DESIGN OF STEEL COLUMN BASE CONNECTIONS FOR LARGE ECCENTRICITIES

BY

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Abstract. In this paper, the concrete underneath the base plate together with the base plate is referred to as "component concrete in compression and base plate in bending" or in short "concrete in compression". The strength of the concrete in compression depends on the concrete base material, the behaviour of the grout layer and the complex phenomena in the contact area between the base plate and the concrete. Models are presented for the determination of the resistance of this component. The models have been validated with tests. In this paper a brief description of literature reviewed is presented along with their various assumptions adopted during modeling.

Key words: base plate; components method; concrete bearing strength.

1. Introduction

The column base connection is one of the critical connections in a steel structure: it is designed to support gravity loads, bending moments and shear forces. The couple of forces of bearing on the concrete and tension in anchor bolts resists to the external bending moment resulted by fixing the column base in foundation.

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The determination of the design value of the external shear force as well as the value of the design bending moment are often performed independently, assuming there is no significant interaction between them. If the base plate remains in compression, shear force may be transmitted through friction between the grout pad or the concrete in foundation. Large shear forces can be resisted through bearing by concrete, either by directly embedding the column base on acertain depth in cast at site concrete or by welding a shear lug at the bottom the base plate, the first being in its turn embedded in cast at site concrete.

The general behavior and distribution of forces for a column base plate connection with anchor rods will be elastic until one of the following failure modes will prevail: formation of a plastic hinge forms in the column, a plastic mechanism in the base plate, crushing of concrete in bearing, yielding of the anchor rods in tension, or tear off of the concrete by the anchor bolts in tension. The failure of the connection mostly consists in brittle fracture of base plate, excessive anchor bolt elongation, unexpected early anchor bolt failure, and concrete crushing.In statically loaded structures, if the strength is much larger than the demand, the ductility criterion is not prevailing,the design at limit state of tensile or shear strength of the anchor rod group being appropriate.

Above observations impose an improved understanding of the beahiour of the column-base plate connection under large eccentricities induced by bending moments and the development of more reliable design methods insuring in the same time an increased ductility for the connections.

2. Existing Design Methods for Base Plates

The prediction of the behaviour of base plate joint is complex due to the bond between the anchor rods and the concrete base material, the behaviour of the bedof mortar layer and the complex evaluation of the stiffness and resistance of the concrete below the compressed part, due to the contact phenomena between the base plate and the concrete.

Two general approaches are adopted for the design of base plates subjected to axial load and bending moment. One is based on the elastic behavior of the material and of all the elements of the connection; the other is based on the failure modes due to post elastic stresses and deformations.

The elastic analysis is based on the assumption of a stiff base plate with full contact to the concrete base which remains plane and develops stresses and strains in the elastic range. The elastic approach (Thambiratnam & Paramasivam, 1986; Ballio & Mazzolani, 1983; Salmon & Johnson, 1980) is covered by all the literature with respect to the approach of designing moment resistant joints.

The strain distribution is linear and the result is that the strain in the anchor bolt is dependent on the strain distribution in the bearing area. This is

not consistent with actual behavior.In fact, the force in the bolt and the bearing in the concrete are independent. This approach (Fig. 1 *b*) is more consistent with the actual behavior when the results are compared to tests (DeWolf & Sarisley, 1980).
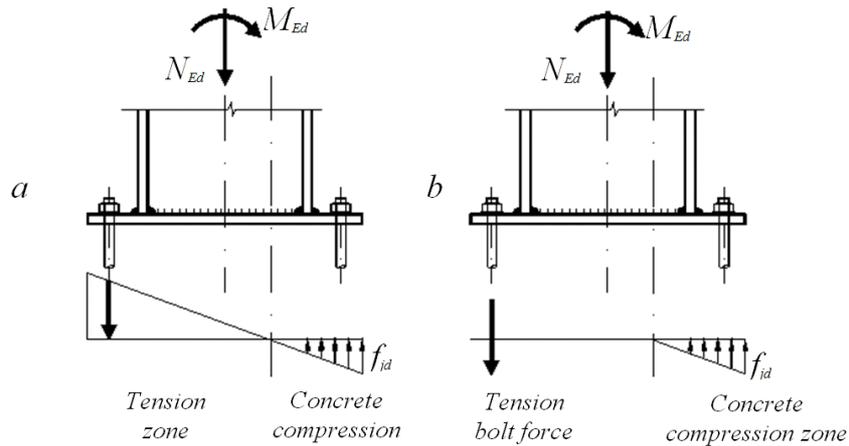

Fig. 1 – Elastic analysis of steel column foundation designed to axial load and bending moment: *a* – theoretical assumption; *b* – actual behaviour.

