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APPLICATION OF THE COMPONENT METHOD TO COLUMN BASES

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ABSTRACT: The present paper is aimed at giving an overview of the recent progress made on investigation of column bases with end plates in the framework of the COST C1 European Action. First, the application of the component method to column bases is introduced. Then the particular components are described including their influence on connection behaviour. Finally, assembly procedures are described for these specific connections with a high interaction of the normal force and the bending moment.

1 INTRODUCTION

In column bases, two levels of "connection" may be identified: the connection between the steel column profile and the concrete foundation on one hand, and the connection between the concrete foundation and the soil on the other hand. The latter requires different means of investigation and is influenced by different probabilistic criteria [15]. Only the connection between column footing and concrete block is taken into account here.
The resistance calculation is provided in Annex L of Eurocode 3 [1]. For the evaluation of the stiffness and the deformation capacity, European rules [4], based on existing studies [8], [9], [10] and [15]], are under preparation. These rules refer to the concept of the revised Annex J of Eurocode 3 dealing with beam-to-column joints and beam splices. The component and assembly calculation procedure for the column bases, which have their own peculiarities, is described below.
The characterisation of the components in terms of stiffness, resistance and ductility is a first important step. Figure 1 presents the list of components to be considered for column bases with base plates. Four components are identified: base plate in bending and bolts in tension, concrete block in compression, component in shear, and column flange and web in compression. The assembly of the components follows this step, which gives the distribution of the internal forces between the components and the derivation of the design resistance and the rotational properties of the whole column base.

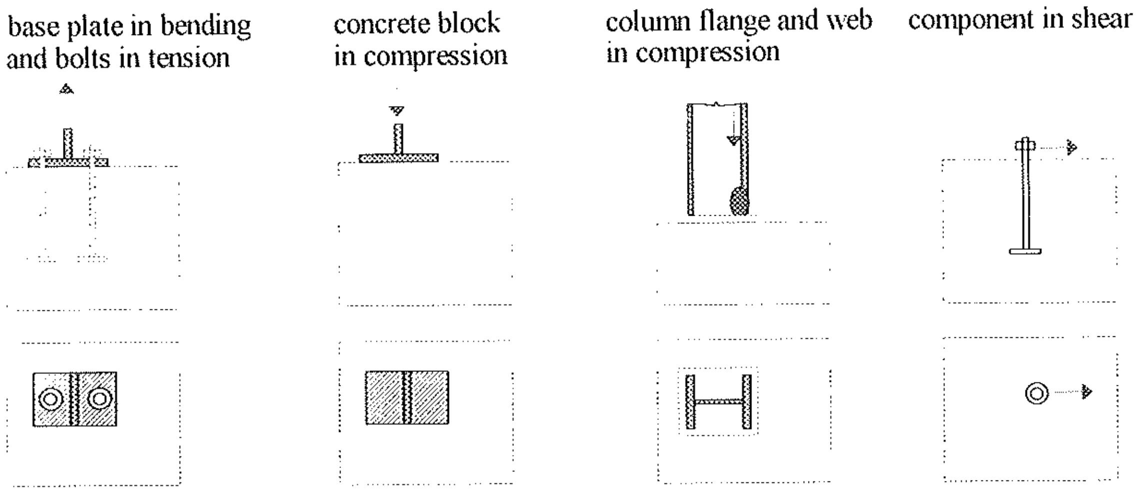


Figure 1 The main components of a column base with base plates

2 COMPONENT MODELLING

2.1 Base plate in bending and bolts in tension

To evaluate the resistance and stiffness properties of the base plate in bending and bolts in tension, reference is made to the so-called "T-stub idealisation", see Figure 2 [2]. It consists of substituting the tensile part of the actual base plate by a T-stub section of appropriate length L_{eff}, connected by its flange (the actual base plate) to a presumably infinitely rigid foundation and subject to a uniformly distributed force F acting in the web plate (the actual column flange). The T-stub behaviour is characterised in [2] by a design resistance F_{Rd} and an initial stiffness $E\,k$ where k is called "stiffness coefficient", see Figure 3.

