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DESIGN OF SEMI-RIGID CONNECTIONS OF A FOUNDATION BASE WITH A METAL COLUMN

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Statement of the problem. The connections of the metal column with the foundation are usually considered rigid or spin. Foreign researches proved that they are in intersidereal form (called flexible or semi-rigid connections). The additional strengths *Q* in a semi-rigid connection increase the load on the bolt in comparision with which in the relatively rigid connection. Prying strengths should be considered for the design of the semi-rigid connections.
Results. The calculations of foundation base of metal columns account the stiffness of all their elements. Three cases of fracture mechanism are considered and the design resistance of the components in all cases is calculated.
Conclusions. The article introduces a method for calculating the T-sub bolted base column of the frames, under bending moment and axial strength.

Keywords: semi-rigid connections, stiffness, resistant, prying strength, bolted T-stub connections, rotational stiffness, rotation, column, foundation.

Introduction

The European Standard [2] using experimental methods or methods of rigidity of a combination of members (*component method*) enables the determination of the load-carrying capacity of bolted joints, displacements and rotational angles in joints, etc. [6, 7, 9].

According to the method of rigidity of a combination of members, the rigidity of a column base depends on the rigidity and load-carrying capacity of members included in anchor bolts working on tension and shear; the support and *T*-shaped slabs experiencing bending and tension; concrete foundation on compression and bending [5, 3, 8].

There are three cases of the failure of joints (Fig. 1):

— crushing of the slab and rupture of anchor bolts (Fig. 1a) — type 3;

— plastic failure of support slabs (Fig. 1b) — type 1;

— combination of the first two (Fig. 1c) — type 2.

1. Statement of the problem. Let us look at a column base of N-shaped section on a steel support slab joined to a concrete foundation by anchor bolts (Fig. 2). A joint is calculated considering the rigidity of members under the effect of a bending element and longitudinal strength [9].

The previously suggested method [3] is improved. Below are (Fig. 2) schemes of the operation of joining columns of N-shaped section to a steel support slab.

The failure of a support slab is due to plastic areas and hinges [2] (рис. 1, 3).