The design of base plates within elastic theory assumptions often leads to thick, uneconomical steel plates.

A minimized steel consumption for this joint may be achieved by approaching the plastic design. A plastic distribution of the internal forces for calculations at the ultimate limit state is adopted for the design of column bases in EN 1993-1-8.

3. Eurocode 3 Design Model for Base Plates

3.1. Component Method for Base Plates

The concept adopted by EN 1993-1-8 is to transform the flexible base plate into an effective rigid plate and to allow the development of stresses in the concrete foundation that will reach ultimately the resistance to compression in a concentrated area (Murray, 1983).

The main advantage of the component method (Fig. 2) is the ability to allow prediction of the rotational capacity of different types of joints by means of a single approach, starting with an appropriate identification in parallel with modeling of all the sources (elements) of both resistance and deformation.

These individual elements are nominated as components (parts of the connection) and they are assembled, producing a complete model of the joint.
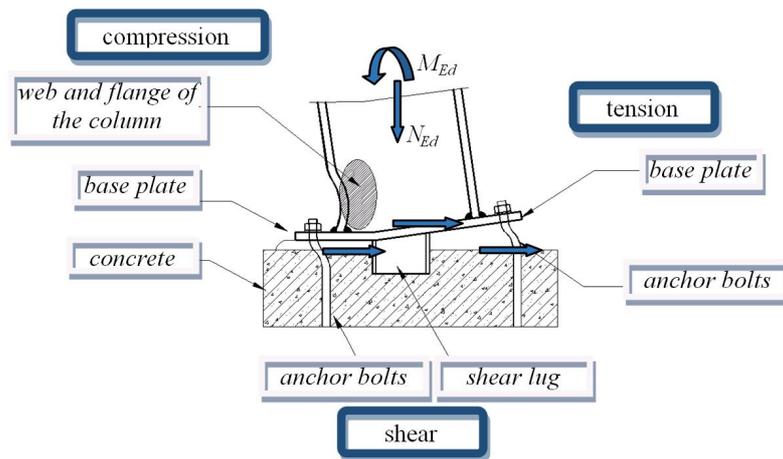
Fig. 2 – Eurocode 3 model – components decomposition.

In addition, the loading process plays an important role in the behaviour of base plate joints.

In the technical literature, two different types of loading processes are usually adopted:

a) the first is characterized by an incremental loading, the vertical load and the bending moment being in direct proportion increased, so that the eccentricity is constant during the loading process;

b) conversely, the second one is characterized by a loading process during which the vertical load is applied in a first loading phase and in the second phase the application of an increasing bending moment is carried out up to failure. In this case, the eccentricity is continuously increasing giving rise to an additional non-linearity source in the joint behaviour.

For the configuration of the column base plate connection given in Fig. 2, according to the procedure proposed by Eurocode 3, three different component groups are identified in relation with their individual loading: the concrete in compression, the base plate in bending, the anchor rods in tension and the column flange and web in compression.

In order to determine whether anchor bolts are necessary, the base plate dimensions are needed by a preliminary sizing.

The application of the component method requires the development of the following steps:

a) determine the compression force under base plate;

b) size the height of compression zone;

c) calculate the inner moment resistance.

If the resistance of the anchor bolts and the frictional resistance are exceeded, the shear force must be transferred to the foundations in other manners (the use of shear lugs or the embedment of the column base into the foundation).

3.2. Bearing Strength of the Concrete

Two assumptions are used in the literature with respect to the resistance of concrete in compression: the base plate is assumed to be rigid or, it is assumed to be flexible.