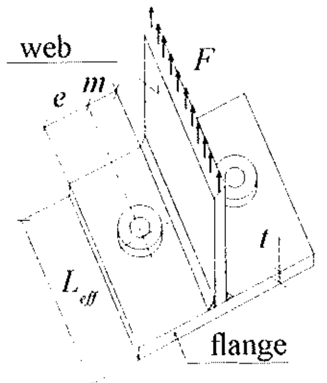


Figure 2 The T-stub on a rigid foundation (one bolt-row)

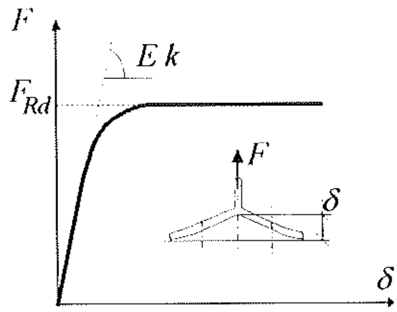


Figure 3 Mechanical properties of the T-stub

Design resistance

In Eurocode 3 Revised Annex J [2], the design resistance of a T-stub flange of effective length L_{eff} is derived as follows for each of the three identified failure modes :

- In Mode 3, the failure occurs by fracture of the anchor bolts without prying forces, as a result of a large plate stiffness, see Figure 4a,

$$F_{Rd.3} = \sum B_{t.Rd} \;. \tag{1}$$

- In Mode 1, a the plastic mechanism develops in the T-stub flange before the strength of the anchor bolts is exhausted

$$F_{Rd.1} = \frac{4\, L_{eff}\, m_{pl.Rd}}{m} \;. \tag{2}$$

- Mode 2 is a mixed failure involving yield lines in the plate – but not a full plastic mechanism – and exhaustion of the anchor bolt strength, see Figure 4c,

$$F_{Rd.2} = \frac{2\, L_{eff}\, m_{pl.Rd} + n \sum B_{t.Rd}}{m+n} \;. \tag{3}$$

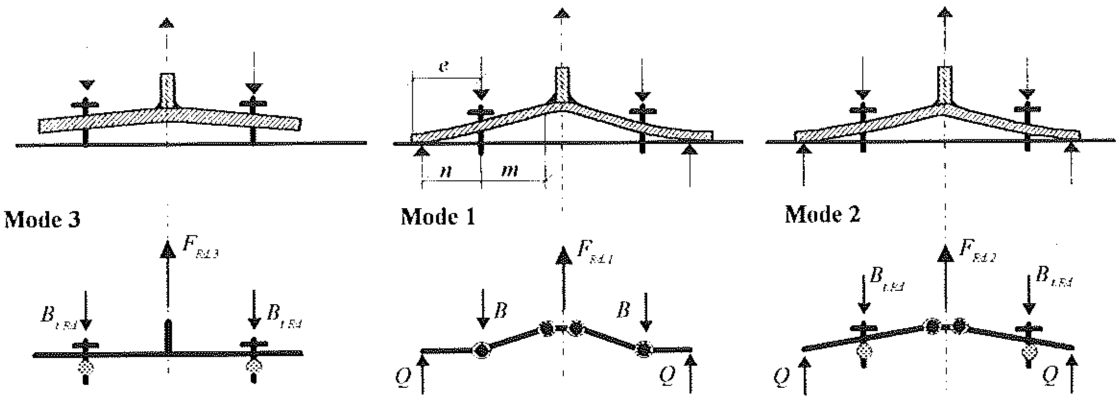


Figure 4 Failure modes in a T-stub

In these expressions, $m_{pl.Rd} = 0,25\, t^2 f_y / \gamma_{M0}$ is the plastic moment of the T-stub flange per unit length, t the flange thickness, f_y yield stress of the flange, γ_{M0} the partial safety factor and m and e are geometrical characteristics defined in Figure 4. $\Sigma B_{t.Rd}$ is the sum of the design resistance $B_{t.Rd}$ of the anchor bolts connecting the T-stub to the foundation. n designates the place where the prying force Q is assumed to be applied, as shown in Figure 4 ($n = e$ but its value is limited to $1,25\ m$). L_{eff} is taken as the smallest value of the effective lengths corresponding to all the possible yield line mechanisms in the specific T-stub flange being considered; it is given in [2].

A less conservative expression for Mode 1 failure is suggested in [2] as an alternative to Formula (2), including the nut size and washer plate in the calculation [8].

It is recommended to use ductile anchor bolts for column bases in steel structures. The ductile anchor bolts have to be sufficiently embedded into the concrete so as to ensure that their failure occurs by excess of tension stress in the net section. Cast-in-place anchors, undercut anchors, adhesive anchors, grouted anchors and some expansion anchors can be ductile anchor bolts if they are sufficiently embedded. The required verification for a single anchor bolt is steel failure, pull out failure, concrete cone failure, and splitting failure of the concrete. Similar verifications are provided for groups of anchors [3].