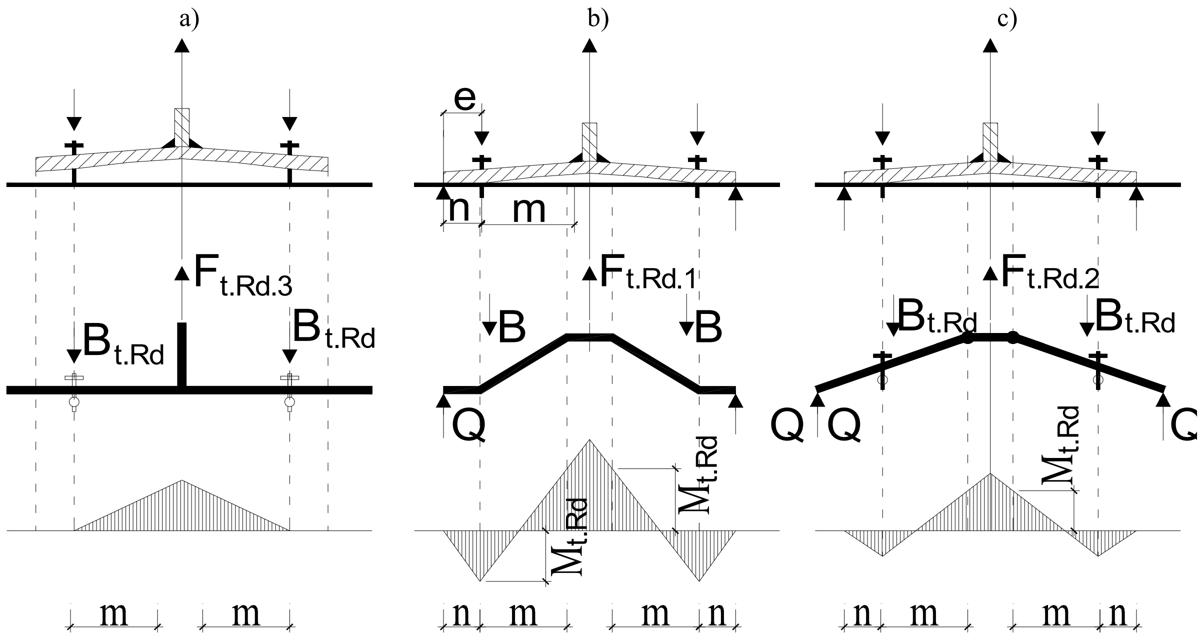

Fig. 1. Types of failure mechanisms, calculation schemes and diagrams of bending moments: $F_{t,\ Rd,1}$ is the compressive resistance of joints corresponding to a plastic failure mechanism (Fig. 1b); $F_{t,\ Rd,2}$ is the compressive resistance of the joints corresponding with a type of a combination of failure mechanisms (Fig. 1c); $F_{t,\ Rd,3}$ is the compressive resistance of the joints corresponding with crushing of the slab and rupture of bolts; $M_{t,\ Rd}$ is a plastic bending moment in the support slab (Fig. 1a); $B_{t,\ Rd}$ is a calculation compressive resistance of anchor bolts; B is a tensile strength on bolts; Q is extra strength [3]

a) b)

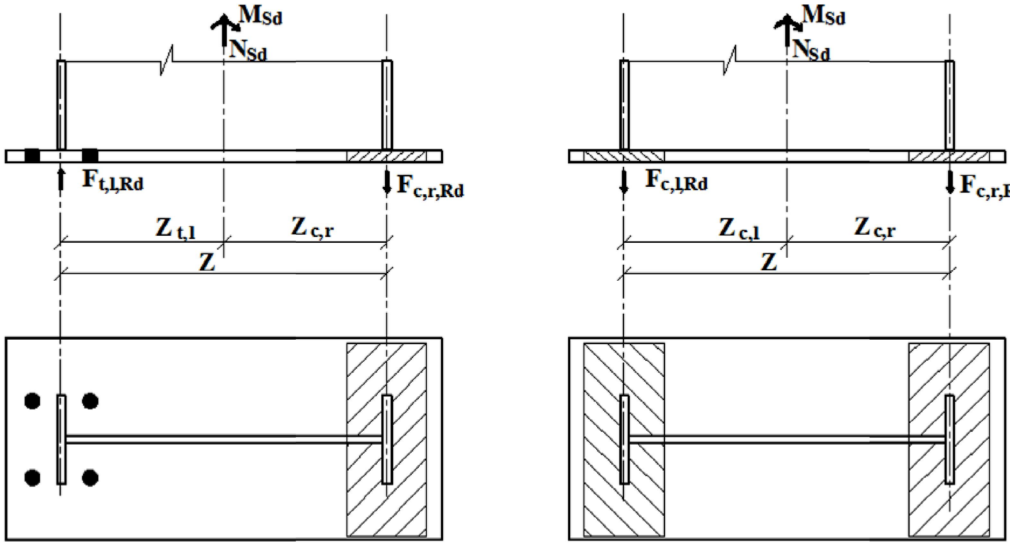

Fig. 2. Strengths applied to a support slab:
a) two rows of anchor bolts are stretched, the slab is compressed under the right cap;
b) support slab is compressed under both caps;
$F_{t,\,\mathrm{l},\,Rd}$ is a tensile load on the left part of the support slab;
$F_{c,\,r,\,Rd}$ is a compressive strength on the right part of the support slab;
$F_{c,\,\mathrm{l},\,Rd}$ is a compressive strength on the left part of the support slab;
M_{Sd} is a bending moment; N_{Sd} is a longitudinal strength;
$z_{c,\,\mathrm{l}}$ is an arm of the left compressive strength; $z_{c,\,r}$ is an arm of the right compressive strength;
$z_{t,\,\mathrm{l}}$ is an arm of the right tensile strength; z is an arm
(distance between the centres of the stretched and compressed zones)

c) d)

