Test specimens; in the tests with 4.6 grade anchor bolts, four bolts were applied and in the tests with 8.8 grade anchors two bolts

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Table 1: *Summary of test results and comparison with design values according to the proposed resistance functions (Stevin, 1989)*

Test	Anchors				Thickness of the grout v	Tensile force F_t	Measured ultimate shear force F_h	Failure mode *)	Design value $F_{v,Rd}$ **)	Test / design value
	number	Class	Yield stress f_{yb}	Ultimate stress f_{ub}						
			MPa	MPa	mm	kN	kN		kN	
D7	4	4.6	290	423	30	0	310	Rupture	124	2,50
D8	4	4.6	290	423	30	0	310	Rupture	124	2,50
D9	4	4.6	290	423	30	0	260	Rupture	124	2,10
D10	2	8.8	-	1196	30	0	300	Rupture	117	2,56
D11	4	4.6	283	423	30	0	234	Rupture	124	1,89
D12	2	8.8	-	1176	60	0	295	Rupture	115	2,57
DT1	4	4.6	290	423	30	182	170	Cracking	124	1,37
DT2	4	4.6	290	423	30	121	250	Cracking	124	2,06
DT3	4	4.6	290	423	30	121	240	Rupture	124	1,94
DT4	4	4.6	290	423	30	121	240	Rupture	124	1,94
DT5	2	8.8	-	1152	30	141	178	Rupture	113	1,57
DT6	2	8.8	-	1076	30	141	200	Rupture	105	1,90
DT7	2	8.8	-	1070	30	141	190	Rupture	105	1,81
DT8	2	8.8	-	1045	60	141	230	Rupture	102	2,25
DT9	4	4.6	290	423	60	121	180	Pull-out	124	1,45
DT10	2	8.8	-	1049	60	141	228	Rupture	102	2,23
DT11	4	4.6	290	423	15	121	270	Cracking	124	2,17
DT12	2	8.8	-	1176	15	141	255	Rupture	115	2,21
DT13	4	4.6	280	414	60	121	320	Rupture	122	2,62
DT14	4	4.6	283	411	60	121	305	Cracking	121	2,52
DT15	2	8.8	-	1089	30	200	200	Cracking	107	1,87
DT16	4	4.6	309	443	30	200	255	Rupture	130	1,96

*) Cracking = cracking of the concrete after large deformation of the anchor, e.g. for test DT2 compare Figure 2.

Rupture = rupture of the anchor

Pull-out = pull-out of the anchor

**) These values were calculated with the measured material properties and dimensions.

4 Test Results and Comparison with the Models

4.1 *Test programme*

The main dimensions of the test specimens are given in Figure 9, as well as the parameters in the test programme. See also Figures 3 and 6. More information on the test set-up is given in the Stevin Laboratory report (1989). In the test programme (Stevin, 1989), three test series were carried out:

- Test series 1 (6 tests D1 – D6), with only shear force. Due to insufficient strength of the concrete, premature splitting of the concrete occurred. These test results are omitted.
- Test series 2 (6 tests D7 – D12), with only shear force. In these specimens, more reinforcement bars were applied in the concrete.
- Test series 3 (16 tests DT1 – DT16), with a combination of tensile force and shear force.

4.2 *Test results and comparison with the Stevin Laboratory model*

In Table 1 a summary is given of the main test results and a comparison with the proposed resistance functions.

4.3 *Comparison with the CEB model*

The results of the comparison for all tests are given in Table 2. The application of the CEB model for one of the tests (DT5) is demonstrated below.