The design strength F_{Rd} of the T-stub is derived as the smallest value from expressions (1) to (3)

$$F_{Rd} = min\,(F_{Rd.1}, F_{Rd.2}, F_{Rd.3})\ . \tag{4}$$

Expressions for Mode 1 and Mode 2 failures apply as long as the elongation of the anchor bolts in tension does not exceed the deformation of the T-stub flange in bending. In other words, as long as prying forces Q develop between the flange and the foundation.
If this is not the case, Modes 1 and 2 do not occur and a so-called Mode 1* has then to be considered, see Figure 5 [15], in which a specific yield lines mechanism develops in the T-stub flange without any contact with the foundation.

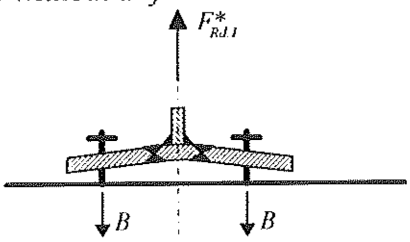


Figure 5 Mode 1* failure

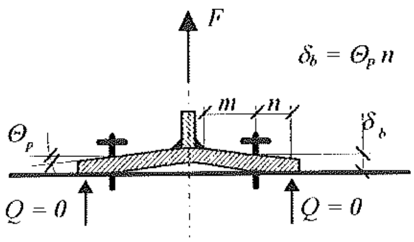


Figure 6 The T-stub deformation when prying force Q vanishes

$$F^*_{Rd.1} = \frac{2\, L_{eff}\cdot m_{pl.Rd}}{m}\ . \tag{5}$$

The criterion to distinguish between situations with and without prying forces is discussed later.

Stiffness

The elastic deformation of a T-stub in tension is elaborately discussed in [8] and accurate formulae for stiffness evaluation are suggested. They have been used in [17] to derive simplified expressions for inclusion in Revised Annex J of Eurocode 3 [2]:

- the stiffness coefficient for the T-stub flange in bending :

$$k_p = \frac{0{,}85\, L_{eff}\cdot t^3}{m^3}\ . \tag{6a}$$

- the stiffness coefficient for the anchor bolts in tension :

$$k_b = 1{,}6\,\frac{A_s}{L_b}\ . \tag{6b}$$

where L_b is the anchor bolt length described hereunder. These two expressions relate to situations where prying forces develop at the extremities of the T-stub flange as a result of a limited bolt-axial deformation in comparison with the bending deformation of the flange.
In "no prying" cases, it is shown [15] that

$$k_p = \frac{0{,}425\ L_{eff}\ t^3}{m^3} \text{ and } k_b = 2{,}0\ \frac{A_s}{L_b}\ . \qquad \text{(7a and 7b)}$$

Boundary for prying effects

The elastic deformed shape of a T-stub in tension depends on the relative deformability of the flange in bending and the anchor bolts in tension [11]. In Figure 6, the bolt and flange deformations compensate such that the contact force Q just vanishes. For a higher bolt deformability, no contact will develop, while contact forces will appear for a lower bolt deformability. The situation illustrated in Figure 6 therefore constitutes a limit case to which a prying boundary may be associated. This is expressed as follows:

$$L_{b,boundary} = \frac{7\ m^2\ n\ A_s}{L_{eff}\ t^3}\ . \qquad (8)$$

If, as a further assumption, n is defined as equal to $1{,}25\ m$ [17], then :

$$L_{b,boundary} = \frac{8{,}82\ m^3\ A_s}{L_{eff}\ t^3}\ . \qquad (9)$$

L_b is the effective free length of the anchor bolts. It is defined as the sum of two contributions: L_{fl} and L_{el} . L_{fl} is the free length of the anchor bolts, i.e. the part of the bolt which is not embedded. L_{el} is the equivalent free length of the embedded part of the anchor bolt; it may be approximated to $8\ d$ [15], where d is the nominal diameter of the anchor bolt. If L_b is higher than $L_{b,boundary}$, formulae (7), (5) and (1) apply, while formulae (6), (1), (2) and (3) are to be referred to in the opposite case. It has to be noted that the bolt in tension contributes to the flexibility of all the column bases in a quite predominant way.

2.2 Column Flange and Web in Compression

The risk of excessive yielding or instability in the column flange and web in compression close to the base plate is similar to that observed in the compression zone of a beam in a beam-to-column joint. For strength evaluation, reference is therefore made to the appropriate rule in the Revised Annex J of Eurocode 3 [2]. As for beam-to-column joints, no contribution of the column flange and web in compression to the overall flexibility of the base plate connection is considered.