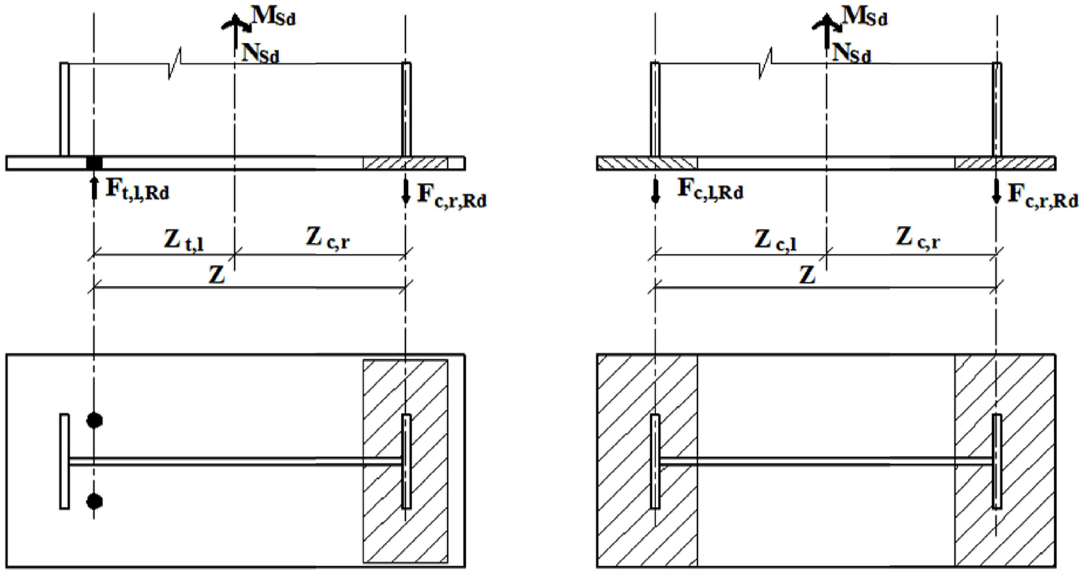

Fig. 2 (end). Strength applied to the support slab:
c) a row of anchor bolts is stretched, the slab is compressed under the right cap;
d) the same as “b” but the tension areas of the slab reach the edges

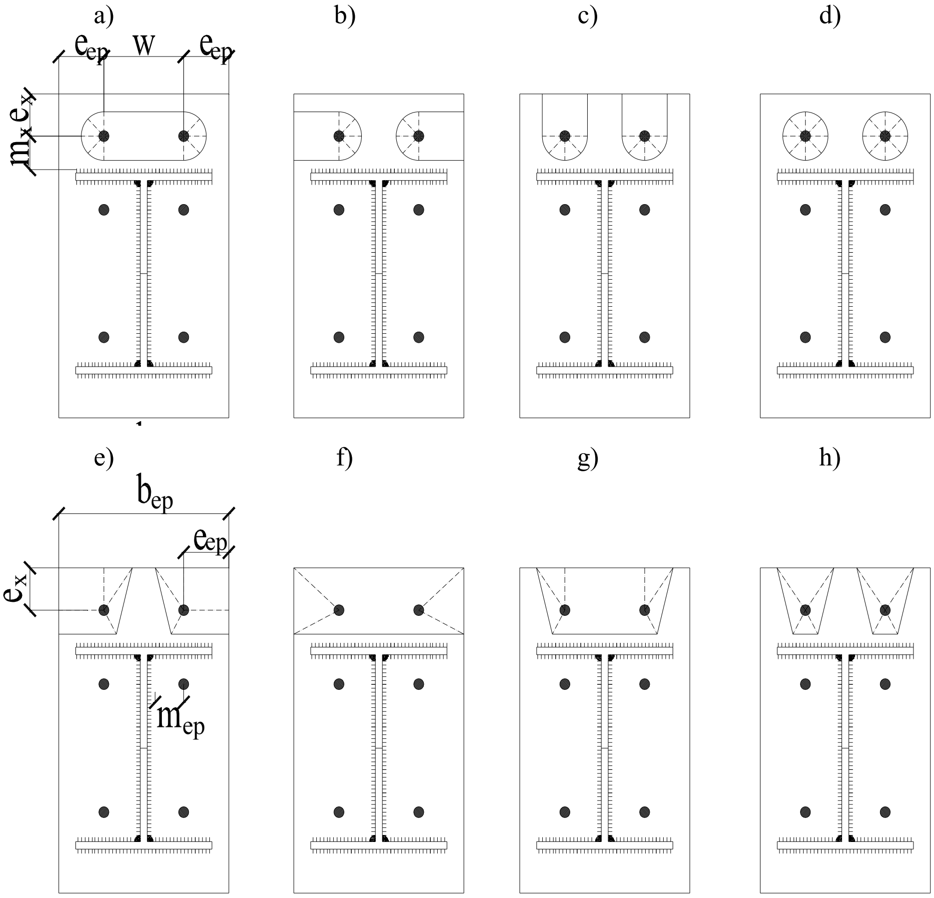

Fig. 3. Scheme of the failure of the support slab:
a, h) plastic areas are joined together; b) plastic areas reaches the transverse and longitudinal sides of the support slab;
c, g) the same for the transverse one; d) round plastic zones; e) angular plastic zones;
f) rectangular plastic zones

