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Anchor Bolt Tensile Load Distribution: Effects of the Column Base-Plate Design

Wide Flange Column Bases - Loading on Additional Line of Bolts

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ABSTRACT

The designer of column base elements usually considers that the uplift force existing in the column member is equally distributed on its anchor bolts. While this simplified approach may be used for the most common cases of a steel structures (for instance, when only 4 equally spaced anchor bolts exist in the column base design), it may lead the designer to overlook that the distribution of uplift loads is highly influenced by factors such as the rigidity of the base plate, the positioning of its stiffeners and the number and geometric arrangement of the anchor bolts. This unequal distribution of uplift loads on the anchor bolts may cause overloading on some of the anchor bolts, leading to diverting failure. This paper analyses through finite element several different wide-flange column base elements, with varying plate thicknesses and geometry. The conclusion summarizes that the distribution of the loads on the anchor bolts largely depend on the typology of the base plate and suggests a revision of the codes to be more precise on when unequal axial tensile loads may arise on the anchor bolts and recommend more refined methods for the estimation of those unequally distributed loads.

Keywords: Base plate, column base, wide flange base, anchor bolt tensile load distribution, steel.

1 INTRODUCTION

As of today, the EUROCODE recommendations for the design of column base connections with base-plates are contemplated within the document EN 1993-1-8 – Eurocode 3: Design of steel structures – Part 1-8: Design of joints [1].

This document mentions in its design assumptions that the joints shall be designed on the basis of a realistic assumption of the distribution of internal forces and moments, and that the assumed distribution of internal forces shall be realistic with regard to relative stiffnesses within the joint. [1, p. 19]. Aligned with the aforementioned guideline, it also states that the prying forces must be accounted for when the bolts are required to carry an applied tensile force (item 3.11 of [1]).

Although the distribution of axial loads on anchor bolts depends on the stiffness of all the other items of the connection (such as column profile, base-plate design, existence of stiffeners, concrete strength, etc.), the recommendations do not bring clear prescriptions for unequal load distribution between fasteners at the ultimate limit state for the case of axial loads (item 3.12 of [1, p. 34]).

1.1 Recommendations for Anchor Bolts

Apart from the material recommendations for anchor bolts in section 3.3, the EUROCODE EN 1993-1-8 [1] also lists recommendations for anchor bolts in tension [1, p. 83], where it says that the anchor bolts should be designed to resist the effects of the design loads, providing resistance to uplift and bending moments where applicable.

The design resistance of each individual anchor bolt is to be taken as the smallest value between the design tension resistance of the anchor bolt and the design bolt resistance of the concrete, which is to be calculated in accordance with EN 1992-1-1 [2].

The calculation of the column bases is recommended to be done in accordance with the analogy to the T-Stub strategy, which has the geometric typology that may be found in Fig. 1. The T-Stub analytical calculation strategy applied the design of wide-flange column base plates is also a subject of two NCCIs [3], [4].

U. Kuhlmann et al. also elaborated on the design of steel to concrete joints, including column bases [5]. Their work, a part of the INFASO project [6], also develops further the application of the T-Stub strategy to the design of column bases.

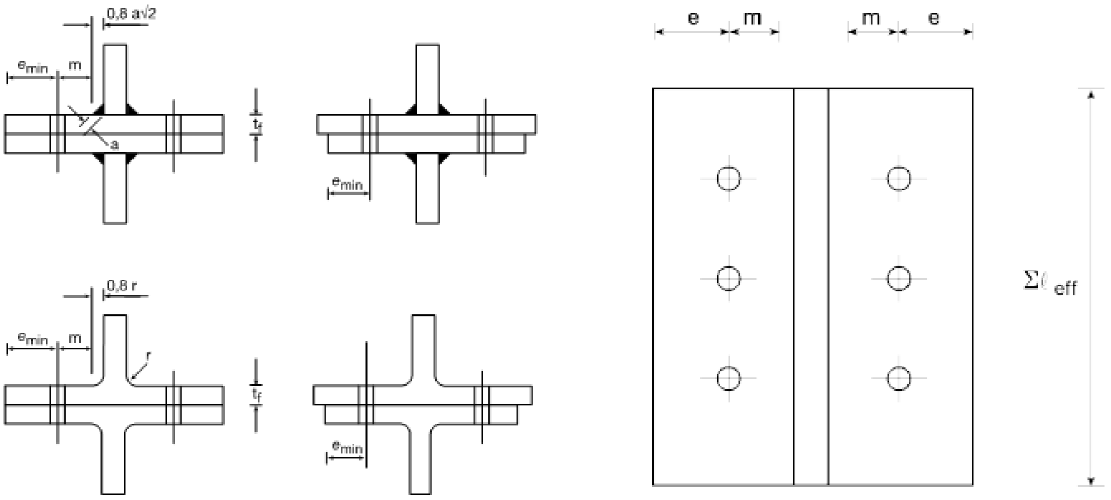

Fig. 1. Typology of a T-Stub (Source: ***[1, p. 67]***).