Bolts M20, grade 8.8

$f_{ub,measured}$ = 1152 MPa

take f_{yk} = $0,8 \cdot 1152$ = 922 MPa

take γ_{Ms} = 1,20 (for 8.8 bolts)

A_s = $\pi \cdot d_s^2 / 4$ = 245 mm² giving d_s = 17,66 mm

$N_{Rk,s}$ = $A_s \cdot f_{yk} = 245 \cdot 922 \cdot 10^{-3} = 226$ kN

$N_{Rd,s}$ = $N_{Rk,s} / \gamma_{Ms} = 226/1,20 = 188$ kN

N_{Sd} = $141/2 = 70,5$ kN

$W_{e\ell}$ = $\dfrac{\pi \cdot d_s^3}{32} = \dfrac{\pi \cdot 17,66^3}{32} = 541$ mm³

$M_{Rk,s}^0$ = $1.5\, W_{e\ell} \cdot f_{yk} = 1,5 \cdot 541 \cdot 922 = 748 \cdot 10^3$ Nmm

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$$M_{Rk,s} \quad = \quad M_{Rk,s}^0(1 - N_{Sd}/N_{Rd,s}) = 748 \cdot 10^3(1 - 70,5/188) = 468 \cdot 10^3 \text{ Nmm}$$

$$V_{Rk,s} \quad = \quad k_2 \cdot A_s \cdot f_{yk} = 0.6 \cdot 245 \cdot 922 \cdot 10^{-3} = 136 \text{ kN}$$

$$V_{Rk,sm} \quad = \quad \frac{\alpha_M \cdot M_{Rk,s}}{\ell} = \frac{2 \cdot 468 \cdot 10^3}{30 + 20/2} 10^{-3} = 23,4 \text{ kN} \leq V_{Rk,s} = 136 \text{ kN}$$

For the test with 2 bolts it follows $2 \cdot 23,4 = 46,8$ kN $\sim$ 47 kN, see Table 2.

Table 2: *Comparison of test results with design values - CEB model and Stevin Laboratory model*

Test	$N_{Rd,s}$ per bolt*)	N_{Sd} per bolt	$N_{Sd}/N_{Rd,s}$	$M_{Rk,s}^0$ *)	$M_{Rk,s}$ *)	Length ℓ	$V_{Rk,sm}$ group*)	Test / CEB	Test / Stevin**)
	kN	kN		Nm	Nm	mm	kN		
DT1	59	45.50	0.77	235	54	40	11	15.6	1.4
DT2	59	30.25	0.51	235	115	40	23	10.9	2.0
DT3	59	30.25	0.51	235	115	40	23	10.4	1.9
DT4	59	30.25	0.51	235	115	40	23	10.4	1.9
DT5	188	70.50	0.37	748	468	40	47	3.8	1.6
DT6	176	70.50	0.40	699	418	40	42	4.8	1.9
DT7	175	70.50	0.40	695	414	40	41	4.6	1.8
DT8	171	70.50	0.41	678	398	70	23	10.1	2.3
DT9	59	30.25	0.51	235	115	70	13	13.7	1.5
DT10	171	70.50	0.41	681	401	70	23	10.0	2.2
DT11	59	30.25	0.51	235	115	25	37	7.3	2.2
DT12	192	70.50	0.37	763	483	25	77	3.3	2.2
DT13	57	30.25	0.53	227	107	70	12	26.2	2.6
DT14	58	30.25	0.52	230	109	70	13	24.4	2.5
DT15	178	100.00	0.56	707	310	40	31	6.5	1.9
DT16	63	50.00	0.79	251	52	40	10	24.5	2.0

*)   Calculated with the measured material properties and dimensions as given in table 1.

**)   The Stevin Laboratory values are taken from table 1.

5   Proposal for Design Rules

On request of the Eurocode 3 Project Team for prEN 1993-1-8 Design of Joints, based on the Stevin Laboratory model, the following design rules were proposed by the authors.