2.3 Concrete Block in Compression

Resistance

The resistance of the grout and the concrete block in compression is limited by the crushing of the grout or concrete under the flexible base plate [5]. In engineering models, the flexible base plate is transferred to an equivalent rigid plate round the column cross section, see Figure 7. The calculation of the bearing resistance $F_{c.Rd}$ under the base plate is based on the evaluation of the concentration factor k_j, see Annex L [1], and the concrete bearing resistance f_j,

$$k_j = \sqrt{\frac{a_1\, b_1}{a\, b}} \quad ; \quad f_j = \frac{\beta\, k_j\, f_{ck}}{\gamma_c} \quad ; \tag{10}$$

$$c = t \sqrt{\frac{f_y}{3 f_j\, \gamma_{M0}}} \; ; \tag{11}$$

$$F_{c.Rd} = A_{eff}\; f_j \quad . \tag{12}$$

In these formulas is f_{ck} the characteristic value of the concrete compressive cylinder strength, γ_c the partial safety factor for concrete and γ_{M0} the partial safety factor for steel. The effective area A_{eff} round the part of the column cross – section, which is in compression is described in figure 7.

The grout quality and thickness is introduced by the joint coefficient β [1]. For $\beta_j = 2/3$, it is expected that the grout characteristic strength $f_{c.g}$ is not less than $0,2$ times the characteristic strength of the concrete foundation f_c ($f_{c.g} \geq 0,2$) and the thickness of the grout is $t_g \leq 0,2 \; min \; (a \; ; \; b)$, see [1]. In cases of a different grout quality or higher thickness of the grout $t_g \geq 0,2 \; min \; (a \; ; \; b)$, it is necessary to check the grout separately. In this case the three dimensional conditions of grout can be treated similar to concrete block.

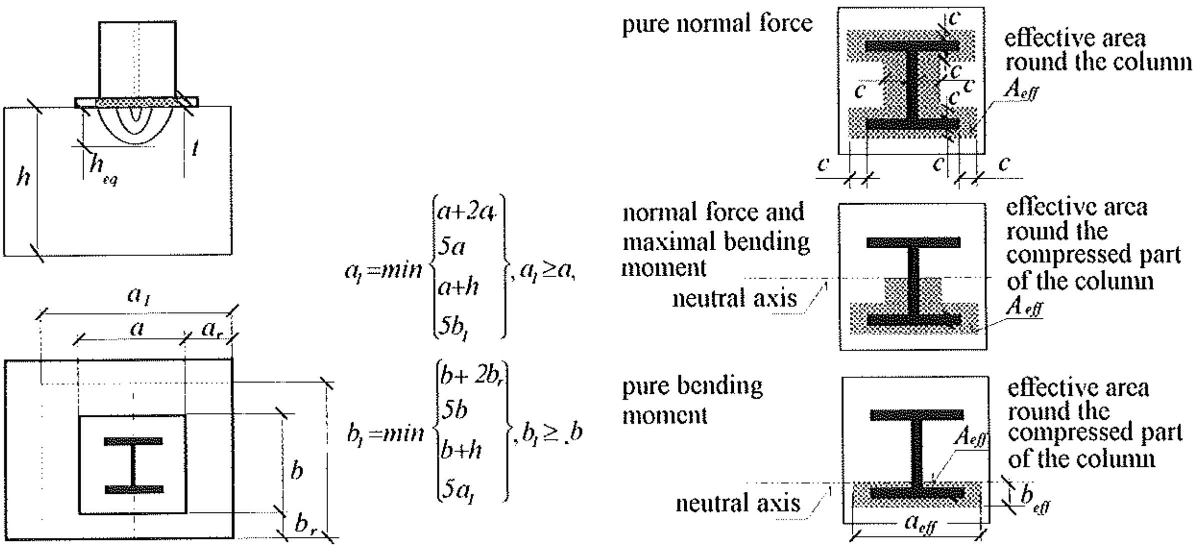


Figure 7 Local deformation of the concrete block, the effective area under the flexible plate

Stiffness

In the stiffness model for this component takes the deformations in the connection area are into account (not the deformations in the supporting structure or subsoil). The deformations in the concrete block depend on the flexibility of the base plate, the size of the concrete block and the stiffness of the concrete and the grout. The depth of the concrete block to be taken into account (the equivalent height) can be taken as the base plate width.