1.2 Current work

A new standard was ratified by the European Committee for Standardization (CEN) on the 04 December 2016 concerning the design of fastenings for use in concrete. The draft for public comment of this standard, called prEN 1992-4 - Eurocode 2: Design of concrete structures - Part 4: Design of fastenings for use in concrete [7], is expected to be made available on the 01 March 2017. Although the draft is not to be regarded as a standard and may be different from the final version, this document sheets some light on the future of the EUROCODE standards concerning the design of anchor bolts. The draft for public comment does contemplate different axial loads that may be found on the anchor bolts. It specifies that the load distribution to the fasteners may be calculated analogous to the elastic analysis of reinforced concrete [7, p. 28] and also considers eccentricity of tensile forces on the load distribution.

Although the technical specification CEN/TS 1992-4-1 - Design of fastenings for use in concrete - Part 4-1: General contained recommendations in its annex B for the plastic design of the anchor bolts [7, p. 48], this annex was removed from the draft for public comment.

The Fig. 2 contains the typology of configuration of headed and post-installed fastenings covered by the EN prEN 1992-4.

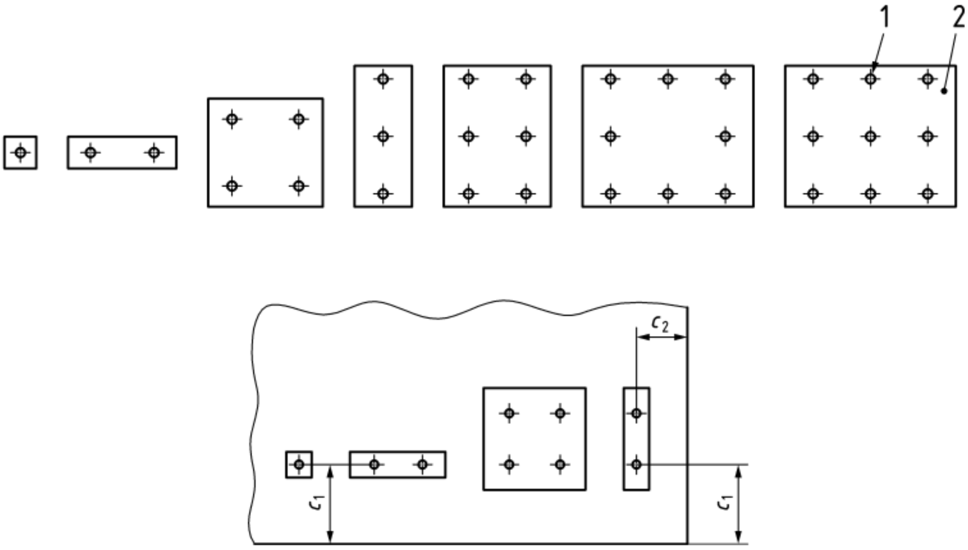

*Fig. 2. Configuration of fasteners covered by prEN 1992-4. (Source: **[7, p. 7]**).*

1.3 Configuration of anchor bolts not covered by the current works

In Fig. 3 it is presented a configuration of anchor bolts that is currently not covered by the standards and the works in progress. Is consists of a configuration with one additional line of anchor bolts away from the column profile.

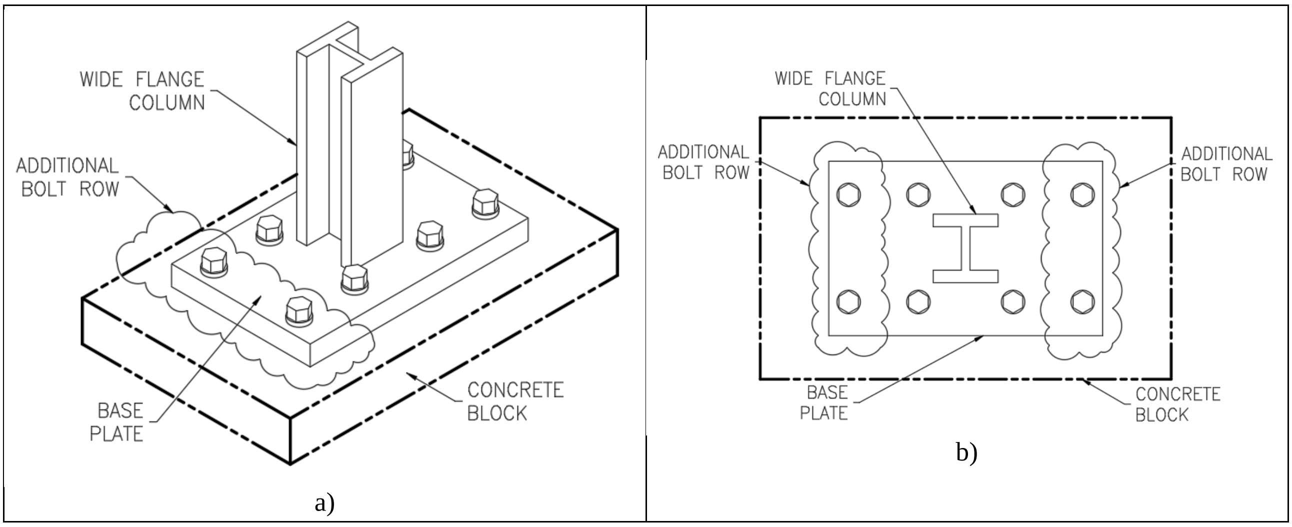

Fig. 3. Example of configuration not covered by the current works. a) Isometric view. b) Top view.

