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Research paper

Resistance and stiffness assessment of reinforced column base using the component method

Przemysław Krystosik[1]

Abstract: The article presents an algorithm for assessing the resistance and stiffness of a reinforced column base, which is based on the component method. The main part of the study formulates a mechanical model of the reinforced column bases, in the form of a stiffened base plate fixed to the concrete by eight anchor bolts. The adopted structural solution was analyzed using the component method for calculations. By referring to standard guidelines and existing literature, the mechanical properties, such as resistance and stiffness, of individual components of the column base are determined. Equivalent mechanical models were then formulated using equilibrium conditions and deflection compatibility, enabling the derivation of formulas for the bending resistance $M_{j.Rd}$ and the initial stiffness $S_{j.ini}$ of the entire column base. In the final part of the work, a comprehensive numerical example is provided to demonstrate the application of the presented method in calculations of the reinforced column bases.

Keywords: column base, component method, resistance, stiffness

[1]PhD., Eng., Koszalin University of Technology, Faculty of Civil Engineering, Environment and Geodetic Sciences, ul. Śniadeckich 2, 75-453 Koszalin, Poland, e-mail: przemyslaw.krystosik@tu.koszalin.pl, ORCID: 0000-0003-2871-8746

1. Introduction

The component method is a recommended way by Eurocode [1] to assess the resistance and stiffness of column bases. The direct application of the standard guidelines [1] allows to calculate connections between steel column and foundation with a simple construction (Fig. 1b) and c) in the form of the base plate, which attached to the foundation with anchor bolts. However, in the literature, e.g. in [2–5], you can find a number of helpful numerical examples that well describe the way of calculating the anchorages of columns shown in Fig. 1a–c.

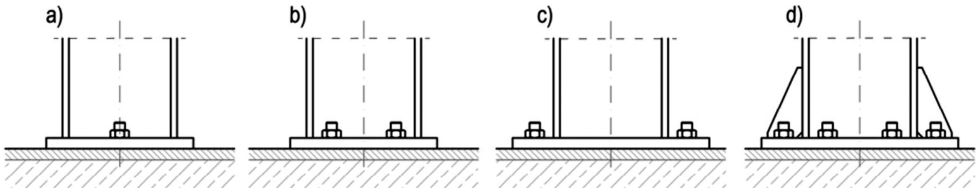

Fig. 1. Examples of column bases: a) column base with one row of bolts near the column web, b), c) column base with two rows of bolts, d) reinforced column base

Although the standard [1] provides guidelines for calculating only column bases with two rows of bolts, the possibilities of using the component method in the design of support joints are greater. This means that the mentioned method allows for the calculation of reinforced column bases, such as stiffened bases or bases fixed with a greater number of anchors in the foundation (Fig. 1d). This circumstance allows for the design of column bases with higher resistance and stiffness, often without the need for more complex solutions that would require calculations using other methods [2, 6].

2. Preliminary CBFEM analysis of stiffened column base

To analyze the assumptions for creating the mechanical model, a preliminary analysis of the stiffened column base (Fig. 1d) was conducted. The numerical calculations were performed using the IdeaStatika software, which can be used for the design of steel structures, including joints and connections [7]. The software operates based on the CBFEM (Component Based Finite Element Model) method, which was developed for effective modelling and calculation of joints and connections, both welded and bolted. The method of model creation and the utilization of an incrementally-iterative calculation algorithm enable the consideration of various effects occurring in different types of joints, such as complex construction, discontinuities in the contact area of plates during tension, force transfer through compression and friction. Additionally, the software offers the possibility to use nonlinear material models. As a result, the IdeaStatica provides a good assessment of the behavior of designed joints under both simple and complex loading conditions.

The calculations were carried out for three similar cases of the column base, differing in the ratio of the height h to the width b of the column cross-section. The adopted ratios of h/b were approximately 1.6, 2.4 and 3.2. An example model of the calculated joint is shown in Figure 2.

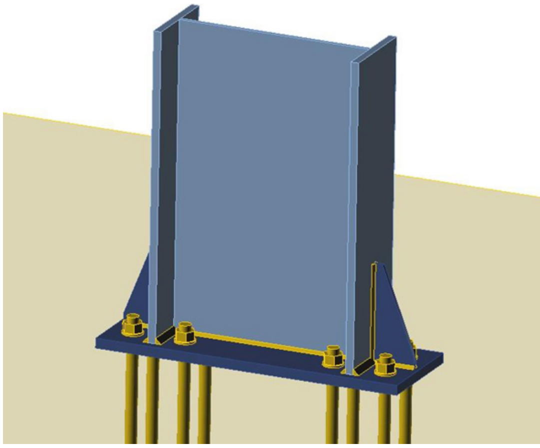

Fig. 2. Calculation model for column base design with proportion: $h/b = 2.4$

The load system consisting of the normal compressive force N_{Ed} and bending moment M_{Ed} was selected in such a way that in each considered case: the compressive stresses in the column reached approximately 80% of the yield strength of the steel (S235), the load eccentricity $e = M_{Ed}/N_{Ed}$, was equal to 1.5 m. The data for the calculated base variants are summarized in Table 1.

