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Optimization of Design Procedure for Column-base Connections according to EN 1993-1-8:2006

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Abstract

The stiffness and the strength of a column-base connection have significant impacts on the behavior of a steel frame. The paper develops an interaction curve between moment and axial force for the column-base connections according to EN 1993-1-8:2006 with the variation of the base plate thickness and the bolt diameter. This is the fundamental base to determine the ultimate strength of a column-base plate that allows the designers to estimate the strength of column-base connections. This research investigates the relationship between the base plate thickness, the bolt diameter, and the moment strength of the column-base plate with a specific axial force to select an optimum solution. Also, the initial rotational stiffness is determined under a specific axial load and varied moments that satisfy the ultimate limit state. The relationship between moment–rotation is subsequently performed with the variation of the base plate thickness or the bolt diameter. The design procedure is proposed based on moment-axial force interaction curves and moment-rotation curves. This allows for optimizing the column-base connection from proper selections of base plate dimensions and bolt diameters.

Keywords

rotational stiffness, moment-rotations curves, interaction curves M-N, moment resistance

1 Introduction

The strength and stiffness of a column-base connection depend on the components in the connection including bolts, base plate, and base concrete. The stiffness and behavior of the connection have noticeable impacts on the strength and behavior of the whole structural system. The connections, however, are only considered as fixed, or pin connections, although their stiffness is "semi-rigid" in practice. Recently, many researchers studied to determine the stiffness of the connections (Wald and Sokol [1], Waynand et al. [2], Abubakar and Ahmad [3], Eröz et al. [4], Daniūnas and Urbonas [5], Shafieifar and Khonsari [6], Kanvinde et al. [7, 8], Jayarajan [9]). The determination of column-base stiffness has been investigated and has been then introduced into Eurocode 3 using the component method [10]. The reliability and effectiveness of this method in design have been illustrated based on experimental and theoretical investigations (Jayarajan [9], Jaspart and Vandegans [11], Wald et al. [12], Latour et al. [13], Krystosik [14]). The component method helps determine the stiffnesses and ultimate limit states of the column-base connections more accurately. This method was presented in the studies about behaviors of the components: base plate in bending, anchor bolts in tension and concrete in compression of Wald et al. [15, 16], Steenhuis et al. [17].

The rotational stiffness of a column-base has significant impacts on the whole structural system and moment distributions but has negligible effects on the axial force at the column base [18]. The effects of rotational stiffness of connections on the behaviors of the whole structural systems have been studied by many researchers (Daniūnas and Urbonas [5], Krytosik [14], Ermopoulos et al. [19],) as well as the economy in this analysis (Waynand et al. [2]) to demonstrate the necessity of connection stiffness in analysis.

The rotational stiffness of a column base depends on the internal forces including moment and axial force. This relationship has been illustrated using the interaction curve *M-N* of the column-base, and the moment rotation curve $M–\phi$ via the rotational stiffness $S_{j,ini}$. These curves have been studied by many researchers (DeWolf and Sarisley [20], Penserini and Colson [21], Thambiratnam and Paramasivam [22],

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Ermopoulos et al. [19]) using theory and experimental investigations. In terms of the interaction curve between moment and axial force (*M-N*), DeWolf and Sarisley [20] and Thambiratnam and Paramasivan [22], have built this interaction curve (*M-N*) for a column-base connection on the basis of test results. An analysis model proposed by Penserini and Colson [21], provided quite accurate this relationship.

A column-base connection model is proposed by Colson and Penserini [23], to show the relationship between the initial rotational stiffness and the ultimate strength of this connection. These two parameters can be determined using the geometrical and material properties of the connections.

The capacities of column-base connections can be estimated using interaction curves between moment – axial force (*M-N*), as proposed by Thambiratnam and Paramasivam [22], Penserini and Colson [21]. Stamatopoulos and Ermopoulos [24] then have built a diagram to determine the dimensions of the equivalent rigid plate and the relationship between the moment and the axial force. The development of interaction diagrams *M-N* based on test results have required times and costs but is only applied for the investigated column-bases.

Wald et al. ([12, 18]) investigated the interaction curves (*M-N*) for H-section columns using the finite element analysis with the variation of parameters of the connections, and then compared these to the predicted curves from Eurocode 3 using the component method. There is a good agreement between the two methods.

Examples for determinations of the interaction curve *M-N* and rotational stiffness have been carried out by Wald et al. [12], Simões da Silva et al. [25], but the design procedure has not been reported. This research, therefore, investigates the effects of elements of the column-base connections on their capacities using H sections. These results are the basis to propose a designing procedure for a column-base connection in a specific frame that allows the designers to easily select a column-base connection. H section is commonly used under the combined actions of the moment and axial load (DeWolf and Sarisley [20], Hawkins [26]). Razzaghi and Khoshbakht [27] and Vayas et al. [28] studied the nonlinear moment-rotation curve $M–\varphi$ for I-section base column connections. Razzaghi and Khoshbakht [27] used the ASIC procedure whereas Vayas et al. [28] applied the regulations in Eurocode 3.

This research investigates the capacities and the stiffness of the column-base connections using the H section column. This procedure can be easily conducted for other built-up sections but checking for local buckling is required.

Under the actions of a load combination in structural analysis, moments are initially obtained at the column-base connections with the assumption that the column ends are fixed. The obtained moments are used to determine the initial rotational stiffness $s_{j,ini}$ which will be incorporated into the structural analysis to get the other moments. This procedure is iterated until the moment and rotational stiffness become nearly unchanged, which helps reflect the behaviors of the structural systems more accurately.

The interaction relationship between moment and axial load depends on the plate thickness, the bolt diameter, the length and locations of the anchor bolts, the material properties, and the axial load. Shaheen et al. [29] and Gomez et al. [30] have investigated the effects of grout properties on shear strengths of the column-base connections.

This paper investigates the influence of the base plate thickness and the bolt diameter on the capacities of H section column-base connections (via the interaction curves *M-N*) under the actions of moments and axial forces according to the Eurocode 3. This helps determine the column-base connections, and the design procedure is then made faster.

The moment-rotation curve $M–\phi$ is also built and then incorporated into model analysis for iteration design procedure. This iteration design is applied by Jayarajan [9], or other authors ([21, 23, 31]). Their studies are only based on experiments or iteration procedures to build the moment-rotation curves $M–\phi$ that are cumbersome for the applications. This paper, therefore, proposes a design procedure for column-base connections in a specific steel frame according to Eurocode 3 with the support of innovative structural analysis programs. This procedure helps select the bolt diameters and base plate thicknesses using the interaction curves *M-N* of the column-base connections more properly. This is the optimization for the column-base connection design.