The distribution of the design axial forces acting on the anchor bolts is not equal and its definition is not trivial. It depends greatly on factors such as the rigidity of the base plate, the relative dimensions of the column profile, the rigidity of the anchor bolts, the positioning and spacing of the anchor bolts, etc.

This typology of connection (illustrated in Fig. 4) is used for heavy large scale industrial buildings in which uncommonly large uplift forces are found in the column bases, such as boiler buildings in regions with strong winds and/or earthquake. In this kind of structures, the columns have a tendency of exhibiting very large thicknesses of the flange and the web.

Fig. 4. Real world utilization of base plate not contemplated by current works. (Source: Author's catalogue.)

1.4 Objectives of this work

This work exhibits some axial load distribution patterns that are found in this kind of typology of base plate. Its main objectives are:

1. Investigating the magnitude of the axial load difference that may be found in the anchor bolts for the configuration exhibited in Fig. 3 and Fig. 4.

2. Identifying some geometric aspects of the base plate that influence the axial load distribution.
3. Highlight to the engineering community the relevance of considering the unequal axial load distribution on the design.

2 INVESTIGATION METHOD

The investigation was carried out by the application of finite element method to various different parametrized geometries of the base plate configuration with additional line of bolts. The basic dimensions of the items is in accordance with a real-world project and is displayed in Table 1.

Table 1. Basic dimensions of the investigated FEM models.

Item	Value
Profile Depth $\boldsymbol{d_P}$	$550mm$
Profile Width $\boldsymbol{w_P}$	$520mm$
Profile Thickness Web $\boldsymbol{t_w}$	$70mm$
Profile Thickness Flange $\boldsymbol{t_f}$	$100mm$
Profile Cross Section Area $\boldsymbol{A_P}$	$128.5 * 10^3 mm^2$
Anchor Bolt Diameter $\boldsymbol{\phi_B}$	$100mm$

The base plate size, thickness and anchor bolt positioning was parametrized in relation with the anchor bolt diameter ϕ_B. The Fig. 5 displays the dimensions that were parametrized, whereas Table 2 exhibits the range of variation of these variables.

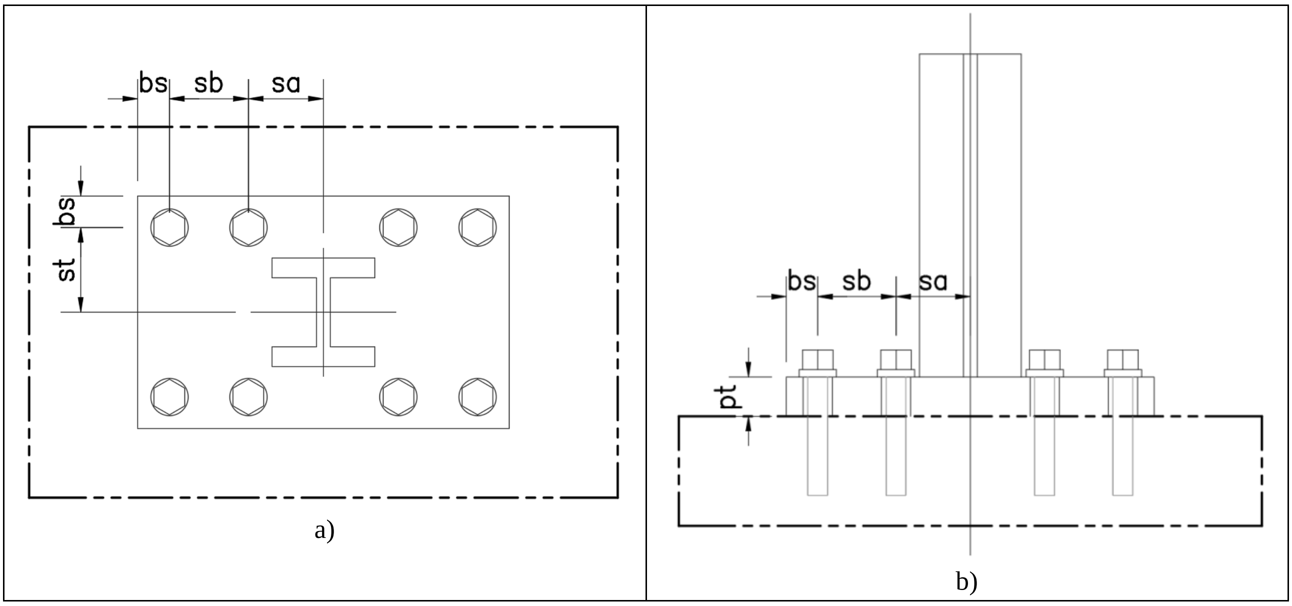

Fig. 5. Parametrized dimensions of the column base plate. a) Top view. b) Front view.