Table 1. Data for calculations in the IdeaStatica software

Concrete C30/37, steel S235, anchor bolts M24 kl. 8.8, anchorage length l_{bd} = 600 mm, base plate thickness t_p = 20 mm			
Dimensions of the column cross-section elements			
Flanges cross-section – $b \times t_f$ [mm]	180 × 16		
Webs cross-section – $h_w \times t_f$ [mm]	250 × 8	400 × 8	550 × 8
Ratio b/h	1.57	2.4	3.23
Loading			
Bending moment M_{Ed} [kNm]	140.3	230.9	327.5
Normal force N_{Ed} [kN]	93.5	153.9	218.3
Load eccentricity $e = M_{Ed}/N_{Ed}$ [m]	1.5		

The presented in the Fig. 3 stress distributions indicate that regardless of the adopted proportions of the column cross-section, the load on the corresponding sections of the column base is quite similar. In the tension zone (on the left side of each analyzed case), the highest stress values occur in the stiffeners, while slightly lower stresses are observed in the flange and part of the web. On the right side, however, it can be observed that the presence of compressive force between the base and the foundation generates significant stresses in the flange and stiffener.

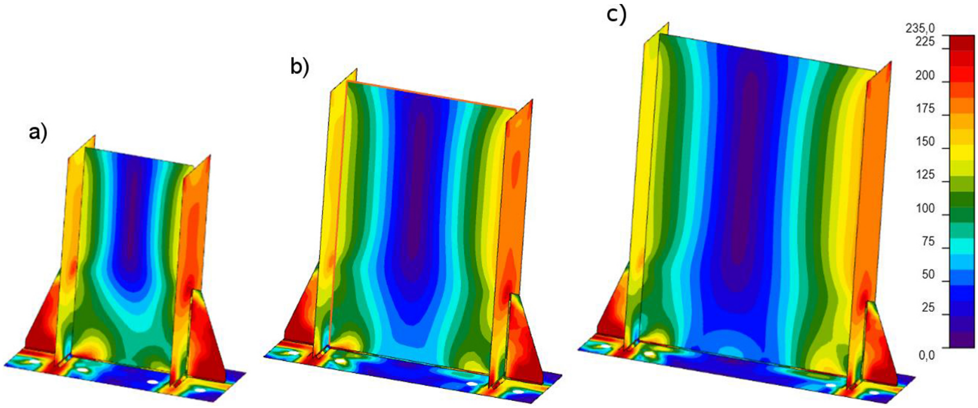

Fig. 3. Equivalent stress maps [MPa] in the column bases with proportions: a) $h/b \approx 1.6$, b) $h/b = 2.4$, c) $h/b \approx 3.2$

This corresponds well with the illustrations depicting the bearing stresses under the base plate (Fig. 4).

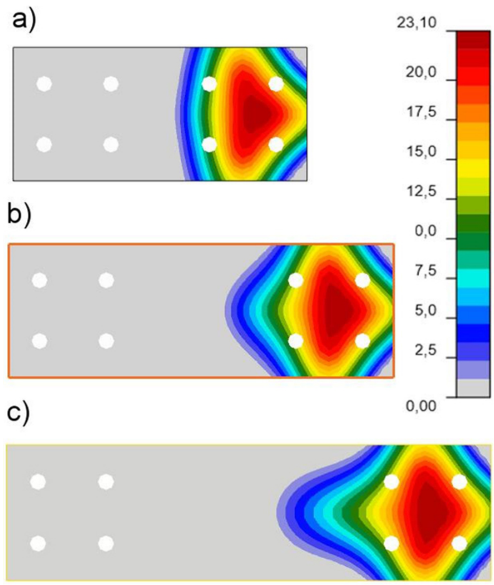

Fig. 4. Maps of compressive stresses [MPa] in the contact surface between the base plate and the concrete foundation with proportions: a) $h/b = 1.6$, b) $h/b = 2.4$, c) $h/b = 3.2$

It is also worth noting that the transfer of tensile and compressive forces through the base plate induces significant bending within the plate. This effect, in the form of high stress values, can be observed near the stiffeners and flanges (Fig. 3).

3. The component model of the reinforced column base

When performing calculations of the column base using the component method [1], it is necessary to identify the so-called basic components. These are the parts of the connection between the column and the foundation, in which a certain characteristic state of loading and deformation can be assumed. In the case of the column base shown in Fig. 5a (refer to Fig. 1d, the following components can be distinguished.

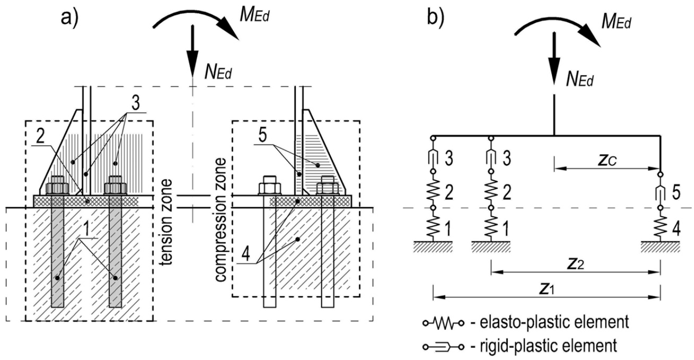

Fig. 5. Reinforced column base: a) basic components of the column base, b) mechanical model of the column base – model I. 1 – anchors fixed in the concrete in the tension zone, 2 – base plate in the tension zone, 3 – stiffener, column flange and column web in the tension zone, 4 – base plate and concrete foundation in the compression zone, 5 – stiffener and column flange in the compression zone

Each of these components is modelled using discrete elasto-plastic element or rigid-plastic element. Subsequently, two mechanical parameters are assigned to each elasto-plastic element: the stiffness coefficient k and the plastic resistance F_{Rd}. Rigid-plastic elements are assigned only one feature – resistance F_{Rd}. By understanding the mechanical characteristics of these discrete elements and their arrangement, a mechanical model of the joint, referred to as model I (Fig. 5b), can be created. This model serves as the starting point for calculating the resistance and stiffness of the entire column base.