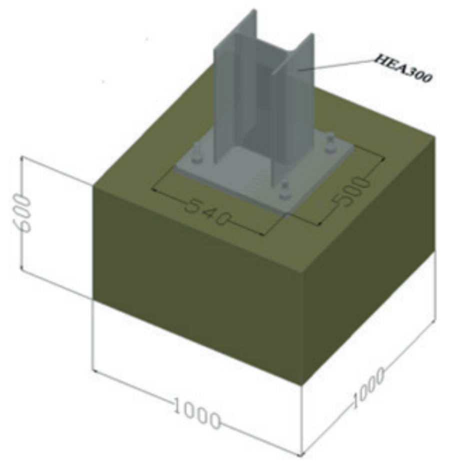
2 M-N interaction diagram

The interaction curve *M-N* of H-section column-base connection (Fig. 1) can be built based on the following points:

Point (–1) corresponds to pure tensile resistance of the column base with and $M_{-1} = 0$ and $N_{-1(M=0)} > 0$ Anchor bolts are in tension.

Pont (0) is the pure bending, where $M_{N=0,mem}$ is the bending design resistance of the column base. Plastic bending is observed of the anchor plate

Point (1) under the actions of the moment M_1 and compressive axial load N_1. The effective section illustrated in Fig. 1 has one flange in compression and a couple of the anchor bolts under tension at the opposite side.



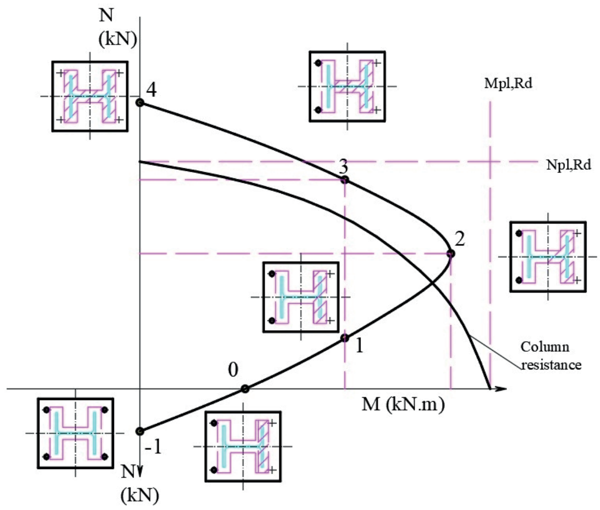


Fig. 1 Interactions diagram *M-N* of column base bending about strong axis [15]

Point (2) under the actions of the moment M_2 and compressive axial load N_2. The effective section includes a half under compression and another half under tension in the anchor bolts at the opposite side.

Point (3) under the actions of the moment M_3 and compressive axial load N_3. The effective section is the T-section including the web and one flange in compression at one side and the anchor bolts in tension at the opposite side.

Point (4) is the pure compression $N_{4(M=0)}$ and is the design compression resistance of the column base whereas anchor bolts do not work.

The capacities of the column section can be determined due to pure moment $M_{pl,Rd}$ pure axial force $N_{pl,rd}$ or combined moment M_{sd} and axial force N_{sd} according to Eurocode 3 [10].

The interaction curve can be constructed as follows:

+ The column section can be designed in a specific steel frame with the assumption that the column-base connections are pinned or fixed. The axial load is negligibly affected and nearly unchanged regardless of the variation of the stiffnesses of the column-base connections and is the base to determine the dimensions of the base plate. The anchor bolts are then arranged based on the selected base plate.

+ Based on the geometric and material properties, the ultimate points on the interaction curve (*M-N*) can be determined with the variation of the base plate thickness and the bolt diameter.

- Step 1: Determine the tensile capacities of the connections from the component method:

$$\text{With prying force: } F_{Rd} = min\left(F_{Rd,1}; F_{Rd,2}; F_{Rd,3}\right), \tag{1}$$

$$\text{Without prying force: } F_{Rd} = min\left(F_{Rd,1*}; F_{Rd,3}\right), \tag{2}$$

where $F_{Rd,1}$, $F_{Rd,2}$ - are tensile capacities of base plate components corresponding to the yielding mechanism at the flanges (or the web) of the column with prying force; $F_{Rd,3}$ is the tensile capacity of bolt connection; $F_{Rd,1*}$ is the capacity of the base plate component corresponding to the collapse mechanism due to the formation of the contacts between the extremities of the T-stub plage and concrete block, as detailed in [10].

- Step 2: Determine the width of the equivalent rigid plate (A_{eff}) [10, 17].

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

where f_y is the yield stress of the base plate material; f_j is the concrete design; γ_{M0} is the safety factor.

- Step 3: Determine the effective area of the compressive concrete area $A_{eff,i}$.

$$N_i = A_{eff,i} f_j - F_{Rd}, \quad i = -1,0,1,2,3,4, \tag{4}$$

where: f_j is the concrete design strength: $f_j = \frac{2}{3}\frac{k_j f_{ck}}{\gamma_c}$ with k_j is the concentration factor; f_{ck} is the compressive design strength of concrete for the foundation, as presented in [10, 17].

- Step 4: Determine the moment capacities of column-base connections at ultimate points

$$M_i = F_{t,l,Rd} . r_t + A_{eff,i} . f_j . r_c, \tag{5}$$

where $F_{t,l,Rd}$ is the tensile capacity of base plate area and anchor bolts on the left side as presented in Eurocode 3 [10]; r_c is the level arm of the centroid of the compressive area to the neutral axis; r_t - is the level arm of the tensile area to the neutral axis.

- Step 5: Determine the moment capacity of the column section [10, 17].

$$M_{Ny,Rd} = M_{pl,Rd} \frac{1 - N_{Sd} / N_{pl,Rd}}{1 - 0,5(A - 2bt_f) / A} \tag{6}$$

+ As a specific axial load, the ultimate moment of the column-base connection M_{rd} is the lesser value of the two intersection values of the axial load line $N = N_{sd}$ with the interaction curve (M-N) ($M_{j,rd}$) or with the capacity line of the column-base section ($M_{Ny,rd}$).

$$M_{rd} = \min\left(M_{j,Rd}, M_{Ny,Rd}\right), \tag{7}$$

where $M_{j,rd}$ - is the moment capacities of column-base connection under the axial load $N = N_{sd}$ as presented in Eurocode 3 [10, 15].

The examples for the determination of these points in the relationship curve (M-N) are illustrated in Table 1.

3 Moment resistance and rotational stiffness

Based on the results of investigated interaction curves in Section 2, a range of bolt diameters and base plate thicknesses are selected for the investigation in this section.

The axial load of a column is nearly unchanged assuming whether the column-based connection is fixed, pinned, or semi-rigid [19]. Therefore, the ultimate moment M_{rd} is determined under a specific axial load N with the variations of the bolt diameters d and the plate thicknesses t.