The value of the border spacing bs was not altered in the analysis and was kept at a constant value of $160mm$.
The interactions where conducted by changing the value of one of the four variables while keeping the other three at a constant value in accordance with Table **2**. The step of each interaction for each of the 4 variables pt, sa, st and bs was of $0.2 * \phi_B$. This results in a total of 25 different models.

Table 2. Relative values of the variable dimensions between the models.

Variable	Absolute Range	Range in relation to $\boldsymbol{\phi_B}$	Values of the other variables
Plate Thickness $\boldsymbol{pt}$	$140mm <=> 260mm$	$1.4 * \phi_b <=> 2.6 * \phi_b$	$sa = 3.8\phi_b = 380mm$ $st = 4.3\phi_b = 430mm$ $bs = 4.0\phi_b = 400mm$
Spacing – Along Flange $\boldsymbol{sa}$	$340mm <=> 460mm$	$3.4 * \phi_b <=> 4.6 * \phi_b$	$st = 4.3\phi_b = 430mm$ $pt = 2.0\phi_b = 200mm$ $bs = 4.0\phi_b = 400mm$
Spacing – Transversal $\boldsymbol{st}$	$390mm <=> 510mm$	$3.9 * \phi_b <=> 5.1 * \phi_b$	$sa = 3.8\phi_b = 380mm$ $pt = 2.0\phi_b = 200mm$ $bs = 4.0\phi_b = 400mm$
Spacing - Between $\boldsymbol{bs}$	$340mm <=> 460mm$	$3.4 * \phi_b <=> 4.6 * \phi_b$	$sa = 3.8\phi_b = 380mm$ $st = 4.3\phi_b = 430mm$ $pt = 2.0\phi_b = 200mm$

2.1 Finite Element Model Characteristics

All of the 25 models shared the same characteristics. The model is illustrated in Fig. 6 and has the following features:

- Arrow A: The interface between the wide flange profile and the base plate is of bounded elements. This simulates a perfect groove weld between the parts.
- Arrow B: The model takes advantage of the dual plane symmetry. The symmetry boundary condition is imposed on the affected elements of the wide flange profile, the base plate and the concrete slab.
- Arrow C: The interface between the base plate and the concrete slab is solely done by contact elements. Friction forces are not considered.
- Arrow D: The boundary condition exists only on the elements of the concrete slab and are fixed (translation and rotation).
- Arrow E: The interface between the base plate and the anchor bolts is solely done by contact elements. Friction forces are not considered.
- Arrow F: The interface between the anchor bolts and the concrete slab is of bounded elements.

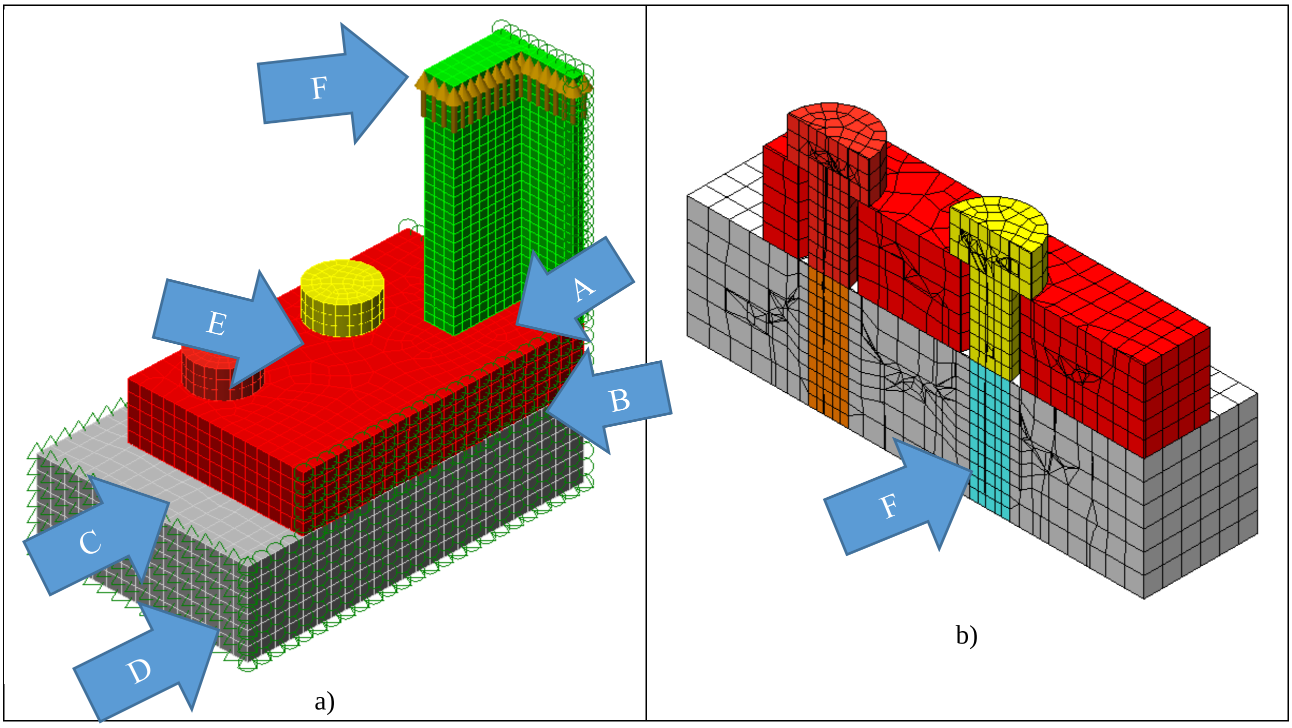

Fig. 6. Finite element model general characteristics. a) General view. b) Cut displaying the anchor bolt interface.