3.1. Resistance of anchors bolts

Determining the resistance of anchors requires considering situations that involve the failure of the anchors themselves as well as the failure of the concrete surrounding the anchor bolts. The resistance of typical anchors can be determined according to the standard [1], taking into account two failure models in tension. In the first one, due to the fracturing, the resistance of the anchor bolt is calculated according to the formula:

$$F_{t.Rd} = 0,9\frac{A_s f_{ub}}{\gamma_{M2}} \tag{3.1}$$

where: A_s is the tensile stress area, f_{ub} is the ultimate strength of the bolt material, $\gamma_{M2} = 1.25$.

In the second model, the resistance is determined due to the punching shear – pull-through of bolt head (or nut) through the steel plate. The value sought is determined according to the following relationship:

$$B_{p.Rd} = \frac{0,6\pi d_m t_p f_u}{\gamma_{M2}} \tag{3.2}$$

where: d_m is the mean diameter of the bolt head or the nut, f_u is the ultimate strength of the plate material.

If necessary, according to [1], the shearing resistance, the bearing resistance, as well as the resistance due to the simultaneous occurrence of shear and tension in the anchor bolts can be determined. A list of appropriate formulas for calculations is provided in Table 3.4 [1].

Designing anchor bolts fixed in concrete is a complex process, primarily due to the requirement of safely transferring significant forces to a brittle material with low tensile strength. The transfer of forces occurs through mechanical anchoring, friction forces, adhesion, or a combination of these effects, which can lead to various potential failure mechanisms. Additionally, the design process may be further complicated by the presence of a complex load state, involving the cumulative effect of tensile and shear forces transmitted from the anchor bolts to the concrete.

Standard [1] indicates that the calculation of anchor bolts resistance should be carried out according to the guidelines [8]. However, a substantial amount of information on anchor design procedures can be found in [9]. Furthermore, when calculating the resistance of a specific type of anchor, it is often necessary to utilize information from technical approvals. A comprehensive commentary on the design methodology and calculation of anchorages is presented in [10, 11]. Ultimately, the sought resistance of a single anchor in tension $F_{t.Rd}$ corresponds to the minimum resistance among all considered failure models.

3.2. Resistance and stiffness of base plate in tension zone

The determination of the resistance $F_{T.Rd}$ and stiffness k_2 of the base plate, according to [1], is achieved through the analysis of the behavior of T-stubs, which are specific areas of the base plate where significant bending occurs due to forces transmitted by the anchors.

In the initial stage of determining the resistance $F_{T.Rd}$, the effective lengths of the T-stubs, referred to as l_{eff}, are determined. These lengths represent hypothetical yield line formations in the plate caused by bending. The possible shapes and formulas for calculating the effective lengths in circular (c_p) and non-circular (n_c) failure mechanisms for the analyzed example of the column base (Figure 5a) are shown in Fig. 6.

From the obtained set of l_{eff} values, for each bolt–row, the minimum values should be determined according to the following relationship:

$$l_{\text{eff}.1} = \min\left(l_{\text{eff}.cp}, l_{\text{eff}.nc}\right) \tag{3.3}$$

$$l_{\text{eff}.2} = l_{\text{eff}.nc} \tag{3.4}$$

Next, it is necessary to check the possibility of the prying effect in anchor bolts, which refers to an increase in forces in the anchors caused by the contact (locking) of the deformed

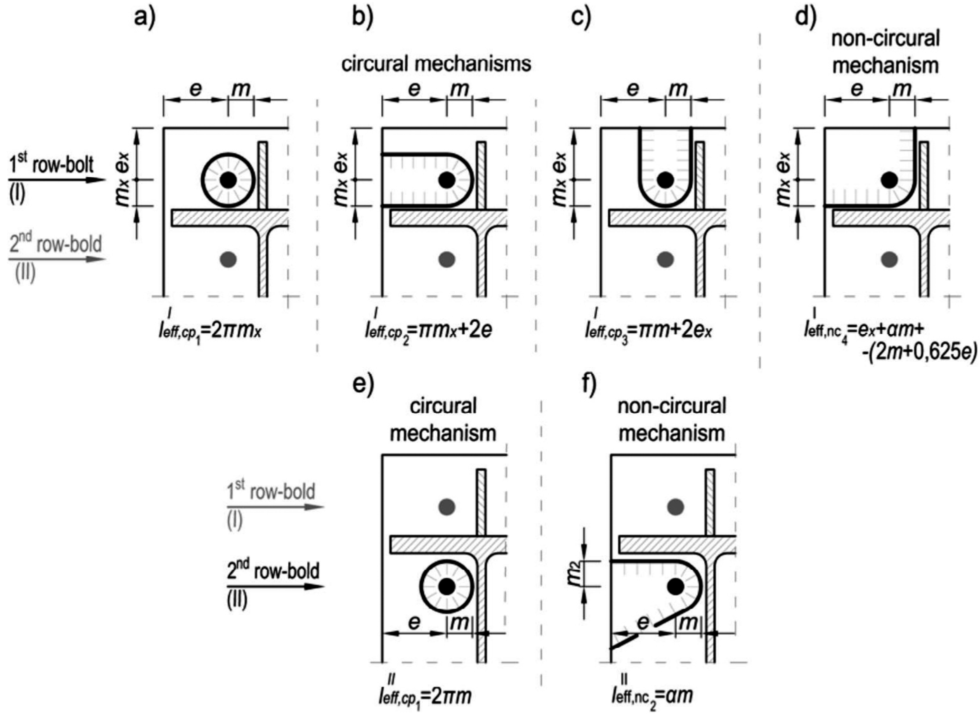

Fig. 6. Effective lengths in: a)–d) the 1st bolt-row (outer), e)–f) the 2nd bolt-row (inner)

plate edges against the concrete surface [12]. According to [1], this effect can occur when the following condition is met:

$$L_b \leq \frac{8,8m^3 A_s}{l_{\text{eff}.1} t_p^3} \tag{3.5}$$

where: L_b is the anchor bolt elongation length, m (or m_x) is the geometrical parameter according to Figure 6. If condition (3.5) is not met, the prying effect will not occur.