2. Solution of the problem

2.1. Determining the compressive resistance of the joints as a minimum of the function [5, 7]:

$$F_{t,Rd} = \min\left\{F_{Rd,1},\, F_{Rd,2},\, F_{Rd,3}\right\}. \quad (1)$$

Considering extra forces at

$$t_p = 2{,}07m\sqrt[3]{\frac{A_b}{L_{bef}l_{eff}}} \succ t_{ep}:$$
$$F_{t,Rd} = \min\left\{\frac{(8n-2d)M_{pl,1,Rd}}{2mn-d(m+n)};\ \frac{2M_{pl,2,Rd}+n\sum F_{t,Rd}}{m+n};\ \sum F_{t,Rd,b}\right\}; \quad (2)$$

without considering extra forces at

$$t_p = 2,07m\sqrt[3]{\frac{A_b}{L_{bef}l_{eff}}} \le t_{ep}:$$
$$F_{t,Rd} = \min\left\{\frac{2M_{pl,1,Rd}}{m};\ \sum F_{t,Rd,b}\right\}, \qquad (3)$$

where m is the distance between plastic hinges and the axis of the bolt (for a welded column $m = e_c - 0,8a_c\sqrt{2}$, a_c is the height of the leg of the weld; e_c is the distance between the axes of the compressed bolts to the column cap; for a rolled beam $m = e_c - 0,8r$, n is the distance between the extra strength Q and axes of the bolts ≤1,25*m)*; d is the diameter of the plate; L_{bef} is the effective length of anchor bolts:

$$L_{bef} = 8d_b + t_g + t_{ep} + t_n / 2,$$

where d_b is the diameter of anchor bolts; t_g is the thickness of the base between the support slab and the upper one with the foundation base; t_n is the thickness of the plate; $M_{pl,1,\ Rd}$, $M_{pl,2,\ Rd}$ are plastic bending moments of the support slab corresponding to the first and second failure mechanisms:

$$M_{pl,Rd} = \frac{l_{eff}t_{ep}^2 f_{y,ep}}{4\gamma_{Mo}},$$

where l_{eff} is the effective length of the compressed zone of the support slab:

$$l_{eff} = \min\{4m + 1,25e_x;\ 4\pi m;\ 0,5b;\ 2m + 0,625e_x + 0,5w;$$
$$-2m + 0,625e_x + e_{ep};\ 2\pi m + 4e_{ep};\ 2\pi m + w\};$$

t_{ep} is the thickness of the support slab; $f_{y,\ ep}$ is the bending resistance of the support slab material;

γ_{Mo} is the coefficient: $\gamma_{Mo} = 1$; w is the distance between two axes of bolts; b is the thickness of the support slab; e_x, e_{ep} are geometrical characteristics (Fig. 3, 4); $F_{t,\ Rd,\ b}$ is a calculated compressive resistance of anchor bolts:

$$F_{Rd,3} = \sum F_{t,Rd,b},\ F_{t,Rd,b} = \frac{0,9A_s f_{ub}}{\gamma_{Mb}}; \qquad (4)$$

A_s is the area of the longitudinal section of tensile bolts; f_{ub} is the tensile resistance of bolts; $\gamma_{Mb} = 1,1$ is the coefficient.