5.1   *Resistance to shear forces*

In a column base the design shear resistance $F_{v.Rd}$ may be derived as follows:

$$F_{v.Rd} = F_{f.Rd} + nF_{vb.Rd} \tag{31}$$

where:

$F_{f.Rd}$ is the design friction resistance between base plate and grout layer:

$$F_{f.Rd} = C_{f.d} \cdot N_{c.Sd} \tag{32}$$

$C_{f.d}$ is the coefficient of friction between base plate and grout layer. The following values may be used:

- for sand-cement mortar $C_{f.d}$ = 0,20   (33a)
- for special grout $C_{f.d}$ = 0,30   (33b)

$N_{c.Sd}$ is the design value of the normal compressive force in the column. If the normal force in the column is a tensile force $F_{f.Rd}$ = 0.

Drafting note: Also, the preload in the anchor bolts contributes to the friction resistance. However, because of its uncertainty (e.g. relaxation and interaction with the column normal force), it was decided to neglect this action.

n is the number of anchor bolts in the base plate

$F_{vb.Rd}$ is the smallest of $F_{1.vb.Rd}$ and $F_{2.vb.Rd}$

$F_{1.vb.Rd}$ is the bearing resistance for the anchor bolt - base plate

$F_{2.vb.Rd}$ is the shear resistance of the anchor bolt

$$F_{2.vb.Rd} = \frac{\alpha_b \, f_{ub} A_s}{\gamma_{Mb}} \tag{34}$$

A_s is the tensile stress area of the bolt or of the anchor bolt

α_b is a coefficient depending on the yield strength f_{yb} the anchor bolt:

$$\alpha_b = 0,44 - 0,0003 f_{yb} \tag{35}$$

f_{yb} is the nominal yield strength the anchor bolt, where: $235 \text{ N/mm}^2 \leq f_{yb} \leq 640 \text{ N/mm}^2$

f_{ub} is the nominal ultimate strength the anchor bolt, where: $400 \text{ N/mm}^2 \leq f_{ub} \leq 800 \text{ N/mm}^2$

γ_{Mb} is the partial safety factor:

$$\gamma_{Mb} = 1,25 \tag{36}$$

5.2 Deformations

In a column base the design shear deformations may be derived as follows:

- If $N_{c.Sd} \leq F_{f.Rd}$ the shear deformation $\delta_v = 0$.

- If $N_{c.Sd} > F_{f.Rd}$ the shear deformation δ_v is the largest of δ_{v1} and δ_{v2}.

$$\delta_{v1} = F_{v.Sd} \frac{\delta_v^*}{F_v^*} \tag{37}$$

$$\delta_{v2} = v_r \left\{ \frac{F_{v.Sd}}{n \cdot f_{yb} \cdot A_s} - C_{fd} \left(1 - \frac{N_{c.Sd}}{n \cdot f_{yb} \cdot A_s} \right) \right\} \tag{38}$$

where

$$\delta_v^* = v_r \sqrt{\frac{2 f_{yb}}{E_a}} \tag{39}$$

$$F_v^* = n \cdot f_{yb} \cdot A_s \left(\frac{\delta_v^*}{v_r} + C_{f.d} \right) - C_{f.d} N_{c.Sd} \tag{40}$$

with

$N_{C.Sd}$ is the design value of the normal force in the column (positive value if the normal force is tensile and negative value if the normal force is compression)

E_a is the elastic modulus of steel

v_r is the design value of the thickness of the grout layer:

$$v_r = v + 0,5 d_b \tag{41}$$

v is the actual thickness of the grout layer.

Remark: The hole clearance may contribute considerably to the horizontal displacements. The hole clearance is not included in the above equations. Displacements due to the hole clearances may be prevented by measures to prevent the bolts moving in the holes, e.g. by filling the hole clearances with a two component epoxy.

5.3 Prerequisites

In the above equations, it is a prerequisite that:

- The grout layer is of adequate quality. See the applicable reference standard.

- The design strength of the anchor – concrete connection is greater than the design rupture strength of the anchor.

- Other failure modes, like splitting of the concrete and pull out of the anchor, are prevented by adequate design and execution of the anchor in the concrete block. Reference is made to

  - EN 1992, Eurocode 2.