In the procedure for determining the resistance $F_{T.Rd}$, the standard [1] distinguishes four failure mechanisms, which are respectively characterized as follow: full yielding of the base plate (model Ia), partial yielding of the base plate (model Ib), partial yielding of the base plate and anchor bolts failure (model II), failure of the anchor bolts (model III).

Calculations of $F_{T.Rd}$ according to models Ia and II should take into account the possibility of the prying effect, while the resistance according to models Ib and III is determined without considering this effect. Detailed guidelines for determining the resistance are provided in Table 6.2 [1], while the key formulas for calculations are presented in Table 2.

The ultimate tension resistance of the T-stubs $F_{T.Rd}$ is determined as the minimum value obtained for the predicted failure mechanisms.

Table 2. Data for calculations in the IdeaStatica software

Prying forces may occur	**No prying forces**
(3.6) $F_{T.1.Rd} = \frac{4M_{pl.1.Rd}}{m}$ – model Ia	(3.7) $F_{T.1b.Rd} = \frac{2M_{pl.1.Rd}}{m}$ – model Ib
(3.8) $F_{T.2.Rd} = \frac{2M_{pl.2.Rd} + n\sum F_{t.Rd}}{m+n}$ – model II	
(3.9) $F_{T.3.Rd} = \sum F_{t.Rd}$ – model III	
$M_{pl.1.Rd} = \frac{1}{4}\frac{\sum l_{\text{eff}.1} t_p^2 f_y}{\gamma_{M0}}$ where $l_{\text{eff}.1} = \min(l_{\text{eff}.nc}, l_{\text{eff}.cp})$ $M_{pl.2.Rd} = \frac{1}{4}\frac{\sum l_{\text{eff}.2} t_p^2 f_y}{\gamma_{M0}}$ where $l_{\text{eff}.2} = \min(l_{\text{eff}.nc})$ $n = e \le 1.25m\gamma_{M0} = 1.0$	

The calculation of the stiffness of the base plate in the tension zone is reduced to determining the k_2 parameter according to the formulas [1]:

$$k_2 = \frac{0,85 l_{\text{eff}.1} t_p^3}{m^3} \quad \text{if the prying effect occurs,} \tag{3.10}$$

$$k_2 = \frac{0,425 l_{\text{eff}.1} t_p^3}{m^3} \quad \text{if there is no prying effect} \tag{3.11}$$

At this point, the stiffness coefficient of the anchor bolts k_1 can also be determined. The value of this parameter is calculated using the relationship [1]:

$$k_1 = \frac{1,6A_s}{L_b} \quad \text{if the prying effect occurs,} \tag{3.12}$$

$$k_1 = \frac{2,0A_s}{L_b} \quad \text{if there is no prying effect.} \tag{3.13}$$

3.3. Resistance of stiffener, column flange and column web in tension zone

In the considerate column base, the tension zone consists of the column flange, a part of the column web and the stiffener, whereby the column flange cooperates with both the external and internal bolt–row (refer to Fig. 3). Since the resistance of the 1st and the 2nd bolt–row is determined separately (these bolt–rows are separated by the flange) the resistance of the 1st bolt–row can be determined by the formula:

$$F_{t.fc.Rd} = \frac{b_s t_s f_y}{\gamma_{M0}} + \frac{0,5 b_f t_f f_y}{\gamma_{M0}} \tag{3.14}$$

where: b_s and t_s are the width and thickness of the stiffening rib in the tension zone, respectively. Assuming conservatively that the effective width of the column web panel in tension b_w is equal to the width of the rib b_s, the resistance of the 2nd bolt–row can be determined similarly using the condition:

$$F_{t.wc.Rd} = \frac{b_w t_w f_y}{\gamma_{M0}} + \frac{0,5 b_f t_f f_y}{\gamma_{M0}} \tag{3.15}$$

Alternatively, the calculation of the tension resistance of the column plates within the 1st and the 2nd bolt–row can be calculated according to the formulas [1]:

$$F_{t.ts.Rd} = \frac{b_{\text{eff}} t_s f_y}{\gamma_{M0}} \tag{3.16}$$

$$F_{t.wc.Rd} = \frac{b_{\text{eff}} t_w f_y}{\gamma_{M0}} \tag{3.17}$$

where: b_{eff} is the effective width of the tensioned plates, which are determined on the basis of the effective lengths l_{eff} on the 1st and 2nd bolt–rows, respectively [1]. Formulas (3.16) and (3.17) can be used specifically when the flange thickness t_f is at least twice the thickness of the stiffeners t_s and the column web t_w.