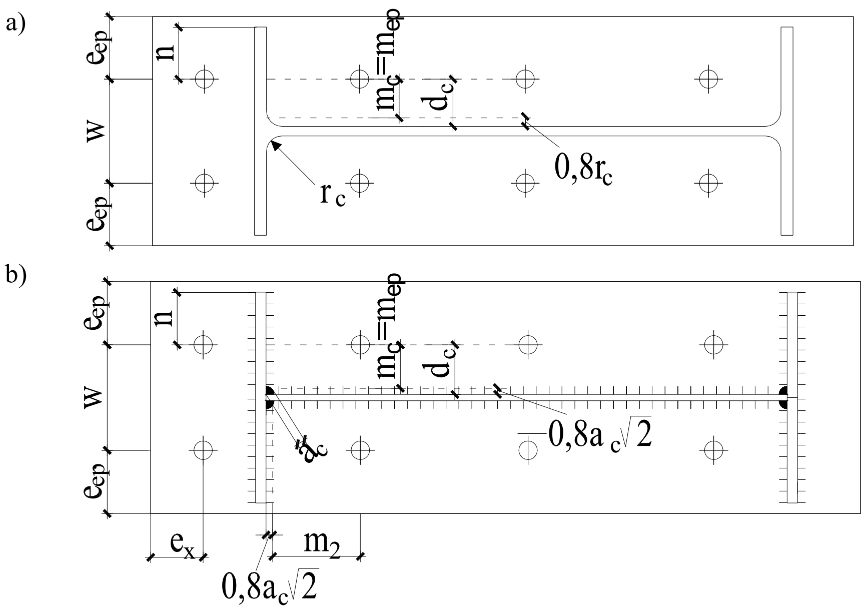

Fig. 4. Denotation of the sizes used in the calculation of the column:
a) of a rolled section; b) of a welded section

2.2. Compressive resistance of the joints [1, 7]:

$$F_{c,Rd} = \min\left\{ f_j b_{eff} l_{eff,c};\ \frac{M_{c,Rd}}{h_c + t_{cf}} \right\}, \tag{5}$$

where f_j is the compressive resistance of concrete under concentrated axial loads determined according to the European Standard [1]:

$$f_j = \frac{2k_j f_{ck}}{3\gamma_c};\ k_j = \sqrt{\frac{a_1 b_1}{ab}},$$

where f_{ck} is the compressive resistance of concrete; *a, b* is the width and length of the support slab (Fig. 5);

$$a_1 = \min\left\{a + 2a_r;\ 5a;\ a + h;\ 5b_1\right\} \ \text{и} \ a_1 \ge a;$$

$$b_1 = \min\left\{a + 2b_r;\ 5b;\ b + h;\ 5a_1\right\} \ \text{и} \ b_1 \ge b;$$

h is the height of a concrete base plate; $\gamma_c = 1{,}5$; $b_{eff,\,c}$, $l_{eff,\,c}$ is the effective width and length of the compressed zone of T-shaped section:

$$A_{eff,c} = \frac{F_{sd} + \sum F_{t,Rd,b}}{f_j},\ b_{eff,c} = \frac{A_{eff,c}}{b + 2c},\ l_{eff,c} = b + 2c,$$

b_c, c are the sizes specified according to Fig.5; $M_{c,\ Rd}$ is a plastic moment in the column considering the shear and axial strengths (according to the European Standard [2]):

– at $e = M_{sd}/N_{sd} > z_{c,\ r}$:

$$M_{c,Rd} = \min\{F_{t,l,Rd}z + N_{Sd}z_{c,r}; F_{t,l,Rd}z - N_{Sd}z_{t,l}\}; \qquad (6)$$

– at $e = M_{sd}/N_{sd} < z_{c,\ r}$:

$$M_{c,Rd} = \min\{F_{c,l,Rd}z + N_{Sd}z_{c,r}; F_{c,r,Rd}z - N_{Sd}z_{c,l}\}. \qquad (7)$$