The initial rotational stiffness $s_{j,ini}$ of the connection can be determined based on the component stiffnesses including base plate component k_p, concrete component k_c and bolt component k_b using case 1 to case 4 [10, 16].

$$S_{j,ini} = \frac{e}{e + a} \frac{E_s z^2}{\mu \sum_{i=1}^{n} 1 / k_i}$$

$$with\ e = \frac{M_{Rd}}{F_{Sd}},\ a = \frac{k_c z_c - k_t z_t}{k_c + k_t}, \tag{8}$$

$$\mu = \left(1,5\gamma\right)^{2,7},\ \gamma = \frac{1 + \dfrac{z/2}{M_{Sd}/N_{Sd}}}{M_{Rd}/N_{Sd} + \dfrac{z/2}{M_{Sd}/N_{Sd}}},$$

where z_t, z_c are the distance from the neutral axis to the centroid of the compression and tension areas; z is the distance between the centroids of the compression and tension areas.

The capacities of the column-base connections can be determined based on the interaction curves M-N and moment rotation curves M-s. This means that the

Table 1 Moment resistances and initial rotational stiffness

Column: HE300A; S235; a_{wf} = 10 mm
Base plate: 540 mm × 500 mm; S235;
e_a = 60 mm; p = 340 mm; e_b = 80 mm; e_c = 65 mm (Fig. 4)
Bolt: Class 4.8; quantity: 4
Foundation C25/30; 1000 mm × 1000 mm × 600 mm

t = 20 mm						
d [mm]	$N_{4(M=0)}$ [kN]	$N_{1(M=0)}$ [kN]	$M_{N=0,pl}$ [kNm]	M_1 [kNm]	N_1 [kN]	$S_{j,ini1}$ [kNm/rad]
12	-1795.7	97.1	18.9	110.8	-680.6	28904.9
16	-1795.7	180.9	35.1	119.6	-638.8	26246.2
20	-1795.7	282.2	54.3	130.3	-588.1	24330.4
22	-1795.7	349.1	66.7	137.3	-554.7	23592.1
24	-1795.7	393.7	75.0	142.0	-532.3	23253.5
27	-1795.7	393.7	75.0	142.0	-532.3	24885.8
30	-1795.7	393.7	75.0	142.0	-532.3	25959.7
33	-1795.7	393.7	75.0	142.0	-532.3	27181.4
36	-1795.7	393.7	75.0	142.0	-532.3	27969.7
39	-1795.7	393.7	75.0	142.0	-532.3	28905.2
42	-1795.7	393.7	75.0	142.0	-532.3	29508.4
d [mm]	M_2 [kNm]	N_2 [kNm]	$S_{j,ini2}$ [kNm/rad]	M_3 [kNm]	N_3 [kNm]	$S_{j,ini3}$ [kNm/rad]
12	118.6	-849.3	51281.3	110.8	-1018	43597.5
16	127.4	-807.4	36098.4	119.6	-976.0	43597.5
20	138.1	-756.7	30300.8	130.3	-925.4	51579.5
22	145.1	-723.3	28362.1	137.3	-891.9	41938.6
24	149.8	-701.0	27469.5	142.0	-869.6	38246.4
27	149.8	-701.0	29126.0	142.0	-869.6	39616.6
30	149.8	-701.0	30199.2	142.0	-869.6	40471.0
33	149.8	-701.0	31404.5	142.0	-869.6	41401.0
36	149.8	-701.0	32173.4	142.0	-869.6	41978.8
39	149.8	-701.0	33077.3	142.0	-869.6	42642.9
42	149.8	-701.0	33655.1	142.0	-869.6	43059.1
t = 24 mm						
d [mm]	$N_{4(M=0)}$ [kN]	$N_{1(M=0)}$ [kN]	$M_{N=0,pl}$ [kNm]	M_1 [kNm]	N_1 [kN]	$S_{j,ini1}$ [kNm/rad]
12	-2139.4	97.1	19.3	132.6	-838.6	33553.9
16	-2139.4	180.9	35.8	141.4	-796.7	31218.1
20	-2139.4	282.2	55.4	152.1	-746.0	29528.8
22	-2139.4	349.1	68.2	159.1	-712.6	28933.4
24	-2139.4	406.7	79.1	165.1	-683.8	28350.6
27	-2139.4	528.8	101.8	177.9	-622.8	27806.5
30	-2139.4	567.0	108.9	182.0	-603.7	28595.3
33	-2139.4	567.0	108.9	182.0	-603.7	30319.7
36	-2139.4	567.0	108.9	182.0	-603.7	31457.2
39	-2139.4	567.0	108.9	182.0	-603.7	32825.9
42	-2139.4	567.0	108.9	182.0	-603.7	33724.1

Continuation of Table 1

d [mm]	M_2 [kNm]	N_2 [kNm]	$S_{j,ini2}$ [kNm/rad]	M_3 [kNm]	N_3 [kNm]	$S_{j,ini3}$ [kNm/rad]
12	140.4	-1021.	46880.0	132.6	-1204	46880.0
16	149.2	-979.3	42899.4	141.4	-1162	46880.0
20	159.8	-928.6	36604.3	152.1	-1111.	46880.0
22	166.8	-895.2	34586.4	159.1	-1078	50192.2
24	172.9	-866.4	33189.5	165.1	-1049	45042.2
27	185.7	-805.3	31536.3	177.9	-987.9	39166.2
30	189.7	-786.2	32079.2	182.0	-968.8	38835.3
33	189.7	-786.2	33781.0	182.0	-968.8	40360.4
36	189.7	-786.2	34891.0	182.0	-968.8	41333.8
39	189.7	-786.2	36213.5	182.0	-968.8	42472.2
42	189.7	-786.2	37073.6	182.0	-968.8	43200.5

interaction curve *M-N* can be used to quickly check the capacities of the column-base connections without iteration of the procedure in design.

The internal forces of the column are in the ultimate areas of the column-base and the capacities of column sections, which helps to determine these proper values of the bolt diameters and base plate thicknesses.

Assuming that column-base connections are fixed, pinned, or semi-rigid, the approximate axial load and moment can be obtained $N = N_{sd}$ and $M = M_{sd}$. The ultimate moment M_{rd} can be determined corresponding to the axial load $N = N_{sd}$. Therefore, the bolt diameters and base plate thicknesses can be properly selected on the basis of the investigated results as presented in Table 2. The optimum of the bolt diameter and the base plate thickness allows the designers to obtain the moment resistance M_{rd} that is approximately equal to the moment M_{sd}.

The rotational stiffness s_{ini} or s_j (see Fig. 2) subsequently can be incorporated into the analysis model to get the moment at the column-base connection M^1_{Sd}. The iteration is applied with the average moment of the obtained moment M^1_{Sd} and the initial moment M^{01}_{Sd}. The iteration process is applied until the obtained moment and the initial rotational stiffness reach these constant values.

The procedure to calculate the capacities and rotational stiffnesses of the connections is illustrated in Fig. 3.

4 Numerical analysis

This section presents two numerical examples to illustrate the proposed designing procedure of the column-base connections.