3.4. Resistance and stiffness of base plate and concrete in compression zone

The transfer of significant compressive force between the column base and the concrete foundation results in strong bending of the base plate and significant stresses in the concrete. The area of stress transfer at the interface between the base plate and the concrete, denoted as A_{eff}, is determined using the parameter c [1]:

$$c = t_p \sqrt{\frac{f_y}{3 f_{jd} \gamma_{M0}}} \tag{3.18}$$

where: f_{jd} is the design bearing strength of concrete according to [8].

In column bases with two rows of bolts, especially in the case of large load eccentricities, A_{eff} is located directly under the compressed column flange (Fig. 7a). In the analyzed base, the presence of stiffeners changes the stress distribution under the base plate (cf. Fig. 4a–c). Therefore, the shape of A_{eff} can be determined according to the drawing (Fig. 7b).

Based on the determined effective bearing area A_{eff}, the resistance can be calculated using the formula [1]:

$$F_{c.pl.Rd} = A_{\text{eff}} f_{jd} \tag{3.19}$$

The stiffness of the base plate-concrete system under compression denoted as k_4, can be determined according to [1], using the following relation:

$$k_4 = \frac{E_c \sqrt{A_{\text{eff}}}}{1.275 E} \tag{3.20}$$

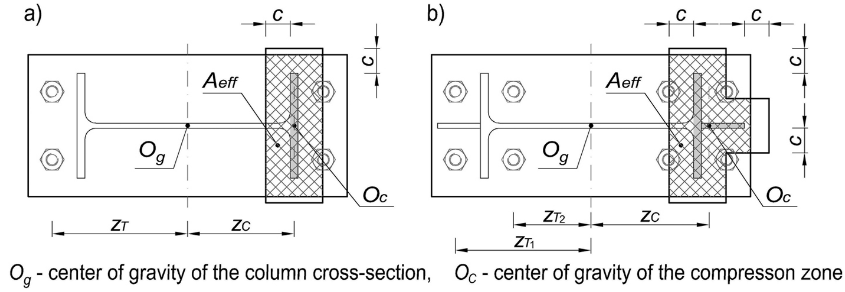

Fig. 7. Way of determining the effective bearing area A_{eff} in the case of: a) column base with two rows of bolts, b) reinforced column base

3.5. Resistance of stiffeners and column flange in compression zone

When determining the resistance of the second component in the compressed zone, it is necessary to consider parts that provide support for the base plate. In the case under consideration, these parts are the column flange and the stiffener, which, as shown in Figure 3a–c, are subjected to significant loads. Therefore, the formula for the resistance can be written as:

$$F_{c.fc.Rd} = \frac{b_f t_f f_y}{\gamma_{M0}} + \frac{b_s t_s f_y}{\gamma_{M0}} \tag{3.21}$$

3.6. Resistance and stiffness of entire column base

The calculation of the column base resistance is determined on the basis of the equilibrium conditions of forces in the ultimate limit state, as presented in Fig. 8a.

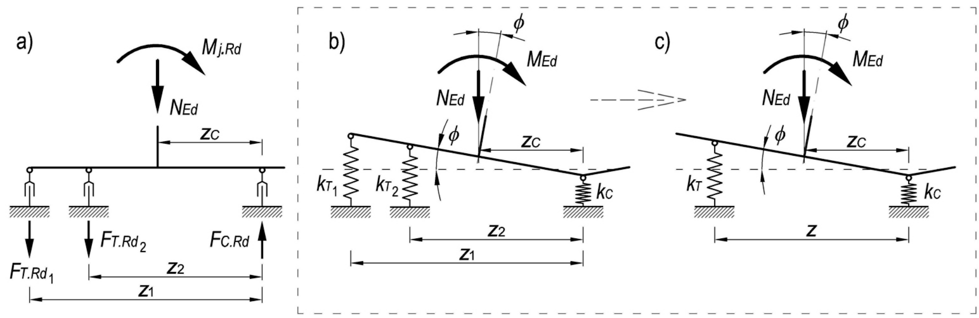

Fig. 8. Equivalent mechanical models of the reinforced column base: a) model used for resistance calculations (model II), b) and c) – models used in stiffness analysis (model III and model IV)

To begin the calculations, it is necessary to determine the relevant limit values of forces in the 1st and the 2nd bolt–row of the tension zone, as well as the resistance in the compression zone. The way of determining the appropriate values can be expressed in the form of equations:

$$F_{T.Rd1} = \min\left(F_{T.Rd}, F_{t.ts.Rd}\right) \tag{3.22}$$

$$F_{T.Rd2} = \min\left(F_{T.Rd}, F_{t.wc.Rd}\right) \tag{3.23}$$

$$F_{C.Rd} = \min\left(F_{c.pl.Rd}, F_{c.fc.Rd}\right) \tag{3.24}$$

following the principle that the "weakest" components determine the resistance of the separated zones. Furthermore, it is necessary to check if the assumed force system satisfies the following condition:

$$F_{C.Rd} \geq \sum_i F_{T.Rd_i} + N_{Ed} \tag{3.25}$$

If inequality (3.25) is not satisfied, then the resistance of the bolt–rows in the tension zone needs to be reduced, starting with the reduction of the internal 2nd bolt–row. Another way to meet the condition (3.25) may involve adopting structural solutions that increase the resistance of the compressed zone accordingly.

Based on the established force system in model II (Fig. 8a), the final calculation of the bending resistance of the column base can be determined using the formula:

$$M_{j.Rd} = \sum_i \left(F_{T.Rd_i} \cdot z_i\right) + N_{Ed} \cdot z_c \tag{3.26}$$

The stiffness of the column-foundation connection can be defined by analyzing the response of the mechanical model of the joint to the applied moment M_{Ed} and the axial force N_{Ed}. This load leads to changes in the length of discrete elements with elastic properties, resulting in the rotation of the base model by a certain angle ϕ.