Due to the flexibility of the base plate, the bearing stresses under the base plate are unevenly distributed. In the model, an effective area is defined where an even distribution of bearing stresses is assumed; also for the initial elastic stage [5]. For this effective area the same value as for the resistance calculation can be applied [11]. For a typical rectangular effective area, with a_{eff}, b_{eff}, the equivalent height is calculated as: $h_{eq} = min\; [h;\; (a_{eff} + b_{eff}) \,/\, 2]$.

The factor k_j is taken from equation (10) in Annex L [1]. For a concrete block of limited size, k_j varies in range from $1{,}0$ to $5{,}0$. These boundaries can be introduced in the prediction by linear interpolation in formula (13) as proposed to the ad-hoc group [4] and which gives the relationship between the displacement δ_c and the applied force F_c to the component in compression

$$\delta_c = \frac{F_c}{E_c\; A_{eff}}\, h_{eq} \left(1 - 0{,}35\, \frac{k_j - 1}{4} \right) \; . \tag{13}$$

The stiffness can be expressed in the form of the component stiffness method [2] as

$$k_c = \frac{A_{eff}\; E_c}{E\; h_{eq}}\, \frac{1}{\left(1 - 0{,}35\, \dfrac{k_j - 1}{4} \right)} \approx \frac{A_{eff}\; E_c}{E\; h_{eq}} \; . \tag{14}$$

Finite element calculations have been carried out [11], in which the effective area A_{eff} is simulated by a rigid plate. In Figure 8 the results of the FE calculations are compared to the analytical prediction (for the design resistance in the elastic stage).

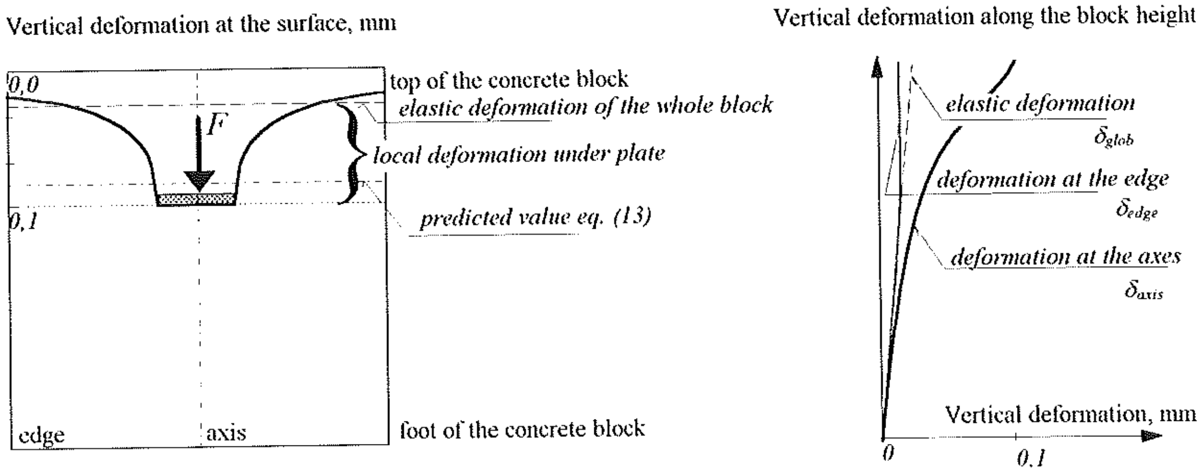


Figure 8 Calculated vertical deformations of a concrete block $0{,}5 \times 0{,}5 \times 0{,}5\ m$ loaded to a deflection of $0{,}01\ mm$ under a rigid plate $0{,}1 \times 0{,}1\ m$. In the figure on the right, the deformations along the vertical axis of symmetry δ_{axis} are given and the calculated deformations at the edge δ_{edge}. Also given are the global elastic deformations according to $\delta_{glob} = F_c\, h /(E_c\,)$, where A_c is the area of the concrete block [11].

2.4 Component in Shear

Horizontal shear force may be resisted either by a) friction between the base plate, grout and concrete footing, b) shear and bending of the anchor bolts, c) a special shear stud, which is usually a block of I-stub or steel pad welded to the underside of the base plate, and d) direct contact, which can be obtained by recessing the base plate into the concrete footing, see Figure

9, [3]. Prestressing the anchor bolts will increase resistance of the shear force transfer by friction.
In most cases, the shear force can be transmitted through friction between the base plate and the grout. The friction depends on the minimum compressive load and on the coefficient of friction, for the characteristic value of friction coefficient and partial safety factors see [3]. Sometimes, for instance in slender buildings, it may happen that due to horizontal forces (wind loading) the normal compressive force is absent or is a tension force. In such cases, the horizontal shear force usually cannot be transmitted through friction between the base plate and the grout. If no other provisions are installed (e.g. shear studs), the anchor bolts will have to transmit these shear forces.