The other characteristics of the models are as listed:

- The finite element mesh is composed of mostly quadrilateral elements (~95% of the total volume). Elements without midside nodes.
- Non-linear model with interactive contact between parts.
- Isotropic linear materials model.
  - Steel parts: Modulus of Elasticity: $210000\ N/mm^2$; Poisson's ratio: $v = 0.3$ [8].
  - Concrete part: Modulus of Elasticity: $35000\ N/mm^2$; Poisson's ratio: $v = 0.2$ [2].

2.2 Applied force

The design normal force N_{Ed} applied on the models was taken as being 50% of the design plastic resistance of the gross cross-section of the profile, calculated in *Eq.1* and *Eq.2*. The material considered for the profile is the S355 material ($f_y = 315 N/mm^2$ [9]).

$$N_{pl,Rd} = \frac{A * f_y}{\gamma_{M0}} = 40477.5\ kN \qquad \text{(1) [8] Eq. 6.6}$$

$$N_{Ed} = 50\% * N_{pl,Rd} = 20238.75\ kN \qquad (2)$$

The design normal force N_{Ed} was applied as an equally distributed pressure on the surface indicated by arrow F of Fig. **6**.a. Since the model is two times symmetric, the applied pressure yields a total load of $N_{Ed,Model} = N_{Ed}/4$.

3 RESULTS OF THE INVESTIGATION

The calculation of the 25 models resulted in a similar displacement pattern. The pattern for the model having the values of $sa = 3.8\phi_b = 380mm$; $st = 4.3\phi_b = 430mm$; $bs = 4.0\phi_b = 400mm$ and $pt = 2.0\phi_b = 200mm$ is displayed in figures Fig. **7** and Fig. **8**.

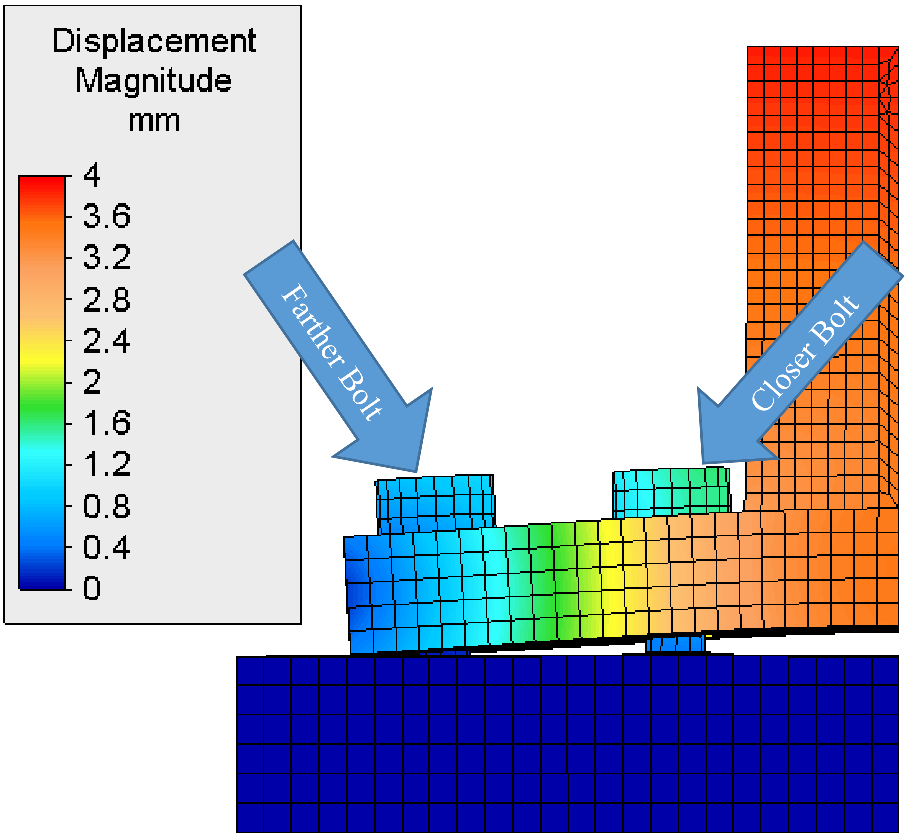

Fig. 7. Typical displacement pattern of the models.