The behavior of the column base can be analyzed on the basis of an equivalent mechanical model of the joint (model III – Fig. 8b), where discrete elements in the 1st and 2nd bolt–row, as well as in the compressed zone, are replaced by equivalent elements with appropriately selected stiffness, according to the following formulas:

$$k_{Ti} = \frac{1}{\sum_j \frac{1}{k_j}} \tag{3.27}$$

$$k_C = k_4 \tag{3.28}$$

At a later stage of the analysis, model III can be replaced with its equivalent counterpart – model IV, where the discrete elements of both bolt–rows of the tension zone are replaced by one element (Fig. 8c). Modifying the mechanical model of the column base requires determining two additional parameters: the equivalent stiffness of the discrete element in the tension zone k_T, and an equivalent lever arm z. These parameters can be determined on geometric relationships. After performing the necessary transformations, the following formulas are obtained:

$$z = \frac{k_{T1} \cdot z_1^2 + k_{T2} \cdot z_2^2}{k_{T1} \cdot z_1 + k_{T2} \cdot z_2} \tag{3.29}$$

$$k_T = \frac{k_{T1} \cdot z_1 + k_{T2} \cdot z_2}{z} \tag{3.30}$$

Alternatively, to simplify the calculations, the lever arm and the equivalent stiffness of the tension zone can be calculated using the following relation:

$$z = \frac{z_1 + z_2}{2} \tag{3.31}$$

$$k_T = k_{T1} + k_{T2} \tag{3.32}$$

Transforming model III to the equivalent mechanical model with a single bolt–row in the tension zone (model IV) allows the use of the standard formula for the stiffness of the column base [1]:

$$S_j = \frac{M_{Ed}}{\varphi} = \frac{E \cdot z^2}{\mu \left(\frac{1}{k_T} + \frac{1}{k_C} \right)} \frac{e}{e + e_k} \tag{3.33}$$

where: E is the modulus of elasticity of steel, μ is the coefficient determining the relation between the initial and the secant stiffness of the joint [1], and e_k is a parameter taking into account the base stiffness and the influence of the eccentricity e. In the considered case, the value of e_k should be calculated according to the formula [1]:

$$e_k = \frac{k_C \cdot z_C - k_T(z - z_C)}{k_C + k_T} \tag{3.34}$$

4. The computational example

The calculations of the resistance and stiffness were performed for two types of column bases, as presented in Fig. 9.

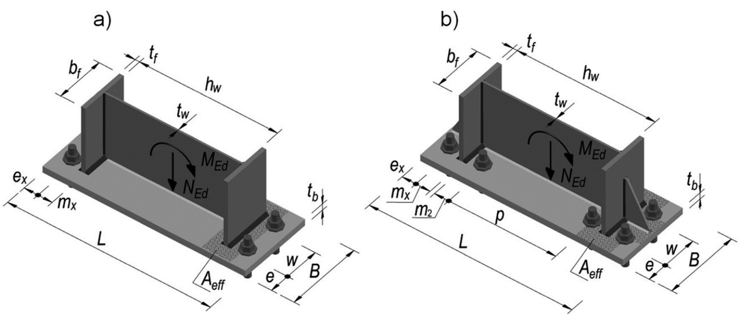

Fig. 9. Analyzed column bases: a) base plate anchored to the foundation by 4 anchor bolts, b) base plate anchored to the foundation by 8 anchor bolts

The first analyzed column base is a typical structural solution consisting of a base plate anchored to the foundation by 4 anchor bolts. In the second case, a stiffened base plate is considered, which is fastened in the concrete using 8 anchor bolts. Both bases have the same column cross-section, base plate, anchors type, and material (steel grade). The calculation data are provided in Table 3.

Table 3. Data for the column bases calculations

Common features of the analyzed column bases
steel S235, E = 210 GPa, f_y = 235 MPa, f_u = 360 MPa; – concrete class: C30/37; $f_{jd} = 2f_{cd}$ (assumption) dimensions of the column cross-section plates: b_f = 180 mm, t_f = 16 mm, h_w = 400 mm, t_w = 8 mm, dimensions of the stiffeners: b_s = 90 mm, t_s = 8 mm, dimensions of the base plate: L = 632 mm, B = 220 mm, t_b = 20 mm, anchors bolt: M24, kl. 8.8, arrangement of the anchor bolts: e_x = 50 mm, m_x = 50 mm, m_2 = 50 mm, m = 46 mm, p = 302 mm, e = 40 mm, w = 100 mm, forces acting on the column base: normal force N_{Ed} = 153.0 kN, bending moment M_{Ed} = 230 kNm, the welds were designed for full resistance of the column bases plats.

The resistance and stiffness calculations for the unstiffened column base were performed following the guidelines in [1], while the calculations for the reinforced column base were based on the algorithm presented in the article. The anchor bolts were calculated according to [1] and [9], taking into account the most important factors that affect their resistance. Finally, the results of the anchor calculations, i.e. the resistance due to anchor failure – $F_{t.Rd}$, and the minimum resistance due to failure of the anchorage in the concrete – $N_{t.Rd}$, were presented.

The summary of results from subsequent stages of calculations for both column bases is shown in Table 4.