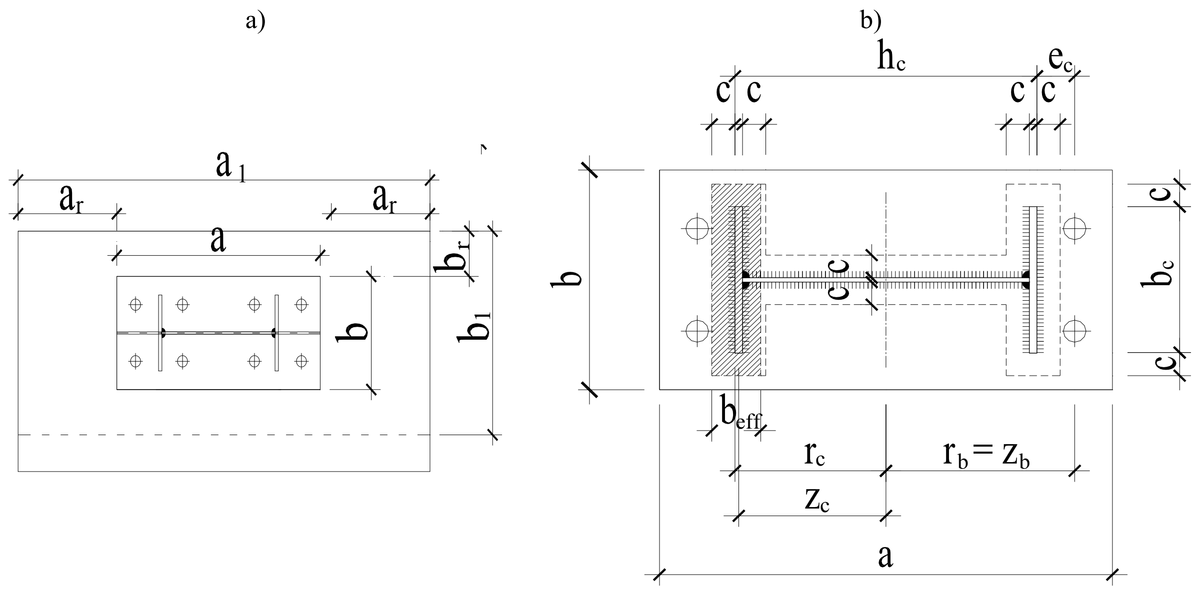

Fig. 5. Sizes of the column base:
a) position of the column on the support slab; b) position of the effective compressed zone on the support slab

2.3. Bending resistance of the column base [1, 7]:

$$M_{Rd} = \sum F_{t,Rd} \cdot r_b + A_{eff} \cdot f_j \cdot r_c, \qquad (8)$$

where r_b is the distance between the axes of the tensile bolts to the neutral line:

$$r_b = \frac{h_c}{2} + e_c;$$

r_c is the distance between the centre of the compressed zone to the neutral line:

$$r_c = \frac{h_c}{2} + c - \frac{b_{eff}}{2}.$$

2.4. Bending resistance of the joints considering the tensile strength [8]:

$$M_{N,Rd} = M_{pl,Rd,b} \frac{1 - N_{sd} / N_{b,pl}}{1 - 0,5(A - 2bt_f)/A}, \tag{9}$$

where $M_{pl,\,Rd.\,b}$ is a plastic moment of the support slab of the column:

$$M_{pl,Rd,b} = W_b f_{yep} / \gamma_{Mo}; \tag{10}$$

W_b is an inertia moment of the support slab of the column; γ_{Mo} = 1,1; f_{yep} is the bending resistance of the support slab material; A is the area of the transverse section of the column; $N_{b,\,pl}$ is a calculation longitudinal strength of the column base: $N_{b,\,pl} = Af_y / \gamma_{Mo}$; f_y is the compressive resistance of the support slab material; t_f is the thickness of the cap of the column section.

2.5. Determining the rigidity of the compressed concrete [7]:

$$K_c = E_c \frac{\sqrt{l_{eff,cp} b_{eff,c}}}{1,275}, \tag{11}$$

where E_c is the elasticity modulus of concrete foundations;

$$l_{eff,cp} = t_f + 2,5t_{ep}.$$

2.6. Determining the rigidity of a bended support slab [7, 8]:

— without considering extra forces:

$$K_{epb} = 0,425 E_{ep} \frac{l_{eff} t_{eff}^3}{m^3}; \tag{12}$$

— considering extra forces:

$$K_{epb} = 0,85 E_{ep} \frac{l_{eff} t_{eff}^3}{m^3}, \tag{13}$$

where E_{ep} is the elasticity modulus of a steel support slab.

2.7. Determining the rigidity of the tensile bolts [7]:

— without considering extra forces:

$$K_b = E_b \frac{2A_b}{L_{bef}}; \tag{14}$$

— without extra forces:

$$K_b = E_b \frac{1,6A_b}{L_{bef}}, \tag{15}$$

where A_b is the area of the longitudinal section of bolts.