  - CEB, 1994. Fastenings to concrete and masonry structures, state of the art report. Comité Euro-International du Béton. Thomas Telford Publishing, London, ISBN: 0 7277 1937 8.

  - CEB, 1996. Design of fastenings in concrete, Design Guide. Comité Euro-International du Béton. Thomas Telford Publishing, London, ISBN: 0 7277 2558 0.

5.4   Application of the equations for the deformation

The equations in section 5.2 are somewhat simplified compared to those given in the section 2, where the Stevin Laboratory model is explained. For the example calculation in section 2.2 (test DT6), it follows:

- For $F_{v.Sd}$ = 94,0 kN: δ_{v1} = *3,60* mm, δ_{v2}= 3,59 mm; the displacement δ_v is the largest of δ_{v1} and δ_{v2}; in this case, δ_v = δ_{v1}= δ_{v2}= 3,6 mm.

- For $F_{v.Sd}$ = 130,0 kN: δ_{v1} = *4,97* mm, δ_{v2}= 7,0 mm; the displacement δ_v is the largest of δ_{v1} and δ_{v2}; in this case, δ_v = δ_{v2}= 7,0 mm.

These values are in agreement with those in section 2.2.

6   Conclusions

6.1   On the behaviour of column bases loaded in shear and tension

- The shear strength of anchor bolts is considerably lower than the shear strength of bolts in bolted connections between steel plates.

- The ductility of the anchor bolts is an important factor for the strength. The lower ductility of 8.8 grade bolts compared to 4.6 grade bolts is reflected in the lower coefficient in the resistance function.

- The influence of a tensile force F_t in the column can be neglected for the determination of the shear resistance.

- The shear resistance is almost independent of the thickness of the grout layer.

- The deformations are greatly dependent on the thickness of the grout layer.

- A "better" grout, e.g. "Pagel IV" gives lower deformations.

- In the design, not only the shear resistance should be checked, but also the deformations at serviceability and ultimate limit state.
- Also other failure modes, like splitting of the concrete block, etc., should be checked.

6.2   *On the models*

- The Stevin Laboratory model gives results that are consistent with test results. It also gives rules to determine the deformation.
- The CEB model gives very conservative results, especially when a large tensile force is present and / or the thickness of the grout layer is large. The main reason is that the CEB model does not take account of the positive influence of the grout layer. The CEB model does not give rules to determine the deformation.

References

CEB, 1994. Fastenings to concrete and masonry structures, state of the art report. Comité Euro-International du Béton. *Thomas Telford Publishing*, London, ISBN: 0 7277 1937 8.

CEB, 1996. Design of fastenings in concrete, Design Guide. Comité Euro-International du Béton. *Thomas Telford Publishing*, London, ISBN: 0 7277 2558 0.

COST, 1999. Column Bases in Steel Building Frames, *COST C1- EU,* Brussels, Luxembourg.

ECCS, 1994. European recommendations for bolted connections with injection bolts. *ECCS publication No. 79*, Brussels.

EN 1993-1-8, 2006. Eurocode 3: Design of Steel Structures, Part 1.8: Design of joints, *CEN*, Brussels.

NEN 6770, 1990. Staalconstructies TGB 1990, Basiseisen en basisrekenregels voor overwegend statisch belaste constructies (TGB 1990 Steel Structures, Basic requirements and basic rules for calculation of predominantly statically loaded structures), *NEN*, Delft.

Stevin, 1989. Bouwman, L.P., Gresnigt A.M., Romeijn, A. Onderzoek naar de bevestiging van stalen voetplaten aan funderingen van beton. (Research into the connection of steel base plates to concrete foundations), *TU-Delft Stevin Laboratory report 25.6.89.05/c6*, Delft.

Nakashima, Shigetoshi, (1998). Mechanical Characteristics of Exposed Portions of Anchor Bolts in Steel Column Bases under Combined Tension and Shear. *Journal of Constructional Steel Research,* 1998, 46:1-3, Paper No. 277.