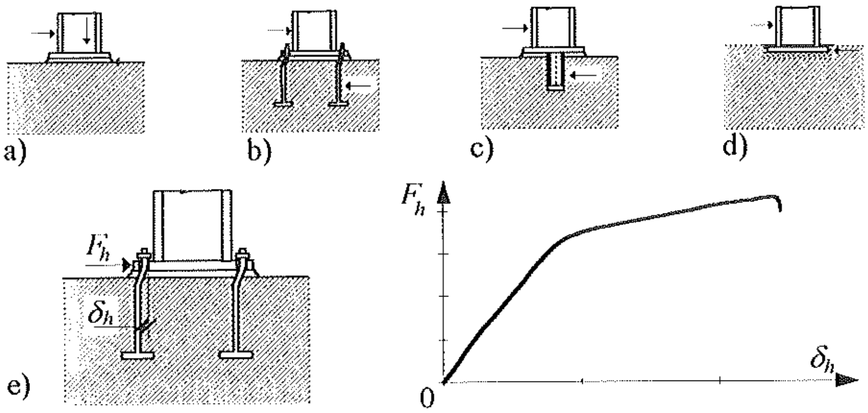


Figure 9 Column bases loaded by shear: a) friction, b) shear and bending of the anchor bolts, c) special shear stud, d) direct contact, e) load deformation behaviour for shear, bending and tension in the anchor bolts [6].

Because the grout does not have sufficient strength to resist the bearing stresses between the bolt and the grout, considerable bending of the anchor bolts may occur, as is indicated in Figure 9. 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 [3].
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. The increasing vertical component gives an increased contribution to the transfer of load by friction. These factors explain the shape of the load deformation diagram in Figure 9.
The thickness of the grout layer has an important influence on the horizontal deformations. In the tests reported in [6], deformations at rupture of the anchor bolts were between about *15 and 30 mm* while grout layers had thicknesses of *15, 30 and 60 mm*. In [6] also an analytical model is developed for the description of the load deformation behaviour. 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 in the case of oversized holes. It may be useful in such cases to apply larger washers under the nuts, that can be welded on the base plate, or to fill the hole by a two component resin.

3 COMPONENT ASSEMBLY

The previous paragraphs describe how the load - deformation curve of each individual component of a column base joint may be determined. In order to end up with a moment-rotation curve which represents the global behaviour of the joint, the component characteristics have to be assembled. For this purpose, appropriate analytical or mechanical models are used, for example spring models. The assembly of the components of a column base joint with an end plate is similar to that of beam-to-column joints. However, the assembly is significantly affected by the interaction of normal forces and bending moments.

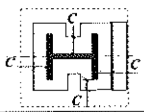
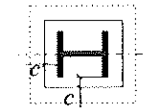
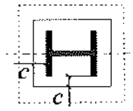
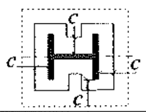
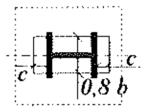
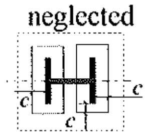
	Mechanical	Analytical				
Model	Sophisticated two dimensional [7]	Complex model [14]	Simplified stiffness [16]	Simplified strength [16]	Simplified strength [7]	Simplified strength and stiffness [12]
M-ϕ curve	Non-linear	Non-linear	Stiffness	Strength	Strength	Non-linear
Components description	Non-linear	Bi-linear	Stiffness only	Strength only	Strength only	Bi-linear
Effective area of an equivalent rigid plate	Annex L 	Rectangular for H section 	Rectangular for H section 	Annex L [1] 	Rectangular 	Web neglected 
Stress to concrete	Non-linear springs	Elasto-plastic (12 stress patterns)	Three patterns only	Plastic only	Plastic only	Plastic only
Compatibility	Yes	Yes	Yes	Not for strain	Simplified	Simplified

Figure 10 Comparison of different assembly procedures

Different researchers developed various assembly models, e.g. [7], [12], [14] and [16]. At present, an ad-hoc group of COST C1 WG2 is investigating these models in order to agree on a common model which should be used as a basis for forthcoming European design rules. The following paragraphs summarise the actual state of the art.
Figure 9 presents a brief overview of the different assembly models. It can be seen that some models consider the full non-linear behaviour, while others only deal with the resistance or with the stiffness of the joint. Most of the models fulfil the requirements for compatibility (i.e. equilibrium of internal forces, deformations, etc.), but some of them in a simplified way only.