The equivalence rigidity of the *i*-th row of bolts [6, 7]:

$$K_{t,i} = \frac{1}{\dfrac{1}{K_{epb,i}} + \dfrac{1}{K_{b,i}}}. \tag{16}$$

2.8. Determining vertical shears of the connections (Fig. 6.) [6, 9]:

$$\delta_{t,l} = \frac{M_{Sd} + N_{Sd} z_{c,r}}{z K_{t,l}}; \tag{17}$$

$$\delta_{c,r} = \frac{M_{Sd} - N_{Sd} z_{t,l}}{z K_{c,r}}. \tag{18}$$

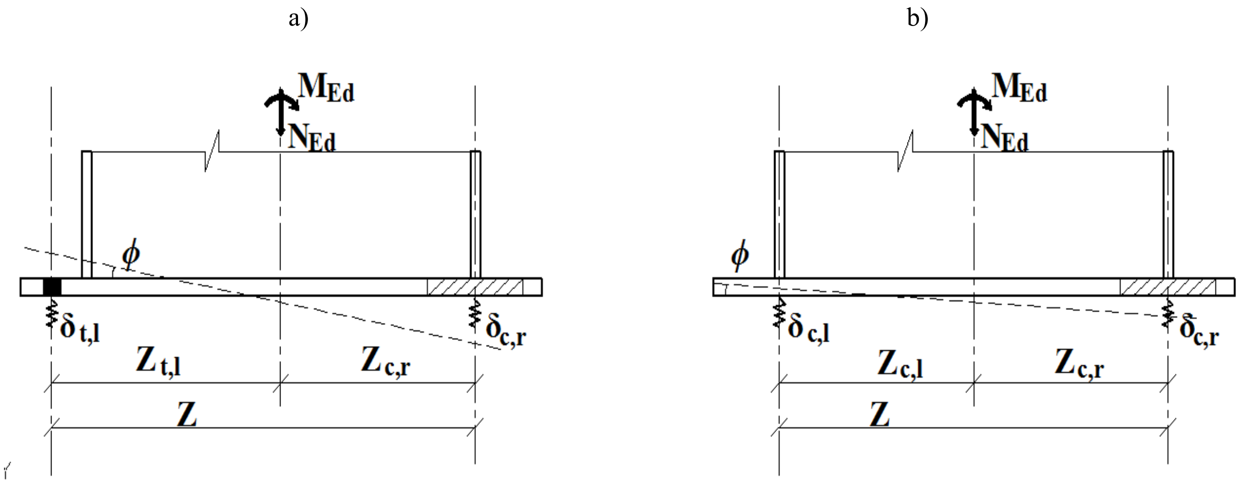

Fig. 6. Mechanical model of the joint:

a) at different signs of efforts in the connections (detachment of the slab from the foundation); b) at identical ones (compressed ones)

2.9. Determining the rotational angle of the support slab (Fig. 6a) [9]:

$$\varphi = \frac{\delta_{t,l}}{z} + \frac{\delta_{c,r}}{z} = \frac{1}{z^2}\left(\frac{M_{Sd} - N_{Sd} z_{t,l}}{K_{c,r}} + \frac{M_{Sd} + N_{Sd} z_{c,r}}{K_{t,l}}\right). \tag{19}$$

2.10. Determining the rotational resistance [5, 9]:

— at a small eccentricity $e < z_{c,r}$:

$$S_r = \frac{e}{e + e_0} \frac{z^2}{\left(\dfrac{1}{K_{c,l}} + \dfrac{1}{K_{c,r}}\right)}; \tag{20}$$

— at a large eccentricity $e > z_{c,\,r}$:

$$S_r = \frac{e}{e+e_0}\frac{z^2}{\left(\dfrac{1}{K_{t,l}}+\dfrac{1}{K_{c,r}}\right)}, \tag{21}$$

where $K_{c,\,l}$ and $K_{c,\,r}$ are the rigidities of the components under tension and shear; μ is the coefficient considering a reduction in the rigidity of a plastic range providing that a bending moment is 2/3 larger than the bending of the components:

$$\mu = \left(1{,}5\frac{M_{Sd}}{M_{Rd}}\right)^{2{,}7};$$

$$e_0 = \frac{K_c z_{c,r} - K_t z_{t,l}}{K_c + K_t}.$$

3. Sample calculation. The base of the column is to be computed: the thickness of the support slab is t_{ep} = 28 mm, thickness and width of a section of the column t_f = 10 mm, b_f = 200 mm, t_{wc} = 6 mm, h_{wc} = 380 mm; bolts A_b = 560 mm^2, f_{ub} = 192 N/mm^2, F_{Sd} = 95 kN; M_{Sd} = 170 kN·m; the height of the plate of the concrete foundation h = 1200 mm (Fig. 7).