A rigid base plate connection loaded with axial force is assumed to develop uniformly distributed stresses under the plate, whilein the case of a flexible plate, the stresses are concentrated around the footprint of the column section under the plate (see Fig. 3).
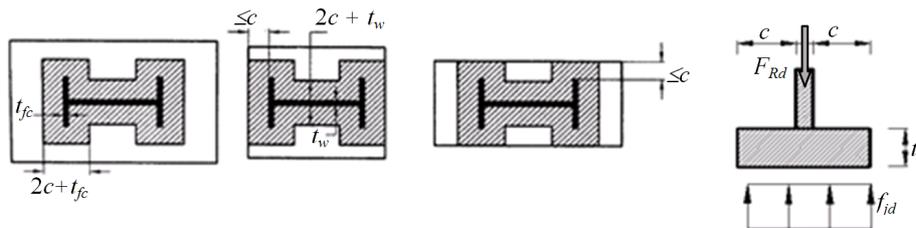

Fig. 3 – Flexible base plate modelled as a rigid plate of equivalent area.

The grout layer between the base plate and the concrete influences the resistance and the stiffness of this component so its resistance and rigidity are included in the whole evaluation of the component.

The bearing strength of the concrete underneath the plate is dependent on the size of the concrete block. The allowable stress, f_{jd}, of the joint, according EN 1993-1-8 and EN 1992-1-1, is evaluated with the following relationships:

$$f_{dj} = \frac{\beta_j F_{Rdu}}{A_{\text{eff}}}, \tag{1}$$

where F_{Rdu} is the local design resistance force given in EN 1992-1-1. According to EN 1993-1-8, (2005), the joint coefficient, β_j, is taken as 2/3 when the grout has at least 20% of the characteristic strength of the concrete foundation.

The design value for the bearing strength concentrated around the footprint of the column section under the base plate (Fig. 3), according EN 1993-1-8, is obtained from a cantilever with the span c:

$$c \leq t \sqrt{\frac{f_y}{3 \cdot f_{jd} \cdot \gamma_{M0}}} \ , \tag{2}$$

where t is the thickness of the base plate.

3.3. Simplified Design

The design starts with assuming an equivalent eccentricity, e, equal to the moment, M, divided by the external axial force, P. It results then that the bending moment and the external axial force are replaced by equivalent axial force acting at distance e from the center of the column, as presented in Fig. 4. For small eccentricities, the equivalent axial force is resisted by bearing only.

Starting from the translational and rotational equilibrium conditions, the joint moment resistance, $M_{j,Rd}$, is expressed as a function of the load eccentricity, e, as it follows:

a) low eccentricity, $e < z_{c,r}$

$$M_{j,Rd} = \min \left\{ \frac{F_{c,l,Rd} z}{\dfrac{z_{c,r}}{e} - 1}, \quad \frac{F_{c,r,Rd} z}{\dfrac{z_{c,l}}{e} + 1} \right\}, \tag{3}$$

b) high eccentricity $e > z_{c,r}$

$$M_{j,Rd} = \min \left\{ \frac{F_{t,l,Rd} z}{1 - \dfrac{z_{c,r}}{e}}, \quad \frac{F_{c,r,Rd} z}{\dfrac{z_{t,l}}{e} + 1} \right\}, \tag{4}$$

where $F_{c,l,Rd}$ is the resistance to compression under the left flange of the column, $F_{c,r,Rd}$ – the resistance to compression under the right flange of the column, $F_{t,l,Rd}$ – the resistance to tension located either under the left flange or in the axis of the bolt situated at left side and $F_{t,r,Rd}$ has similar significance with respect to the right side, depending on the sign of the bending moment; finally $z_{c,l}$, $z_{c,r}$, $z_{t,l}$ are the distances from the column axis to the left, respectively to the right components – flange and bolt (Fig. 4). The distance z is the lever arm of the couple of forces designed to resist to the combined action of external force and bending moment, being equal with $z_{c,l} + z_{c,r}$, in case of small eccentricity, and equal to $z_{t,l} + z_{c,r}$, in case of big eccentricity (Fig. 4).