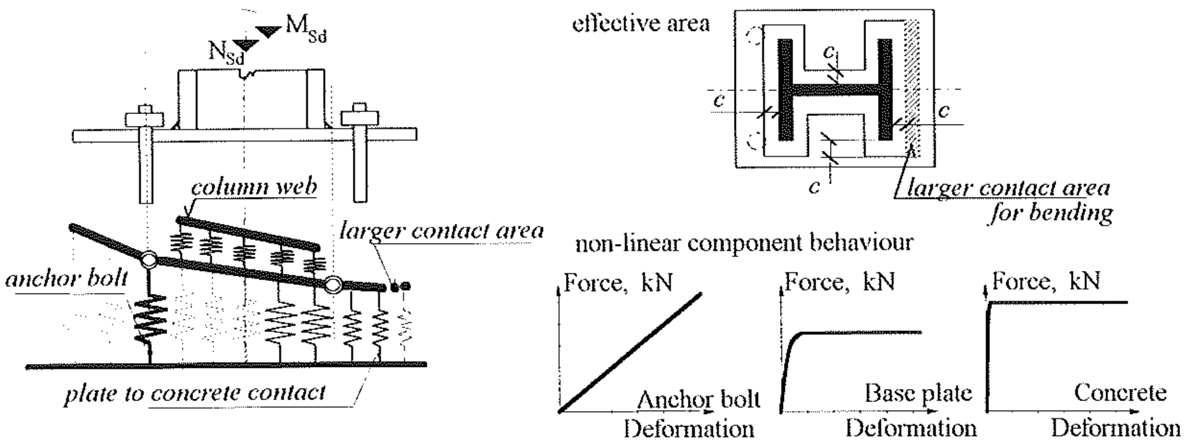


Figure 11 A mechanical model for the assembly procedure of the components acc. to [7]

The mechanical model presented in [7] is based on a 2D non-linear spring simulation. It can take into account not only the non-linear behaviour of each component, but it can also simulate the positive influence of changes of the effective area under bending, see Figure 11. This mechanical model is certainly useful for researchers performing scientific background studies and comparisons. Test results demonstrate a good accuracy of the model. However, the model is too complex for daily design practice. A more practical approach is the component method to predict the design resistance, stiffness and deformation capacity.

Resistance

As can be seen in Figure 9, the various models use different approaches to determine the effective area. In the models it is assumed that this effective area represents a rigid plate with a certain stress distribution in the compression zone. It can be understood that the shape of this effective area will strongly influence the complexity of the assembly models. This is because the assembly procedure should take the normal forces and the bending moments acting to the joint into account. Their actual values will influence the position of the neutral axis of stresses, which also depends on the shape of the effective area.