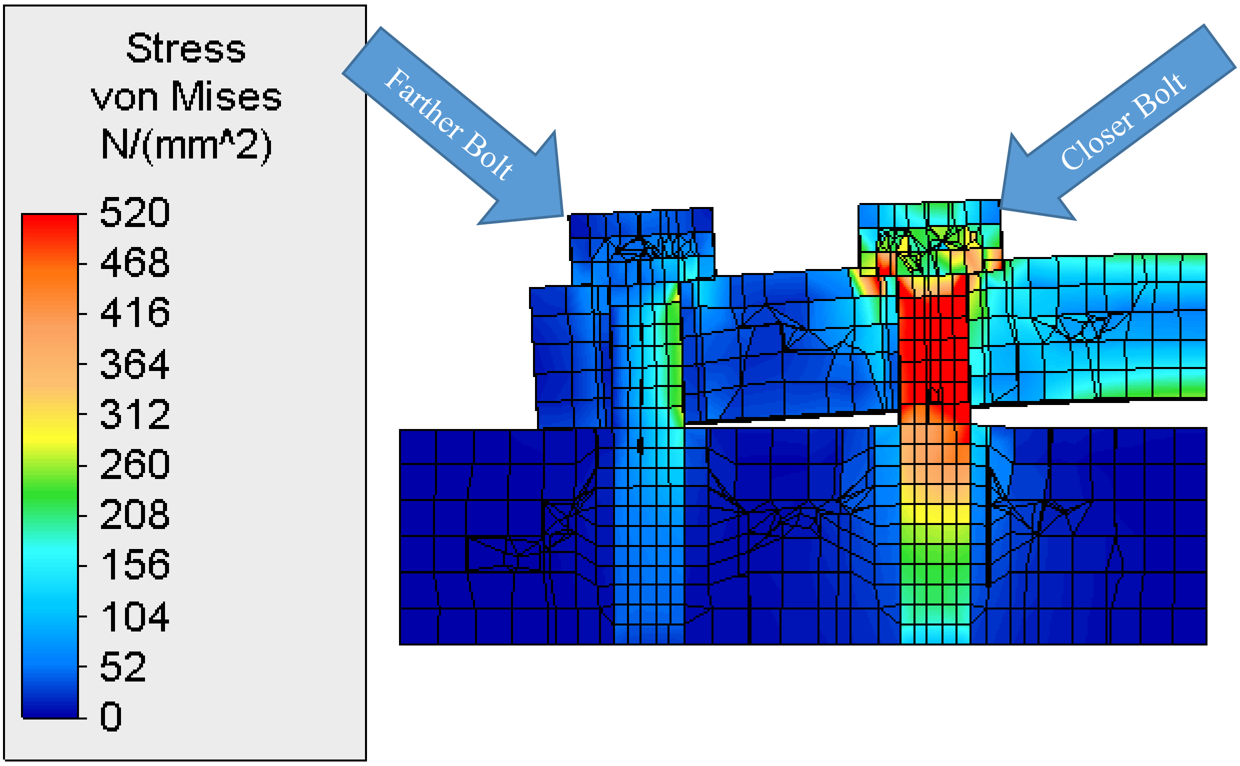

Fig. 8. Typical stress distribution on the anchor bolts of the models. The model view is sliced as Fig. 6.b.

The most relevant aspects of those images ate that:

- There is a considerable prying effect that occurs.
- The stress distribution on the anchor bolts is very unequal – the anchor bolt closer to the centre of the column member carries much more load than its counterpart.

3.1 Compilation of data

The tables 3, 4, 5 and 6 display the axial tensile forces that are transmitted to the bolts of the model. In those tables, the (*) near the value of the control variables denotes the values as per the last row of Table **2** (model displayed in Fig. 7 and Fig. 8).

Table 3. Distribution of axial loads on the models with a variation of the plate thickness value.

	Plate thickness ratio pt/ϕ_B						
	1.4	**1.6**	**1.8**	**2.0***	**2.2**	**2.4**	**2.6**
F_{closer} $[N]$ **Closer Bolt Axial Force**	4.93E+06	4.75E+06	4.53E+06	4.28E+06	4.06E+06	3.84E+06	3.65E+06
$F_{farther}$ $[N]$ **Farther Bolt Axial Force**	5.80E+05	6.87E+05	8.25E+05	9.67E+05	1.12E+06	1.29E+06	1.48E+06
$F_{total}\ [N] = F_{closer} + F_{farther}$ **Sum of axial forces [N]**	5.51E+06	5.44E+06	5.36E+06	5.25E+06	5.17E+06	5.13E+06	5.13E+06
$F_{total}/N_{Ed,Model}$ **Added load due to prying**	108.93%	107.50%	105.89%	103.68%	102.24%	101.46%	101.43%
F_{closer}/F_{total} **Closer bolt %**	89.47%	87.37%	84.61%	81.57%	78.42%	74.80%	71.14%
$F_{farther}/F_{total}$ **Farther bolt %**	10.53%	12.63%	15.39%	18.43%	21.58%	25.20%	28.86%
$F_{farther}/F_{closer}$ **Ratio of forces**	11.77%	14.45%	18.19%	22.59%	27.52%	33.68%	40.57%

Table 4. Distribution of axial loads on the models with a variation of the spacing - between value.