Table 2 Moment resistance M_{rd} and rotational stiffness sj of column base (for column section HEA300)

t [mm]	20		22		24	
d [mm]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]
12	51.9	14580.6	52.9	14913.5	54.0	15076.5
16	67.0	15952.8	68.2	16740.5	69.4	17291.6
20	84.9	16888.9	86.4	18034.9	87.8	18902.9
22	96.6	17466.7	98.2	18813.1	99.8	19861.1
24	104.3	17856.0	108.3	19240.4	110.0	20406.3
27	104.3	19340.5	120.3	20579.5	131.3	21734.0
30	104.3	20336.8	120.3	21785.7	137.9	22961.8
33	104.3	21489.9	120.3	23198.7	137.9	24620.5
36	104.3	22245.3	120.3	24136.9	137.9	25735.3
39	104.3	23153.5	120.3	25275.3	137.9	27099.1
42	104.3	23746.0	120.3	26026.0	137.9	28007.5
t [mm]	26		28		30	
d [mm]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]
12	55.0	15119.4	56.0	15077.9	57.0	14977.3
16	70.6	17663.0	71.8	17898.7	73.0	18032.5
20	89.3	19549.5	90.7	20022.5	92.1	20360.5
22	101.4	20665.6	103.0	21275.5	104.6	21731.5
24	111.7	21316.3	113.5	22019.3	115.2	22556.9
27	133.3	22874.0	135.4	23779.5	137.4	24494.0
30	**152.5**	23992.7	154.8	25055.4	157.1	25909.0
33	152.5	25878.6	154.8	27150.8	157.1	28190.0
36	152.5	27159.5	154.8	28586.2	157.1	29764.2
39	152.5	28737.3	154.8	30363.3	157.1	31721.6
42	152.5	29797.7	154.8	31566.2	157.1	33055.1
t [mm]	32		34		36	
d [mm]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]
12	58.0	14835.6	59.1	14665.4	62.1	14064.7
16	74.2	18089.5	75.4	18088.5	79.0	17862.2
20	93.6	20593.5	95.0	20744.9	99.2	20868.0
22	106.1	22066.2	107.7	22305.4	112.4	22628.4
24	116.9	22963.0	118.6	23264.7	123.7	23734.6
27	**139.4**	25053.9	141.4	25489.4	147.3	26266.8
30	159.3	26591.4	161.6	27134.5	168.3	28164.1
33	159.3	29035.6	161.6	29721.9	168.3	31084.0
36	159.3	30733.8	161.6	31530.3	168.3	33154.9
39	159.3	32853.0	161.6	33793.9	168.3	35764.3
42	159.3	34305.0	161.6	35353.0	168.3	37585.0

Continuation of Table 2

t [mm]	38		40	
d [mm]	M_{rd} [kNm]	s_j [kNm/rad]	M_{rd} [kNm]	s_j [kNm/rad]
12	61.1	14274.3	62.1	14064.7
16	77.8	17965.5	79.0	17862.2
20	97.8	20869.9	99.2	20868.0
22	110.8	22572.6	112.4	22628.4
24	122.0	23635.6	123.7	23734.6
27	145.3	26078.6	147.3	26266.8
30	166.1	27901.9	168.3	28164.1
33	166.1	30724.9	168.3	31084.0
36	166.1	32718.3	168.3	33154.9
39	166.1	35225.3	168.3	35764.3
42	166.1	36967.7	168.3	37585.0

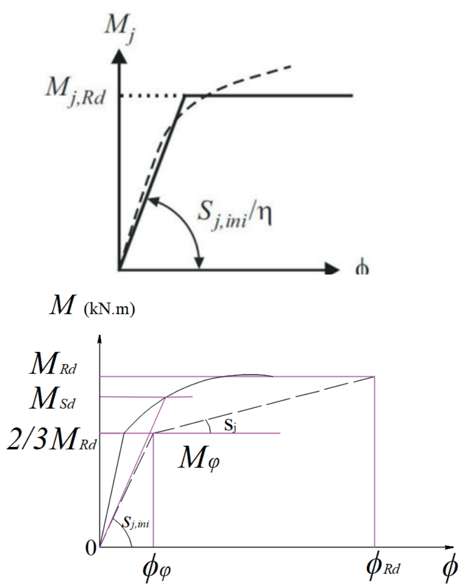


Fig. 2 Moment-rotation curves for base plate joint, a) Experimental curve [24] a) ---- Experimental curve [24]. — Idealized curve, b) ---- Modeling curve Jayarajan P. [9], — Moment-rotation curve according to EC3 [10]

4.1 Example 1

Design the column-base connection in a steel structural frame as follows:

Sections HEA300 and IPE400 regulated in [10] are used as column and rafter sections.

Actions are applied to the investigated frame according to the EN 1991-1-1 [32], including: the dead load of self-weight of the rafter g = 3.315 kN/m, the dead load of the roof (purlins & roof sheet) gf = 6.6225 kN/m; Live load q = 3 kN/m; Wind load for the roof: wd = 0.8 kN/m, ws = –3.9 kN/m and for the wall: h_{ws} = 2.4575 kN/m, h_{wd} = 3.9 kN/m; The point load on the top of the column H_{wd} = 1.56 kN/m; The snow load: s = 5 kN/m.

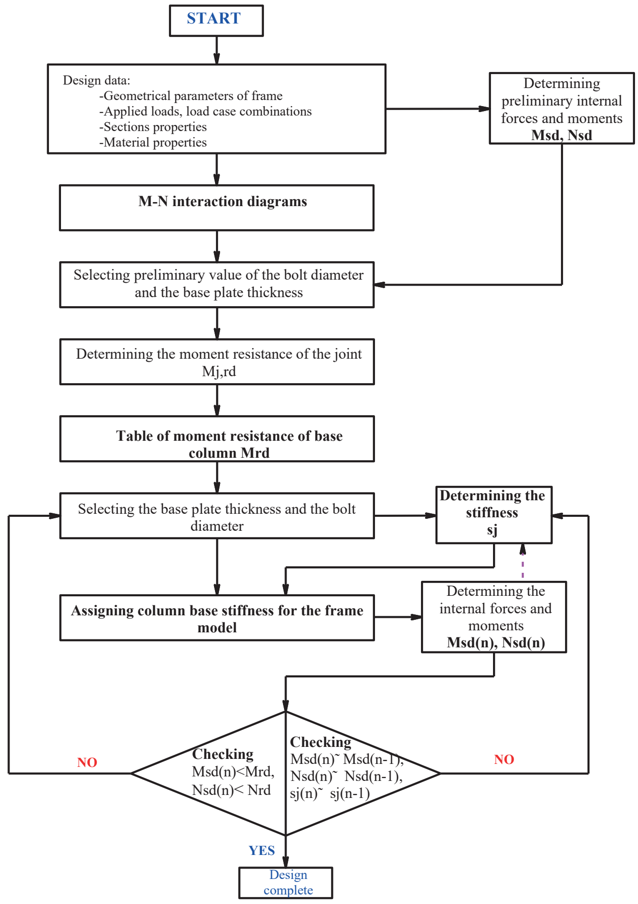


Fig. 3 Flow chart for design semi-rigid base plate connection

Load combinations are listed as follows:

LC1: $1.35\times(g+gf)$

LC2: $1.35\times(g+gf)+1.5\times s$

LC3: $1.35\times(g+gf)+1.5\times s+1.5\times 0.7\times q$

LC4: $1.35\times(g+gf)+1.5\times s+1.5\times 0.6\times(wd+h_{wd}+H_{wd})$
$+1.5\times 0.7\times q$

LC5:
$1.35\times(g+gf)+1.5\times 0.5\times s+1.5\times(wd+h_{wd}+H_{wd})$
$+1.5\times 0.7\times q$

LC6: $1.35\times(g+gf)+1.5\times s-1.5\times 0.6\times(wd+h_{wd}+H_{wd})$
$+1.5\times 0.7\times q$

LC7: $1.35\times(g+gf)+1.5\times 0.5\times s-1.5\times(wd+h_{wd}+H_{wd})$
$+1.5\times 0.7\times q$

LC8: $1.0\times(g+gf)+1.5\times(ws+h_{ws})$

The column-base connections are initially assumed as fixed ends for model analysis, and the internal force diagrams are subsequently obtained as shown in Fig. 4.

The obtained internal forces (M_{max} and N_{max}) are shown to be less than the design capacities of the column and girder ($M_{el,Rd}$, $M_{pl,Rd}$ and $N_{pl,Rd}$).

The base plate dimensions are illustrated in Fig. 5 including $a \times b$ = 540 mm × 500 mm, e_a = 60 mm, e_b = 80 mm, e_c = 65 mm. The steel grade S235 is used for this investigation as regulated in EN 1993-1-1:2005 [33]. The material properties are f_y = 235 MPa, E_s = 210000 MPa. Bolt class 4.8 is used with the ultimate strength f_{ub} = 400 MPa. Material properties of concrete grade C25/30 include f_{ck} = 25 MPa, E_c = 31476 MPa. The footing dimensions ($a_1 \times b_1 \times h$) are equal to 1000 mm × 1000 mm × 600 mm.

The internal forces at the base are M_{max} = 136.6 kNm and N_{max} = 214.6 kNm corresponding to the load combinations of 3, 4 and 6. The internal forces of the column and rafter with the assumption of rigid connections are checked as demonstrated in Table 3.

The capacities of column sections HEA300 include ultimate pure axial force $N_{pl,Rd}$ = 2644.4 kN and pure ultimate moment $M_{pl,Rd}$ = 325.07 kN.

The investigated bolt diameters vary from 12–42 mm; and the base plate thicknesses vary from 20–40 mm.

The results are listed in Table 1 when t = 20 mm and t = 24 mm. The whole results are then used to develop the interaction curves in Fig. 6 and Fig. 7.

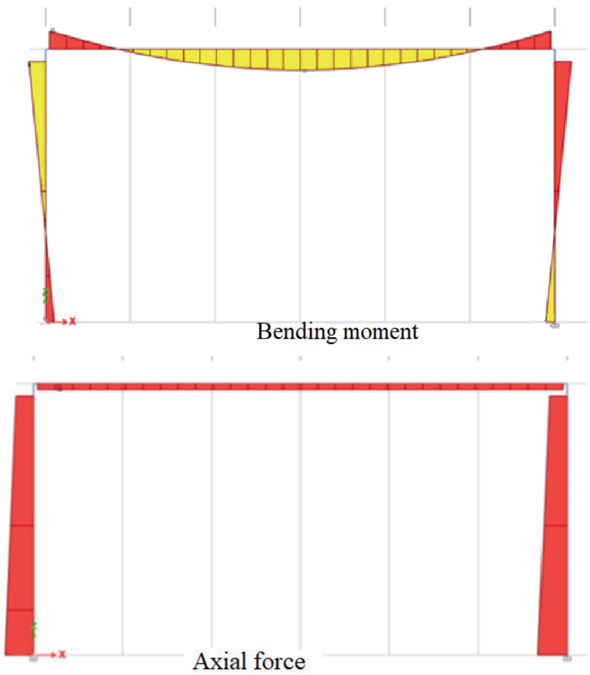


Fig. 4 Bending moment and axial force distribution of frame F1 (LC3)

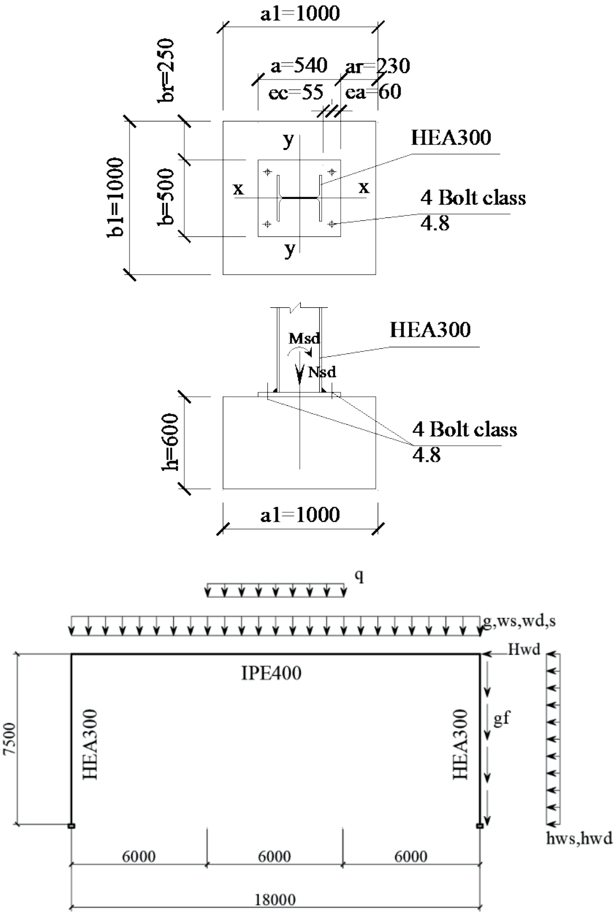


Fig. 5 Geometrical parameters of frame

Table 3 Checking sections of F1 with rigid joint

Validation	Column HEA300	Rafter IPE400
M_{max} [kNm]	-136.6 ÷ 259.93	-260.4 ÷ 303.3
N_{max} [kN]	214.6	16.1
$M_{pl,Rd}$ [kNm]	325.07	307.18
$N_{pl,Rd}$ [kN]	2664.4	1984.89
$M_{el,Rd}$ [kNm]	295.99	271.76

The bolt diameter d = 27 mm and the plate thickness t > 24 mm can be selected for the base connections corresponding to the moment M_{sd} = 136.6 kNm and axial load N_{sd} = 214.6 kNm that are lower than the ultimate capacities based on the interaction curves in Fig. 6 and Fig. 7.