Table 4. Summary of the calculation results of the resistances of the column bases

Column base with two rows of bolts			**Reinforced base**	
Tension zone				
Resistance of the single anchor bolt				
$F_{t.Rd}$ = 172.8 kN, $N_{t.Rd}$ = 125.2 kN				
Resistance of the base plate				
The effective lengths (acc. to [1])			The effective lengths (acc. to Fig. 6)	
1st bolt–row	$l_{\text{eff}.cp.1}$ = 314 mm $l_{\text{eff}.cp.2}$ = 277 mm $l_{\text{eff}.cp.3}$ = 257 mm	$l_{\text{eff}.nc.1}$ = 263 mm $l_{\text{eff}.nc.2}$ = 191 mm $l_{\text{eff}.nc.3}$ = 181 mm $l_{\text{eff}.nc.4}$ = 110 mm	1st bolt–row	$l^{I}_{\text{eff}.cp.1}$ = 314 mm, $l^{I}_{\text{eff}.cp.3}$ = 245 mm, $l^{I}_{\text{eff}.cp.2}$ = 277 mm, $l^{I}_{\text{eff}.nc.4}$ = 276 mm,
			2nd bolt–row	$l^{II}_{\text{eff}.cp.1}$ = 289 mm $l^{II}_{\text{eff}.nc.2}$ = 271 mm
1st bolt–row	$F^{I}_{T.1.Rd}$ = 206.8 kN – model Ia $F^{I}_{T.2.Rd}$ = 176.9 kN – model II $F^{I}_{T.3.Rd}$ = 250.4 kN – model III		1st bolt–row	$F^{I}_{T.1b.Rd}$ = 205.5 kN – model Ib $F^{I}_{T.3.Rd}$ = 250.4 kN – model III
			2nd bolt–row	$F^{II}_{T.1b.Rd}$ = 277.3 kN – model Ib $F^{II}_{T.3.Rd}$ = 250.4 kN – model III

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Table 4 – *Continued from previous page*

Column base with two rows of bolts		**Reinforced base**	
Resistance of the plates (stiffener, flange and web)			
1st bolt–row	$F^{I}_{t.fc.Rd}$ = 676.8 kN	1st bolt–row	$F^{I}_{t.fc.Rd}$ = 507.6 kN
		2nd bolt–row	$F^{II}_{t.wb.Rd}$ = 507.6 kN
Tension zone – final results			
1st bolt–row	$F^{I}_{T.Rd}$ = 176.9 kN	1st bolt–row	$F^{I}_{T.Rd}$ = 205.5 kN
		2nd bolt–row	$F^{II}_{T.Rd}$ = 250.4 kN
Compression zone			
Resistance of the base plate and concrete			
c = 27 mm → A_{eff} = 15417 mm^2 $F_{c.pl.Rd}$ = 660.8 kN		c = 27 mm → A_{eff} = 19 946 mm^2 $F_{c.pl.Rd}$ = 854.9 kN	
Resistance of the flange (and the stiffener)			
$F_{c.fc.Rd}$ = 676.8 kN		$F_{c.fc.Rd}$ = 846 kN	
Compression zone – final results			
$F_{C.Rd}$ = 660.8 kN		$F_{C.Rd}$ = 846 kN	
Check the condition (x)			
660.8 kN ≥ 176.9 kN		846 kN ≥ 205.5 kN +250.4 kN	
Bending resistance of the entire base plates			
z_c = 208 mm, z_1 = 474 mm		z_c = 0.23 m, z_1 = 0.49 m, z_2 = 38 mm	
$M_{j.Rd}$ = 97.4 kN·m		$M_{j.Rd}$ = 234.4 kN·m	

The calculations of the initial rotation stiffness $S_{j.ini}$ for the bases are included in Table 5, providing the numerical values of the individual stiffness components and the final calculation results.

Table 5. Summary of the calculation results of the stiffness of the column bases

Column base with two rows of bolts		**Reinforced base**			
Stiffness coefficients of the base plate in bending					
1st bolt–row	k_1 = 2.12 mm	1st bolt–row	k^{I}_{1} = 2.64 mm	2nd bolt–row	k^{II}_{1} = 2.64 mm

Continued on next page

Table 5 – *Continued from previous page*

Column base with two rows of bolts		**Reinforced base**			
Stiffness coefficients of the plates in tension					
1^{st} bolt–row	k_2 = 5.98 mm	1^{st} bolt–row	k_2^I = 5.47 mm	2^{nd} bolt–row	k_2^{II} = 9.48 mm
Equivalent stiffness coefficients of the tension zone [mm]					
1^{st} bolt–row	k_T = 1.57 mm	1^{st} bolt–row	k_T^I = 1.78 mm	2^{nd} bolt–row	k_T^{II} = 2.06 mm
		k_T = 3.78 mm			
Stiffness coefficients of the compression zone					
$k_C = k_4$ = 14.84 mm		$k_C = k_4$ = 16.88 mm			
Stiffnesses of the column bases					
$S_{j.ini}$ = 60300 kNm/rad		$S_{j.ini}$ = 116 000 kNm/rad			

5. Summary and closing remarks

In the presented article, an algorithm for assessing the resistance and stiffness of a reinforced column base is discussed, based on the component method.

In the first part, preliminary numerical calculations were performed for three cases of stiffened column bases. The obtained results indicate areas where significant stress can be expected, both in the steel elements of the base and in the contact area between the base and the foundation.

In the second, main part of the study, a mechanical model of the reinforced column base was formulated. In the model distinguished two main zones – the tension zone and the compression zone.