The resistance of the base plate in tension, $F_{t,Rd}$, may be modeled by means of an equivalent T-stub element according to the well-known EN 1993-1-8 formulations.
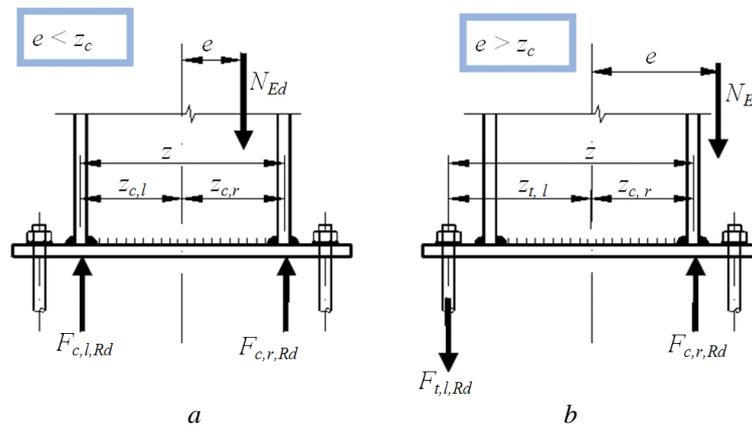
Fig. 4 – Base plate design cases: *a* – small eccentricity – full plate
in compression; *b* – large eccentricity – reduced surface of the base
plate in compression.

Therefore, the resistance of the base plate in tension in the absence of
prying forces may be determined with the following relationships:

$$F_{t,Rd} = \min\left\{ \frac{2M_{pl,1,Rd}}{m}, \quad \sum B_{t,Rd} \right\}, \tag{5}$$

where: $M_{pl,1,Rd}$ is the plastic bending moment of the base plate corresponding to
type 1 collapse mechanism, m – the distance between the plastic hinge and the
bolt axis and $\sum B_{t,Rd}$ – the design resistance in tension of the anchor bars.

The resistance of the components in compression, $F_{c,Rd}$, is given by the
minimum value between the bearing resistance of the concrete and the
resistance to failure in compression of the column flange and web, as follow:

$$F_{c,Rd} = \min\left\{ f_{jd} b_{eff} l_{eff}, \quad \frac{M_{c,Rd}}{h_c - t_{fc}} \right\}, \tag{6}$$

where: f_{jd} is the resistance in compression of concrete under axial point loads,
b_{eff} and l_{eff} – the effective width and, respectively, length of the compressed *T*-
stub flange, $M_{c,Rd}$ – the column plastic resistant moment accounting for the
interaction with shear and axial stresses, according to EN 1993-1-8, h_c – the
column section height and t_{fc} – the column flange thickness (Fig. 5).

3.3. Discussion Upon the Components Method Applied for Base Plates

The validation of this method for the design of column bases in EN
1993-1-8 has some limitations. In case of column-base joints subjected to axial
load and bending moment, a simplified approach is proposed by the code

suggesting to neglect the contribution due to the web of the *T*-stub. Eurocode 3 assumes that the instantaneous center of rotation should be in the axis of the column flange, this being a very conservative hypothesis adopted for the position of the concrete compression force (Fig.5).
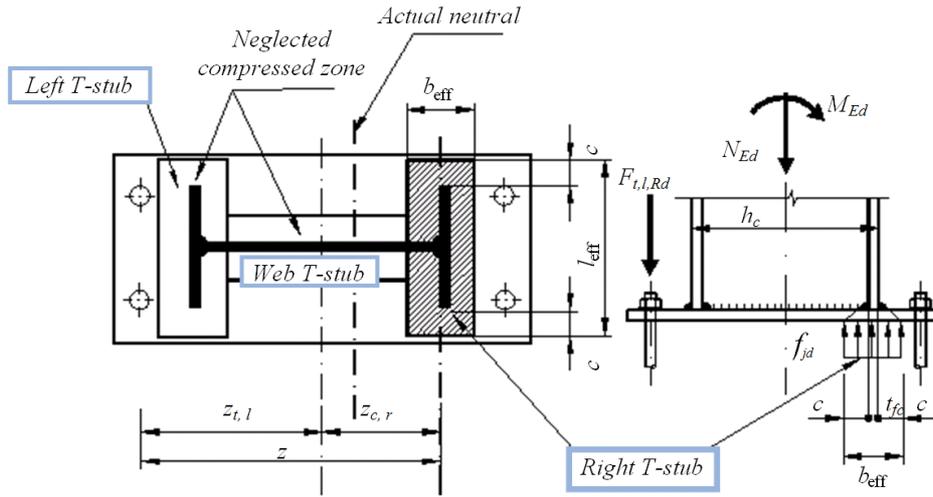
Fig. 5 – Position of the actual neutral axis *versus* Eurocode 3 model.