The axial loads for investigation should be less than the design compression load of the column section $N_{pl,Rd}$ = 2644.4 kN and the base plate $N_{4(M=0)}$. The investigated axial loads are from 200 kN to 1200 kN.

The ultimate moment M_{rd} and rotational stiffness s_j under the axial load of 200 kN are determined and presented in Table 3.

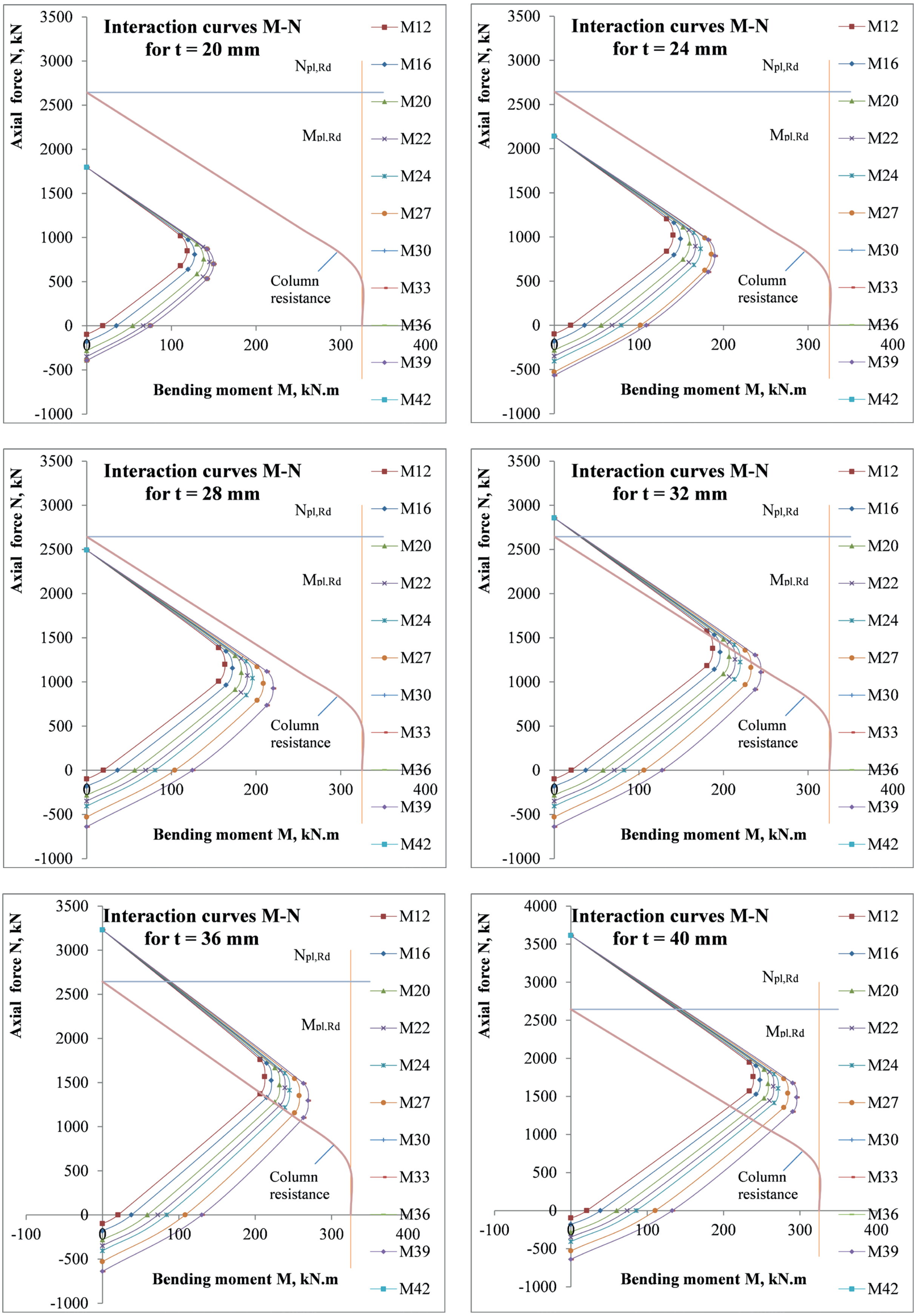


Fig. 6 M-N Interaction diagrams for different bolt diameter (Column HEA300, f_y =235 MPa; Bolt 4.8, n = 4, f_{ub} = 400 MPa; Concrete: C25/30; Base plate, e_a = 60 mm, e_b = 80 mm, e_c = 65 mm)