Subsequently, based on the guidelines of standards, literature studies, and certain insights obtained from numerical analysis, fundamental relationships for calculating the mechanical characteristics of the individual components of the base model were formulated. Equivalent mechanical models of the column base were then formulated, and their behavior under load was analyzed, allowing the determination of formulas for the resistance $M_{j.Rd}$ and the initial stiffness $S_{j.ini}$ of the entire column base.

Additionally, the study includes a comprehensive numerical example demonstrating the application of the component method in calculations for both: unstiffened and stiffened column base. The obtained results clearly indicate that the adopted design solutions significantly increase its resistance and stiffness compared to the column base with one row of bolts near the column flange, by approximately 241% and 192%, respectively.

Although the aforementioned conclusions directly relate to the examples analyzed in the article, it can be assumed that they have a more general character and may apply to the majority of engineering practices in practice.

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Obliczenia nośności i sztywności wzmocnionych podstaw słupów metodą składnikową

Słowa kluczowe: podstawa słupa, metoda składnikowa, nośność, sztywność

Streszczenie:

Metoda składnikowa jest zalecanym przez Eurokod sposobem oceny nośności i sztywności połączeń słupów z fundamentami. Bezpośrednie zastosowanie wytycznych EC3 pozwala obliczać połączenia słupów z fundamentami o prostej budowie w postaci poziomej blachy, którą do fundamentu mocuje się za pomocą śrub kotwiących. Pomimo to możliwości wykorzystania samej metody składnikowej w projektowaniu węzłów podporowych są większe. Oznacza to, że wspomniana metoda pozwala obliczać wzmocnione połączenia słupów z fundamentami, np. podstawy użebrowane, czy zamocowane w fundamencie większą liczbą kotwi. W przedstawionym artykule zaproponowano algorytm oceny nośności i sztywności wzmocnionej podstawy słupa, który oparto na metodzie składnikowej. W pierwszej części pracy przeprowadzono wstępne obliczenia numeryczne trzech przypadków wzmocnionej podstawy słupa. Symulacje komputerowe wykonano w programie IdeaStatika, służącym do projektowała, m.in. węzłów i połączeń stosowanych w konstrukcjach stalowych. Przedmiotowe obliczenia zrealizowano dla trzech podobnych przypadków podstawy, różniących się między sobą stosunkiem wysokości h do szerokości b przekroju poprzecznego słupa, wynoszącym odpowiednio: 1,6, 2,4 oraz 3,2. Otrzymane wyniki wskazały

miejsca, w których należy się spodziewać znacznego wytężenia, zarówno stalowych elementach podstawy, jak również obszaru kontaktu podstawy z podłożem betonowym. W drugiej, zasadniczej części pracy przeprowadzono proces tworzenia modelu obliczeniowego wzmocnionej podstawy słupa. W przyjętym rozwiązaniu konstrukcyjnym połączenia słupa z fundamentem, dla przyjętego układu sił, wyróżniono dwie główne strefy – rozciąganą i ściskaną. Następnie, zgodnie z podstawowymi założeniami metody składnikowej, wyszczególniono w nich podstawowe składniki: kotwy utwierdzone w betonie, w strefie rozciąganej, blachę podstawy w strefie rozciąganej, żebro usztywniające, pas słupa oraz środnik słupa w strefie rozciąganej, blachę podstawy oraz podłoże betonowe w strefie ściskanej, żebro usztywniające oraz pas słupa w strefie ściskanej. Bazując na wytycznych normowych, studiów literaturowych, oraz pewnych wskazówkach uzyskanych z analizy numerycznej sformułowano podstawowe związki do obliczeń cech mechanicznych – nośności i sztywności poszczególnych składników modelu podstawy. W kolejnym, zasadniczym kroku algorytmu obliczeniowego, wykorzystując równania równowagi oraz warunki zgodności przemieszczeń utworzono końcowe zależności na obliczenia wzmocnionej podstawy słupa. Na podstawie analizy modelu mechanicznego w stanie granicznym nośności sformułowano związki do obliczeń nośności $M_{j.Rd}$ podstawy sł upa na zginanie. Z kolei ocena deformacji modelu podstawy słupa w stanie sprężystym pozwoliła wyznaczyć sztywność $S_{j.ini}$ na zginanie. Dodatkowo w pracy zawarto obszerny przykład liczbowy, w którym przedstawiono sposób obliczeń metody składnikowej. Obliczenia nośności oraz sztywności przeprowadzono dla dwóch postaw słupów. Pierwsza analizowana podstawa jest typowym rozwiązaniem konstrukcyjnym w postaci blachy poziomej, utwierdzonej 4 kotwami do fundamentu. W drugim przypadku rozpatruje się użebrowaną blachę podstawy, która jest zamocowana w podłożu betonowym 8 śrubami fundamentowymi. W obu podstawach przyjęto ten sam trzon słupa, blachę poziomą, rodzaj kotwi oraz materiał (gatunek stali). Obliczenia nośności i sztywności podstawy nieużebrowanej wykonano (zasadniczo) zgodnie z wytycznymi EC3, natomiast nośność wzmocnionej podstawy wyznaczono na podstawie prezentowanego w artykule algorytmu. Otrzymane wyniki wyraźnie wskazują, że przyjęte rozwiązania konstrukcyjne w znacznym stopniu zwiększają jej nośność i sztywność względem prostej podstawy. Wymienione wnioski bezpośrednio odnoszą się do analizowanych w artykule przykładów, należy jednak sądzić, że mają one bardziej ogólny charakter i mogą dotyczyć większości stosowanych w praktyce inżynierskiej.

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