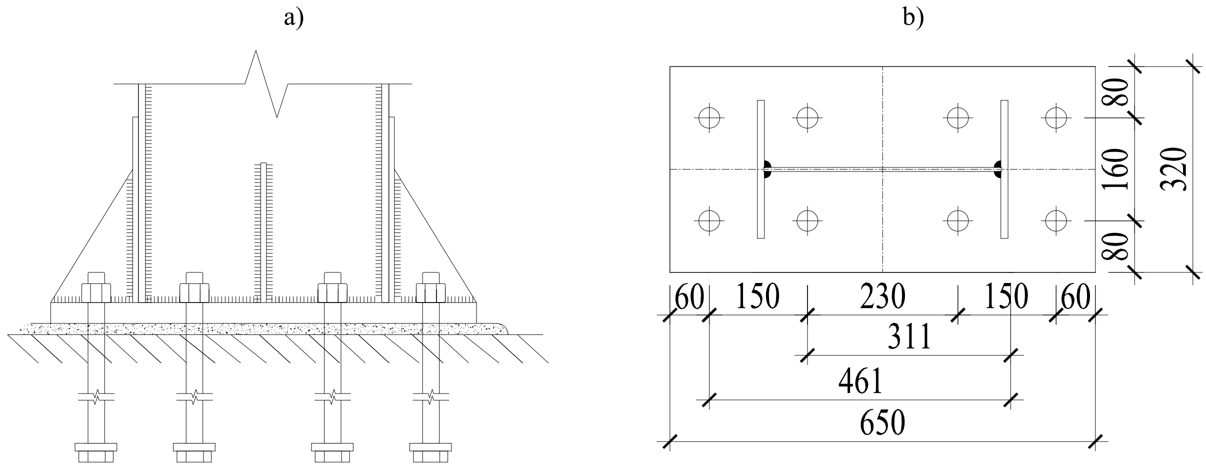

Fig. 7. Distribution of bolts in the column base:
a) a cut; b) a plan

The results of the calculation are specified in Table.

Table

Calculation data

Tensile resistance of the joints of the first row of bolts	$F_{1,t,Rd} = \min\{F_{t,Rd,1};\ F_{t,Rd,3}\} = \min\{230750;\ 193536\} =$ $= 193,5\ kN \succ F_{Sd} = 95\ kN$
Tensile resistance of the joints of the second row of bolts	$F_{2,t,Rd} = \min\{F_{t,Rd,1};\ F_{t,Rd,3};\ F_{bwt,Rd}\} =$ $= \min\{319555;\ 337882;\ 193536\} = 193,5\ kN \succ F_{Sd} = 95\ kN$
Bending resistance of the column base	$M_{Rd} = \sum F_{t,Rd} \cdot r_b + A_{eff} \cdot f_j \cdot r_c =$ $= 181,6\ \text{kN} \cdot m \geq M_{Sd} = 170\ \text{kN} \cdot m$
Bending resistance of the joint considering the tensile force	$M_{N,Rd} = M_{pl,Rd,b} \dfrac{1 - N_{sd} / N_{b,pl}}{1 - 0,5(A - 2bt_f)/A} =$ $= 173,7\ \text{kN} \cdot m \geq M_{Sd} = 170\ \text{kN} \cdot m$
Displacements of the support slab	$\delta_{t,l} = \dfrac{M_{Sd} + N_{Sd} z_{c,r}}{zK_{t,l}} = 0,46\ mm$; $\delta_{c,r} = \dfrac{M_{Sd} - N_{Sd} z_{t,l}}{zK_{c,r}} = 0,13\ mm$
Rotational angle of the support slab	$\varphi = \dfrac{\delta_{t,l}}{z} + \dfrac{\delta_{c,r}}{z} = \dfrac{0,46 + 0,13}{434,12} = 1,36 \cdot 10^{-3}$
Rotational resistance	$S_r = \dfrac{e}{e + e_0} \dfrac{z^2}{\mu\left(\dfrac{1}{K_{t,l}} + \dfrac{1}{K_{c,r}}\right)} = 1,95 \cdot 10^{10}\ Nmm/radian$

Conclusions

1. A method of the evaluation of the rigidity and strength of joints of metal columns with foundations under the effect of a bending moment and axial vertical force considering the rigidity and strength of members of a joint.

2. A degree of accuracy of calculations using the *component method* in compliance with the Eurocode 3.

3. The previously suggested [6] method of predicting the operation of members of a joint due to more accurate determination of the sizes and shapes of elastic and plastic compressive zones depending on the models suggested in [5, 6, 9].

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