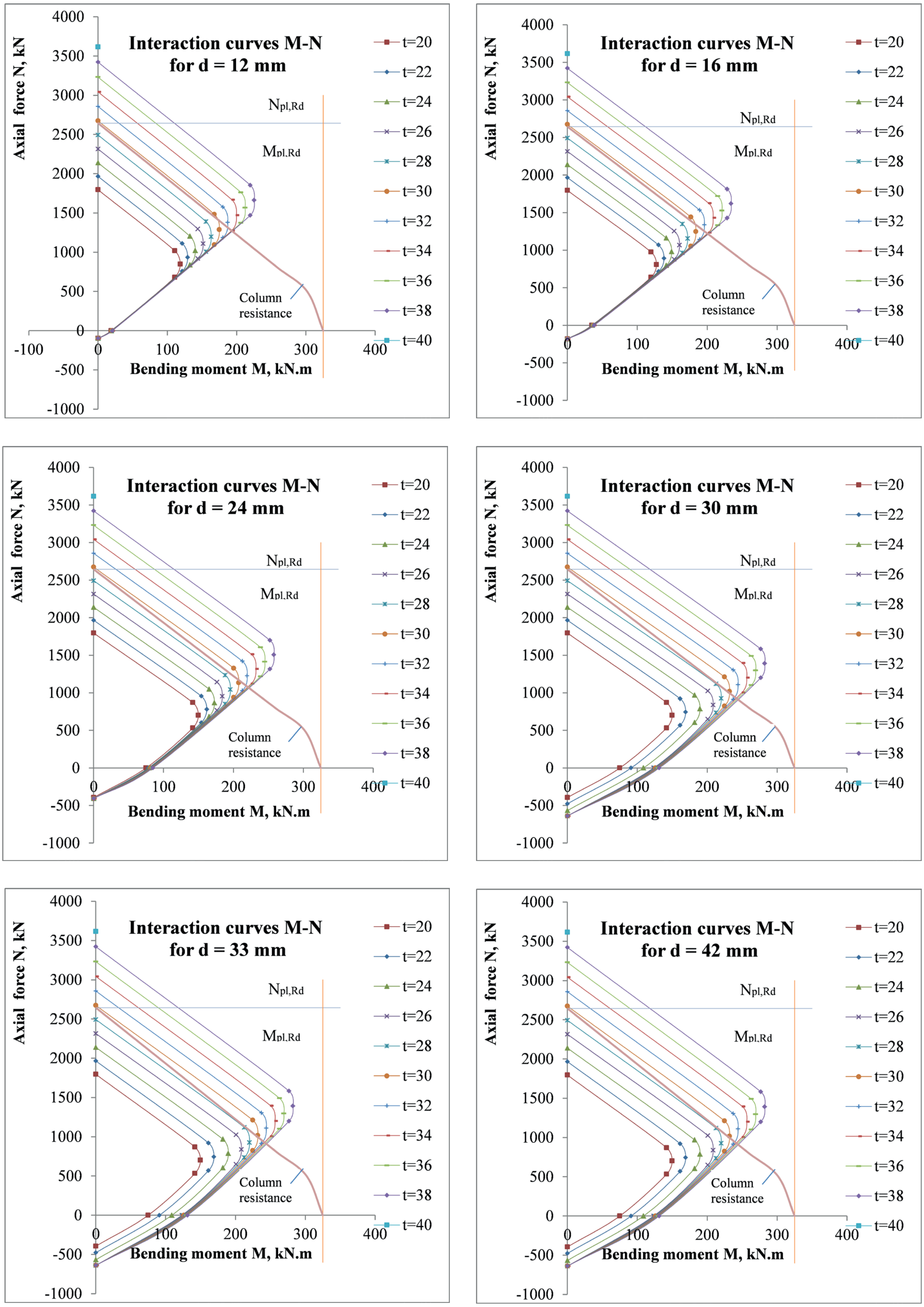


Fig. 7 M-N Interaction diagram for different base plate thickness (Column HEA300, f_y = 235 Mpa; Bolt 4.8, n = 4, f_{ub} = 400 MPa; Concrete: C25/30; Base plate , e_a = 60 mm, e_b = 80 mm, e_c = 65 mm)

The moment capacity $M_{j,Rd}$ of the base connection is determined, as presented in Table 2. The moment M_{sd} = 136.6 kNm and the axial load of 214.6 kN (Table 3) are used to select the bolt diameter (*d*) and the plate thickness (*t*). The first selection d = 27 and t = 32 mm (M_{rd} = 139.4 kNm); the second selection d = 30 and t = 26 mm (M_{rd} = 152.5 kNm)

With a specific axial load, the initial rotational stiffness can be calculated corresponding to the variations of moment values from 10 kNm to 310 kNm. The relationships *M-s* can be built with a specific axial load. This section provides the values of the relationship *M-s* as presented in Table 4 with the axial load of 214.6 kN.

The initial rotational stiffnesses, therefore, are determined corresponding to these above selections using Table 4 and subsequently listed in Table 5.

The iteration calculations are applied to get the final results as follows:

In the first selection d = 27 and t = 32 mm and, the internal forces at the column base are $M_{Sd}^{4} = 108 kNm$ and axial load N_4 = 214.6 kN with the rotational stiffness s_j of 41046 kNm/rad.

In the second selection d = 30 and t = 26 mm and, the internal forces at the column base are $M_{Sd}^{4} = 113.8 kNm$ and axial load N_4 = 214.6 kN with the rotational stiffness s_j of 54069 kNm/rad.

After applying the component method in Eurocode 3, it is found that the moment at the column base is reduced when using the semi-rigid connections, which makes the process more economical. The design procedure becomes faster and simpler to select these optimum solutions for column-base connections and can utilize the capacities of the column-base connections corresponding to the moment varying from 2/3 $M_{j,Rd}$ to $M_{j,Rd}$.

4.2 Example 2

The design of the column-base connections for frame F2 has similar dimensions and load actions to those of frame F1, but sections HEA400 and IPE450 are replaced for the columns and rafter (Table 6).

The design procedure is similar to Example 1.

The column base plate dimensions are also similar to this in Example 1, as follows: $a \times b$ = 540 mm × 500 mm, e_a = 60 mm, e_b = 80 mm, e_c = 65 mm. The steel grade S235 is used for this investigation as regulated in EN 1993-1-1:2005 [10]. The material properties are f_y = 235 MPa; E_s = 210000 MPa. Bolt class 4.8 is used with the ultimate strength f_{ub} = 400 MPa. Material properties of concrete grade C25/30 include f_{ck} = 25 MPa; E_c = 31476 MPa. The footing dimensions ($a_1 \times b_1 \times h$) are equal to 1000 m × 1000 m × 600 mm.

The internal forces at the column base are 71.09 kNm for moment Mmax and 221.7 kN for the combinations of LC3, LC4 and LC6.

Table 4 Values of moment and stiffness corresponding to the axial load N = 214.6 kN with the variation of bolt diameters d and base plate thicknesses t (for column section HEA300)

t [mm]		24	26	28	30	32
M [kNm]	*d* [mm]					
90	12	fail	fail	fail	fail	fail
	16	fail	fail	fail	fail	fail
	20	19184.3	19939.1	20520.3	20965.4	21303.9
	22	21194.8	22134.7	22873.4	23452.3	23904.6
	24	33602.8	35200.0	36471.0	37480.6	38281.5
	27	71782.7	75640.4	78771.6	81310.7	**83370.2**
	30	76122.6	**80542.8**	84176.5	87161.7	89616.5
	33	81214.2	86332.2	90594.5	94141.5	97096.6
	36	84607.7	90223.5	94940.8	98899.5	102225.8
	39	88728.3	94971.9	100266.0	104749.3	108550.1
	42	91454.4	98135.4	103836.1	108693.1	112835.2
110	12	fail	fail	fail	fail	fail
	16	fail	fail	fail	fail	fail
	20	fail	fail	fail	fail	fail
	22	fail	fail	fail	fail	fail
	24	20738.4	21733.5	22521.7	23144.0	23633.8
	27	32847.0	34635.9	36082.2	37249.0	**38189.4**
	30	42140.5	**61686.8**	64502.5	66805.2	68687.8
	33	45069.4	66299.4	69622.3	72376.5	74659.4
	36	47029.4	69413.9	73106.3	76194.0	78776.5
	39	49418.1	73229.6	77393.8	80909.6	83877.8
	42	51003.6	75781.2	80279.9	84102.4	87350.0
130	12	fail	fail	fail	fail	fail
	16	fail	fail	fail	fail	fail
	20	fail	fail	fail	fail	fail
	22	fail	fail	fail	fail	fail
	24	fail	fail	fail	fail	fail
	27	22045.2	23255.9	24232.4	25017.6	**25647.8**
	30	23457.8	**32780.9**	34288.3	35517.5	36518.8
	33	25127.5	35293.0	37078.7	38555.2	39775.2
	36	26247.8	36994.0	38983.6	40643.6	42028.0
	39	27616.3	39083.5	41334.4	43231.1	44828.3
	42	28526.6	40484.2	42920.9	44988.0	46740.0

Note: "Fail" stands for the moment is larger than the moment resistance of the connection and/or the column section.