3.4. Bearing Area of the Concrete According to EN 1992-1-1

The extension of the compression zone, x (see Fig. 6), may be determined based on the allowable stress f_{jd} in the connection according EN 1993-1-8 and EN 1992-1-1.

In Eurocode 2, x is the distance to the plastic neutral axis, the width of the stress block being αx (see Fig. 7). Consideration of a rectangular stress distribution in accordance with Eurocode 2 ($\alpha = 1$) leads to the following eq.:

$$F_c = \alpha x b_{\text{eff}} . \tag{5}$$

Vertical force equilibrium requires that

$$F_t = F_c - N_{Ed} . \tag{6}$$

Thus the lever arm and the moment resistance of the base plate can be determined as follows (Fig. 7):

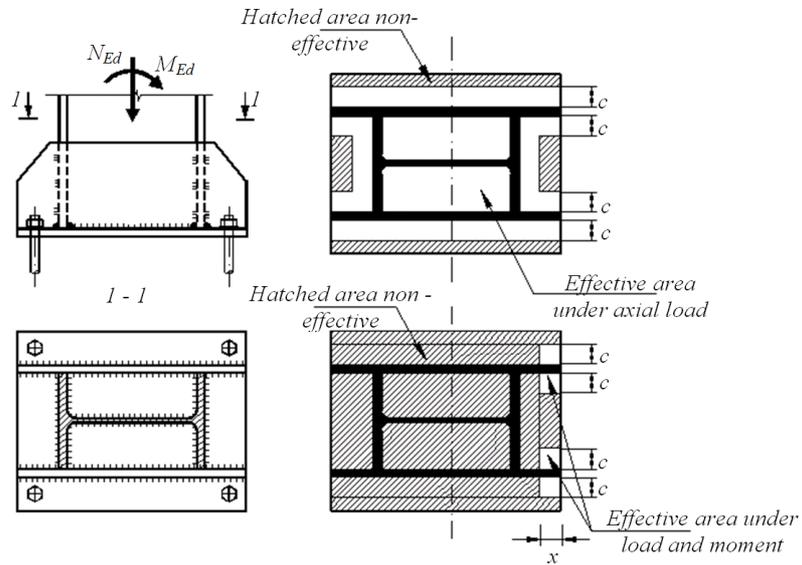$$M_{Ed} = F_c(d_1 - 0.5x) - \frac{N_{Ed}}{2}(2d_1 - L) . \tag{7}$$

Fig. 6 – Effective bearing area under axial load and moment.

Substituting F_c from eq. (5)

$$M_{Ed} = xd_1 b_{\text{eff}} f_{jd} - 0.5 x^2 b_{\text{eff}} f_{jd} - \frac{N_{Ed}}{2}(2d_1 - L) , \qquad (8)$$
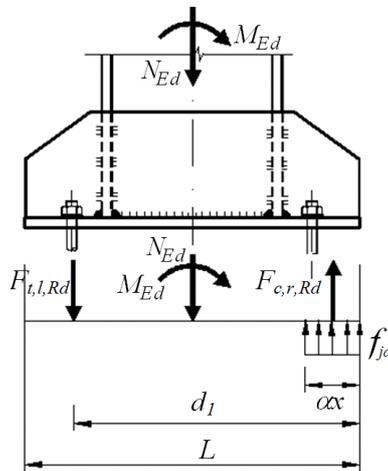

Fig. 7 – Plastic distribution of actions.

Then, adequacy of anchor bolts and base plate in bending in tension zone in accordance with Eurocode 3-1-8 may be verified.

4. Numerical Parametric Study

In order to study the degree of accuracy of Eurocode 3 component method for steel column base connections, numerical studies are conducted regarding the component "concrete in compression".

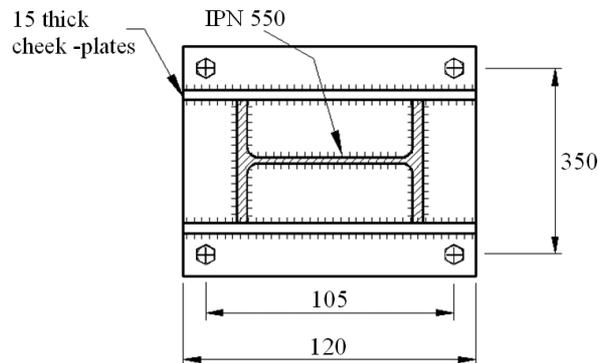The base plate configuration as showed in Fig. 8 is adopted.