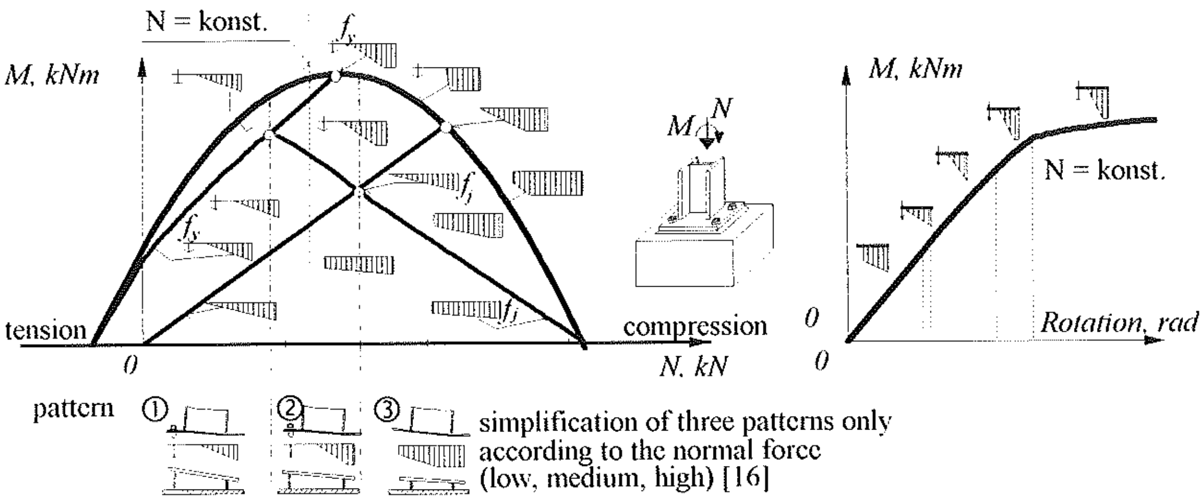


Figure 12 Moment-normal force diagram with possible boundaries of the internal force distribution [14], the simplification to three patterns only and a predicted moment-rotation diagram.

Most proposals for the effective area are based on the model given in Annex L of Eurocode 3 [1], which assumes a certain distribution of stresses in the base plate under the column profile (bearing width 'c').
Furthermore, the models assume a certain pattern for the compressive stresses. The simplest approach is a full plastic stress distribution for the resistance calculation.

Rotational stiffness

The prediction of the rotational stiffness has to be based on simplifications of the effective area in order to allow for the development of a procedure with a limited degree of complexity. The simplified area using a rectangular shape enables taking all stress distributions (12 patterns) into account. A more simple solution, for example with only three categories of high, medium and low normal force is also an option, see Figure 12 [15], where f_y represents yielding in the tension part and f_j represents the concrete bearing resistance. The simplest modelling takes the areas under the flanges only into account, see Figure 13 [12]. This has the advantage of simple modelling without losing accuracy under pure bending, when the contact is correctly predicted, but it has the disadvantage of losing the accuracy under high normal force and a very small bending moment; especially for cross sections with a significant effective area under the column web.

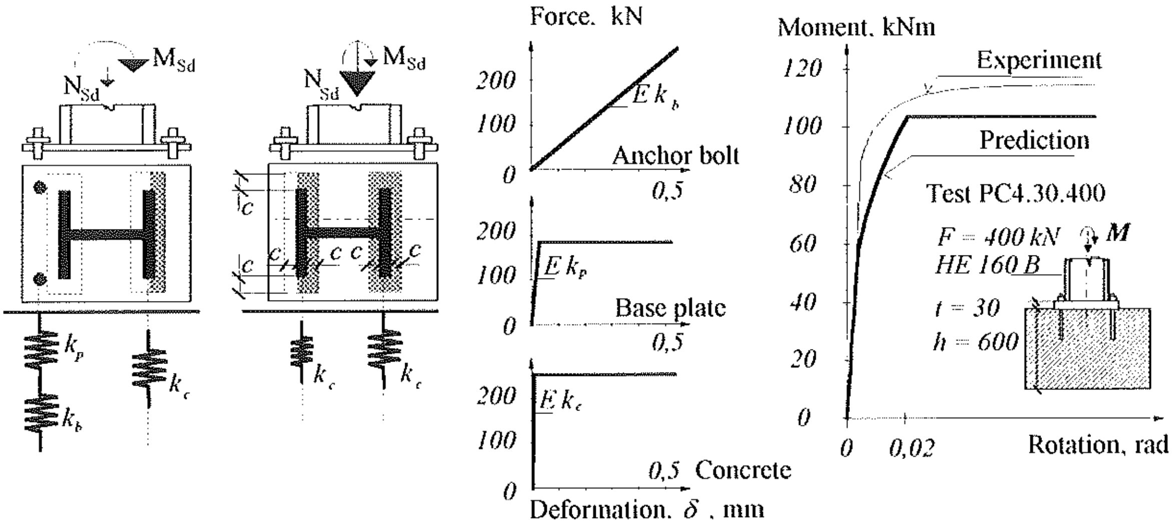


Figure 13 The assembling with an effective area around the column flanges only [12]. For high bending moments and low bending moments respectively, the bi-linear load-deformation curves of the components and the moment-rotation diagram for the joint in comparison to test no PC 4.30.400 are shown, see [13].

4 CONCLUSIONS

- The component method describes the column base with end plates in terms of design resistance, bending stiffness and rotation capacity with good accuracy.

- The prediction of the main components, the base plate in bending and the anchor bolt in tension, and the concrete block in compression, is developed for practical application, based on tests, FE simulation and analytical sensitivity studies.

- The assembly of the components is influenced by the interaction of bending moment and normal force. The resistance prediction can be based on the effective contact area [1], but for the calculation of the bending stiffness requires its simplification.

Acknowledgement

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