	Spacing - Between ratio bs/ϕ_B						
	3.4	**3.6**	**3.8**	**4.0***	**4.2**	**4.4**	**4.6**
$F_{closer}\ [N]$ **Closer Bolt Axial Force**	4.20E+06	4.14E+06	4.22E+06	4.28E+06	4.35E+06	4.33E+06	4.47E+06
$F_{farther}\ [N]$ **Farther Bolt Axial Force**	1.03E+06	1.08E+06	1.02E+06	9.67E+05	9.31E+05	9.08E+05	8.10E+05
$F_{total}\ [N] = F_{closer} + F_{farther}$ **Sum of axial forces [N]**	5.23E+06	5.23E+06	5.24E+06	5.25E+06	5.28E+06	5.24E+06	5.28E+06
$F_{total}/N_{Ed,Model}$ **Added load due to prying**	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06
F_{closer}/F_{total} **Closer bolt %**	103.37%	103.31%	103.48%	103.68%	104.29%	103.55%	104.27%
$F_{farther}/F_{total}$ **Farther bolt %**	80.25%	79.26%	80.52%	81.57%	82.36%	82.67%	84.65%
$F_{farther}/F_{closer}$ **Ratio of forces**	19.75%	20.74%	19.48%	18.43%	17.64%	17.33%	15.35%

Table 5. Distribution of axial loads on the models with a variation of the spacing - transversal value.

	Spacing – Transversal ratio st/ϕ_B						
	3.9	**4.1**	**4.3***	**4.5**	**4.7**	**4.9**	**5.1**
$F_{closer}\ [N]$ **Closer Bolt Axial Force**	4.38E+06	4.33E+06	4.28E+06	4.23E+06	4.18E+06	4.23E+06	4.18E+06
$F_{farther}\ [N]$ **Farther Bolt Axial Force**	8.97E+05	9.27E+05	9.67E+05	1.00E+06	1.04E+06	1.06E+06	1.09E+06
$F_{total}\ [N] = F_{closer} + F_{farther}$ **Sum of axial forces [N]**	5.28E+06	5.26E+06	5.25E+06	5.23E+06	5.23E+06	5.29E+06	5.27E+06
$F_{total}/N_{Ed,Model}$ **Added load due to prying**	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06
F_{closer}/F_{total} **Closer bolt %**	104.32%	103.96%	103.68%	103.45%	103.28%	104.51%	104.11%
$F_{farther}/F_{total}$ **Farther bolt %**	83.01%	82.38%	81.57%	80.80%	80.04%	79.95%	79.32%
$F_{farther}/F_{closer}$ **Ratio of forces**	16.99%	17.62%	18.43%	19.20%	19.96%	20.05%	20.68%

Table 6. Distribution of axial loads on the models with a variation of the spacing – along flange value.

	Spacing – Along Flange ratio sa/ϕ_B						
	3.4	**3.6**	**3.8***	**4**	**4.2**	**4.4**	**4.6**
$F_{closer}\ [N]$ **Closer Bolt Axial Force**	4.02E+06	4.19E+06	4.28E+06	4.38E+06	4.40E+06	4.58E+06	4.71E+06
$F_{farther}\ [N]$ **Farther Bolt Axial Force**	1.15E+06	9.89E+05	9.67E+05	9.00E+05	8.89E+05	7.87E+05	7.01E+05
$F_{total}\ [N] = F_{closer} + F_{farther}$ **Sum of axial forces [N]**	5.17E+06	5.17E+06	5.25E+06	5.28E+06	5.28E+06	5.36E+06	5.41E+06
$F_{total}/N_{Ed,Model}$ **Added load due to prying**	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06	5.06E+06
F_{closer}/F_{total} **Closer bolt %**	102.13%	102.28%	103.68%	104.32%	104.45%	106.01%	106.94%
$F_{farther}/F_{total}$ **Farther bolt %**	77.80%	80.88%	81.57%	82.95%	83.17%	85.33%	87.05%
$F_{farther}/F_{closer}$ **Ratio of forces**	22.20%	19.12%	18.43%	17.05%	16.83%	14.67%	12.95%

The ratio of the axial tensile forces $F_{farther}$ encountered on the father bolt in relation with the axial tensile forces at the closer bolt F_{closer} has been plotted on the charts of Fig. **9**.