Fig. 8 – General arrangement of column base (dimensions in mm).

The base column connection is subject to axial load N_{Ed} = 425 kN and bending moment M_{Ed} = 240 kN.m, giving an eccentricity $e = M_{Ed}/N_{Ed}$ = 0.56 m. Parametric study concerns evaluations of bearing of the compression zone and design moment resistance, $M_{j,Rd}$, of column base (DO ENV 1993-1-1). In order to have more information about the effect of various joint parameters, S235 and S275 steel grade and C20/25, C 25/30 concrete class are considered.

In Fig. 9, the effect of base plate thickness on the length of the compression zone for C20/25 is presented. For both two steel grades, S235 and S275, respectively, keeping C20/25 concrete class, the width of the compression zone is considerably affected by the base plate thickness. In Eurocode 3 component model the effective strength bearing area vary linearly with the base plate thickness, while in Eurocode 2 formulation this bearing area decreases, due to the equilibrium with the tension zone.

Figs. 10 and 11 illustrate the effect of the base plate thickness on the design moment resistance, $M_{j,Rd}$, of column base connection obtained by Eurocode 3 *versus* Eurocode 2 method.

The most important difference between the examined cases is the capacity of the compression zone, which significantly increases in Eurocode 3 if a thicker base plate is considered with no effects at all upon the tension zone.

The relationship again seems to be linear (see Figs. 10 and 11). In Eurocode 2, the advantage obtained by increasing the thickness of the base

plate, is diminished by the increasing of the tension zone resistance, following by the decrease of the compression zone; the effect of which is reflected by the practically horizontal plateau of the thickness *versus* design moment resistance, $M_{j,Rd}$. It is important to mention that similar curves may be obtained for other concrete classes, too.
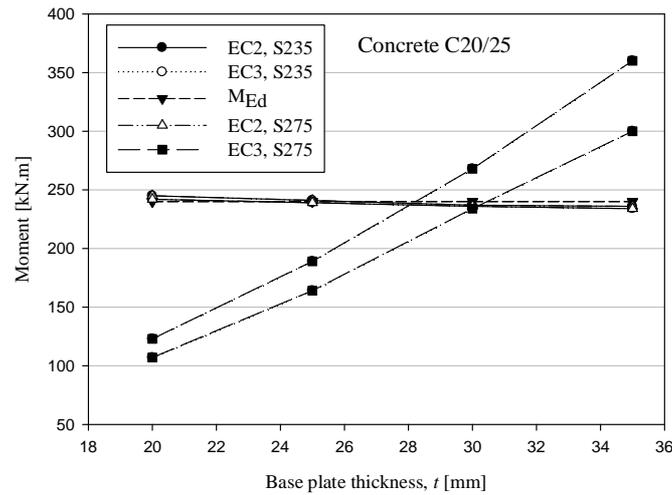

Fig. 9 – Effect of the thickness base plate on the design moment resistance, $M_{j,Rd}$, for C25/30.
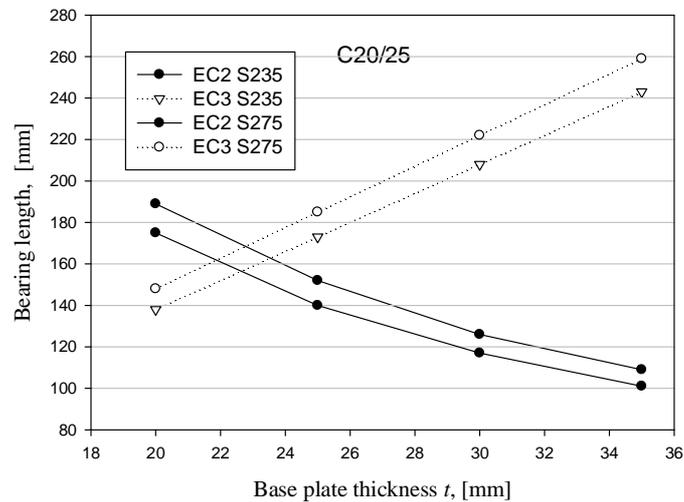