Table 5 Iterative results and comparisons between two selected solutions of column-base connections in the Frame F1

Validation	d = 27 mm, t = 32 mm		d = 30 mm, t = 26 mm	
	M [kNm]	s [kNm/rad]	M [kNm]	s [kNm/rad]
From Table 4	90	83370	90	80543
From Table 4	110	38189	110	61687
From Table 4	130	25648	130	32781
Modeling M_{Sd}^{01} (Table 1)	136.6	25425	136.6	27372
1st iterative result (M_{Sd}^{1})	95.7		97.8	
$M_{Sd}^{02} = 0.5(M_{Sd}^{01} + M_{Sd}^{1})$	116.1	30985	117.2	48300
2nd iterative result (M_{Sd}^{2})	101.1		111.5	
$M_{Sd}^{03} = 0.5(M_{Sd}^{02} + M_{Sd}^{2})$	108.6	40159	114.8	52279
3rd iterative result (M_{Sd}^{3})	107.5		113.1	
$M_{Sd}^{04} = 0.5(M_{Sd}^{03} + M_{Sd}^{3})$	108	41046	114	53704
4th iterative result (M_{Sd}^{4})	107.99		113.6	
$M_{Sd}^{05} = 0.5(M_{Sd}^{04} + M_{Sd}^{4})$			113.8	54069
5th iterative result (M_{Sd}^{5})			113.73	

Table 6 Checking sections of F2 with rigid joint

Validation	Column HEA400	Rafter IPE450
M_{max} [kNm]	-71.09 + 300.26	-277.15 + 295.4
N_{max} [kN]	221.71	43.43
$M_{pl,Rd}$ [kNm]	602.02	399.92
$N_{pl,Rd}$ [kN]	3735.98	2322.29
$M_{el,Rd}$ [kNm]	543.14	352.43

Based on the interaction curves M-N (similar to Example 1) for the section HEA400, bolt diameter of 16 mm and the thickness of larger than 20 mm are selected for the column-base connections. The M_{sd} = 71.09 kNm and N_{sd} = 221.7 kNm are in the interaction curve (M-N).

The moment capacity $M_{j,Rd}$ of the base column connection is then determined using the database as presented in Table 7.

Therefore, the moment M_{sd} = 71.09 kNm and the axial load of 221.7 kN are used to select the bolt diameter (d) and the plate thickness (t) with the following values: the first selection d = 20 and t = 20 mm.

The iteration calculations are similar to those in Example 1, and the results are subsequently listed in the Table 8.

With d = 27 and t = 32 mm, the internal forces at the column base are $M_{Sd}^{6} = 108 kNm$ and axial load N_6 = 221.7 kN with the rotational stiffness s_j of 46226 kNm/rad.

Table 7 Moment resistance M_{rd} corresponding to normal force N_{sd} = 221.7 kN

t [mm]	20	22	24	26	28	30
d [mm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]
12	69.7	70.9	72.0	73.1	74.3	75.4
16	87.6	88.9	90.3	91.6	92.9	94.2
20	**108.9**	110.5	112.1	113.6	115.2	116.8
22	122.8	124.5	126.3	128.0	129.7	131.4
24	134.6	136.5	138.4	140.3	142.1	144.0
27	159.4	161.6	163.8	166.0	168.1	170.3
30	171.7	185.3	187.8	190.2	192.7	195.2
33	171.7	198.8	212.4	215.2	218.0	220.7
36	171.7	198.8	212.4	215.2	218.0	220.7
39	171.7	198.8	212.4	215.2	218.0	220.7
42	171.7	198.8	212.4	215.2	218.0	220.7
t [mm]	32	34	36	38	40	
d [mm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	M_{rd} [kNm]	
12	76.6	77.7	78.8	79.9	81.0	
16	95.6	96.9	98.2	99.5	100.8	
20	118.3	119.9	121.4	123.0	124.5	
22	133.2	134.9	136.6	138.3	139.9	
24	145.8	147.7	149.5	151.3	153.2	
27	172.4	174.6	176.7	178.8	180.9	
30	197.6	200.0	202.4	204.9	207.2	
33	223.5	226.2	228.9	231.7	234.4	
36	223.5	226.2	228.9	231.7	234.4	
39	223.5	226.2	228.9	231.7	234.4	
42	223.5	226.2	228.9	231.7	234.4	

5 Discussions

As the bolt diameter increases to 30 mm, the tensile capacity of the connection is unchanged due to the occurrence of the yield stress. This means that the increase of bolt diameter larger than 30 mm becomes ineffective, as the interaction curves (M-N) showed in Fig. 7.

The development of interaction curves M-N for a variety of base plate thicknesses and bolt diameters is the basis to determine the capacities of the column-base connections and to select the optimum solutions of these connections.

The proposed designing procedure has been illustrated to be simple and effective thanks to the optimum selections of bolt diameters and base plate thicknesses based on capacities of column-base connections.

The capacities of column-base connections are determined using the rotational stiffness of the connections, which helps to utilize the maximum capacities of the connections and create more economical benefits.

Table 8 Iterative results of the solution of Frame F2

Validation	d = 20 mm, t = 20 mm		
	M [kNm]	s [kNm/rad]	N [kN]
Modeling M_{Sd}^{01} (Table 6)	71.09	127365	
1st iterative result (M_{Sd}^{1})	127.3		
$M_{Sd}^{02} = 0.5(M_{Sd}^{01} + M_{Sd}^{1})$	99.2	36209	
2nd iterative result (M_{Sd}^{2})	85.1		
$M_{Sd}^{03} = 0.5(M_{Sd}^{02} + M_{Sd}^{2})$	92.1	53278	
3rd iterative result (M_{Sd}^{3})	99.9		221.7
$M_{Sd}^{04} = 0.5(M_{Sd}^{03} + M_{Sd}^{3})$	96	42818	
4th iterative result (M_{Sd}^{4})	91.6		
$M_{Sd}^{05} = 0.5(M_{Sd}^{04} + M_{Sd}^{4})$	94	47797	
5th iterative result (M_{Sd}^{5})	95.8		
$M_{Sd}^{06} = 0.5(M_{Sd}^{05} + M_{Sd}^{5})$	94.6	46226	
6th iterative result (M_{Sd}^{6})	94.56		

Iteration calculations provide more accurate results of the rotational stiffness, which reflects the actual working of the structural systems in reality.

6 Conclusions

With specific column-base connection dimensions and the location of the anchor bolts, the interaction curves *M-N* can be constructed to estimate the capacities of these connections with the variations of the bolt diameter and the plate thickness.

Under the actions of applied loads, the bolt diameters and the plate thicknesses can be fundamentally selected on the basis of the interaction curves. These interaction curves can also be used to optimize the bolt diameter and plate thickness to utilize the ultimate capacities of the column-base connections.

The initial rotational stiffnesses are determined and incorporated into the analysis models to reflect the actual behaviors of the connections.

Iteration calculations for semi-rigid connections can be carried out by using interaction curves as discussed. Therefore, the designing procedure proposed in this paper allows this procedure to become faster, simpler and more economical.

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