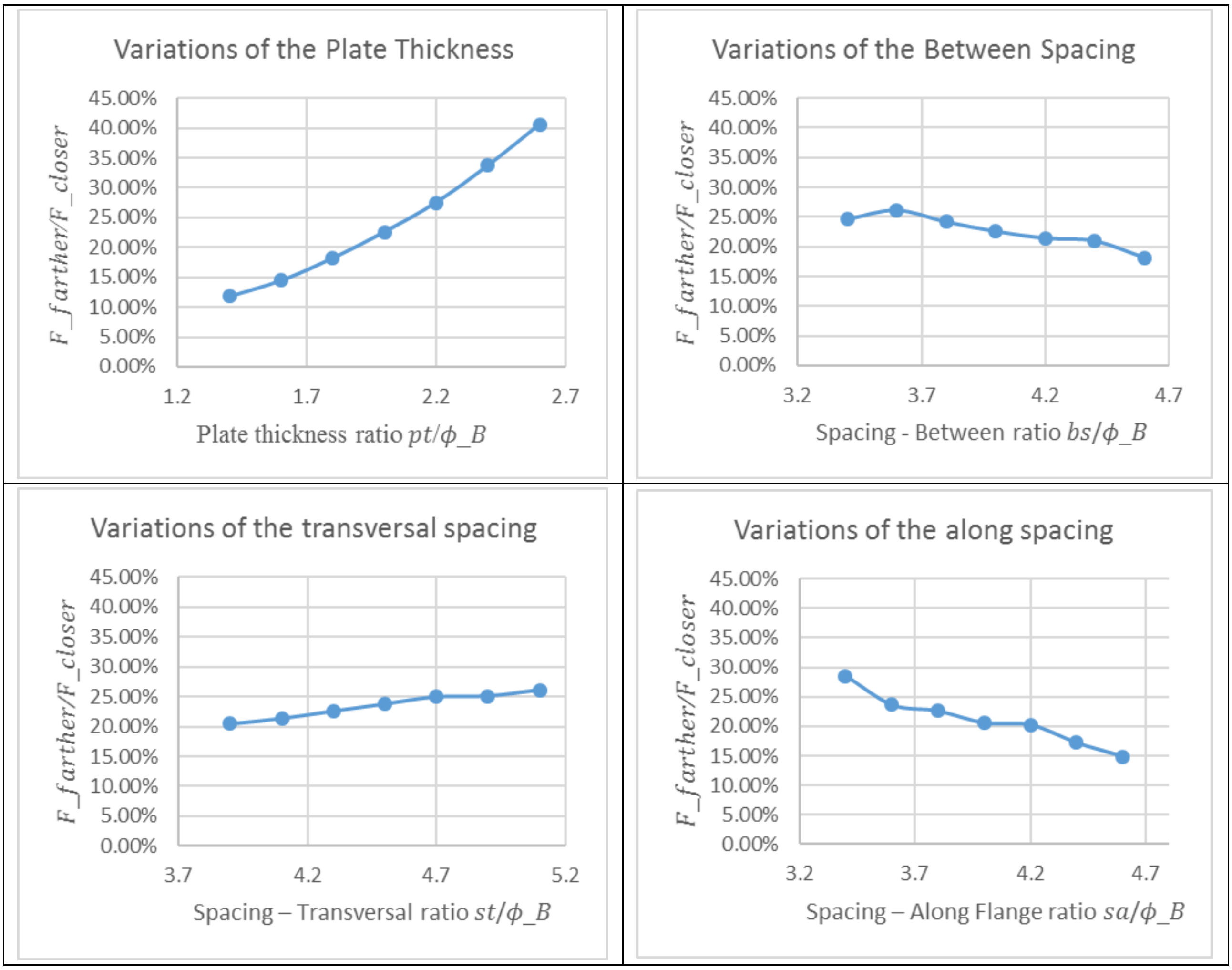

Fig. 9. Charts displaying the impact of the variation of the control variables on the distribution of loads between the anchor bolts.

3.2 Relevant aspects of the data

From the data displayed in Tables 3 to 6 and the charts of Fig. 9, it is possible to verify that:

- Regardless of the geometric configuration of the base plate and the positioning of the anchor bolts, there is a considerable difference between the tensile axial loads on the closer bolt and the on the farther bolt.
- For the variations analyzed, the change that brings the best distribution of loads between the bolts is when the plate thickness is increased. This is expected, as with a larger thickness the plate is more rigid, which in turn will be more capable of transmitting the tensile loads to the farther bolt.
- As expected, the magnitude of the additional tensile loading on the anchor bolts due to prying is influenced by the overall rigidity of the base plate. This behavior, seen on Table 3, is due to the fact that the lesser rigid the plate is, the more it will be bent by the tensile loading of the column base. The more it bends, the more it will add prying loads. Table 6 also displays that the spacing along the column flange also influences the magnitude of the prying loads.

4 CONCLUSION

The investigation herein described clearly displays that the simple design (with only the column and the base plate, with no additional design item) of a base plate connection is incapable of equally distributing the loads on the anchor bolts when an additional line of anchor bolts is inserted.
Although the distribution of loads may be rendered more equal by changes in the column base design, such as by inserting stiffener plates to increase the localized rigidity of the base plate and making it better distribute the loads to the additional line of anchor bolts, the authors believe that the required total tensile resistance of the anchor bolt group may be better achieved by a more rational positioning of the anchor bolts around the column profile. Therefore, the authors recommend that a different typology of column base connection be used.
Regardless of the recommendation to avoid this typology of column-base plate, the authors suggest that the Eurocodes be revised to more precisely describe cases in which unequal distribution of axial tensile loads may arise on anchor bolts and give recommendations on how to proceed with the estimations of the tensile forces in those cases (such as by the recommendation of refined methods such as FEA). This information should be added for instance to the item 3.12 of [1, p. 34].

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