Fig. 10 – Width variations of the compression zone obtained by component method (Eurocode 3) and Eurocode 2.
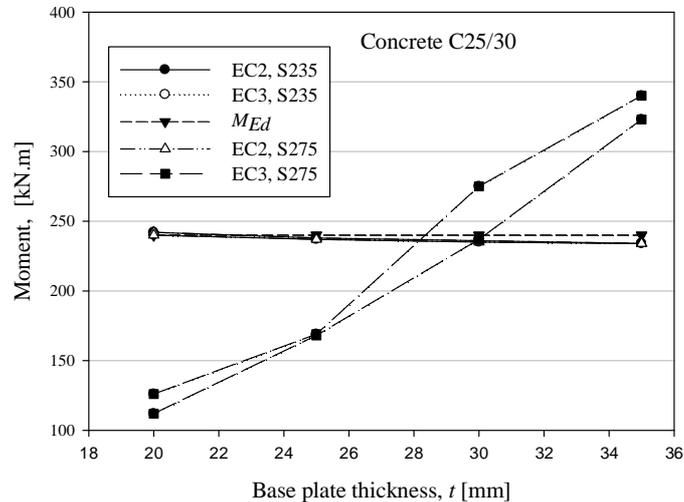
Fig. 11 – Effect of the thickness base plate on the design moment resistance, $M_{j,Rd}$, for C20/25.

Eurocode 3 *T*-stub method has pointed out the degree of accuracy of component method, giving a safety design for flexible plates, while for thicker base plates, some uncertainties may be observed.

4. Conclusions

A review of literature and codes for column base plates shows there are various different design procedures. Each model has different assumptions for bearing pressure area under the base plate. The strength of the concrete in compression depends on the thickness of the base plate, steel grade and concrete class.Different sizes of base plates and various steel grades and concrete classes were analysed. The parametric study should be carried out to develop a better understanding of the behaviour of steel base connections.The component method of SR EN 1993-1-8 is enlarged in the paper.

REFERENCES

Ballio G., Mazzolani F.M., *Theory and Design of Steel Structures.* Chapman and Hall, London and New York, 1983.

DeWolf J.T., Sarisley E.F., *Column Base Plates with Axial Loads and Moments.* J. of the Struct. Div., ASCE, **106**, *ST11*, 2167-2184 (1980).

Eligehausen, Fuchs, Genesio, Grosser (Eds.), *Design of Connections between Steel and Concrete in Eurocodes.* Sec. Symp. Conn. between Steel and Concrete, **1**, Verlag, 2007.

Murray T.M., *Design of Lightly Loaded Steel Column Base Plate*s. Engng. J. AISC, **20**, 143-152 (1983).

Salmon C.G., Johnson J.E., *Steel Structures*. 2nd Ed., Harper and Row, New York, 1980.

Thambiratnam D.P., Paramasivam P., *Base Plates Under Axial Loads and Moments*. J. of the Struct. Division, ASCE, **112**, *5*,1166-1181 (1986).

* * *Design of Concrete Structures* – Part 1-1: *General Rules and Rules for Buildings*. EN 1992-1-1:2004: Eurocode 2, Europ. Comm. for Stand., 2004.

* * *Design of Steel Structures* – Part 1-8: *Design of Joints*. EN 1993-1-8:2005: Eurocode 3, Europ. Comm. for Stand., 2005.

* * *Worked Examples for the Design of Steel Structures*. Based on. BSI publication DO ENV 1993-1-1:Eurocode 3, Build. Res. Establ., The Steel Constr. Inst., Ove Arup & Partners, 1992.

PROIECTAREA BAZELOR DE STÂLPI SOLICITAȚI LA COMPRESIUNE ȘI ÎNCOVOIERE

(Rezumat)

Mortarul de sub placa de bază împreună cu placa de bază este denumit "componenta betonului la compresiune și, respectiv, componenta la încovoiere a plăcii" sau direct "componenta la compresiune". Rezistența betonului la compresiune depinde de materialul de bază din beton, comportamentul stratului de mortar și de fenomenele complexe de contact dintre placa de bază și beton. Se prezintă diferite modele de calcul pentru determinarea rezistenței acestei componente; modelele au fost validate prin simulări numerice. De asemenea se prezintă o scurtă descriere a modelelor existente în literatura de specialitate, împreună cu diferitele ipoteze utilizate.