EFFECTIVE DESIGN TENSION RESISTANCE OF BOLT-ROWS IN BEAM-TO-COLUMN END PLATE CONNECTION

Esmerald Filaj[1], Markel Baballëku[2], Erdit Leka[3]

[1]*Department of Building Construction and Transport Infrastructure, Faculty of Civil Engineering, Albania*
[2]*Department of Mechanics of Structures, Faculty of Civil Engineering, Albania*
[3]*Department of Building Construction and Transport Infrastructure, Faculty of Civil Engineering, Albania*

Abstract

Bolted beam-to-column end plate connection behaviour is quite complex and as a consequence similarly can be defined its design procedure. This behaviour is a function of many aspects starting from the materials of the structural elements and other connection components, overall configuration, its geometry, bolts, fillet weldings, etc. These aspects may in turn depend by certain parameters. In this study, based on the procedure described in Eurocode 3, the focus is towards the bending resistance, especially the effective design tension resistance in the bolt-rows and their possible plastic or triangular distribution due to the ductility conditions, as a function of the parameters related to the bolts, more exactly: their strength grade, their diameter and possible position. At this aim a common 90° beam-to-column end plate connection was considered. It can be concluded that for different strength grades different effective design resistances can be achieved in the bolt-rows, so different distributions, most of the time limited because of the lack of ductility. Similarly, any variation of the diameter causes also redistribution of the effective design tension resistances - in every case a triangular distribution was necessary. In both of the cases, moment resistance increases with the tension strength of the bolts. Based on the results achieved in the 3rd case, careful bolt-rows configuration should be chosen in order to maximize their efficiency.

Keywords: *End plate connection, bolt-row, effective tension resistance, triangular limit, plastic distribution, EC 3*

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1. INTRODUCTION

The resistance of beam-to-column bolted end plate connections is provided by a combination of tension forces in the bolts adjacent to one flange and compression forces in bearing at the other flange [1]. Unless there is axial force in the beam, the total tension and compression forces are equal and opposite. Vertical shear is resisted by bolts in bearing and shear; the force is usually assumed to be resisted mainly by bolts adjacent to the compression flange. At the Ultimate Limit State, the centre of rotation is at or near the compression flange of the connected member and for simplicity in design, it should be assumed to be exactly its centre of gravity [1], [2].The bolt-row furthest from the compression flange will tend to attract the greatest tension force and design practice in the past has been to assume a "triangular limit" distribution of forces, pro rata to the distance from the centre of rotation/compression [1], [3], [4]. In simple terms this means that the resistance of the bolt-rows closer to the defined centre cannot be fully utilized. Current design method [2], based on the overall behavior of the connection, for certain conditions, supports a more rational approach. Instead of the triangular distribution a plastic one is considered possible, but only if the materials of the connection's parts and the composition of the latter in a structural and geometrical sense provide an acceptable level of ductility (Fig-1). This level of ductility corresponds to well defined failure modes, and somehow it can be numerically quantified, however not in a discrete closed form [2]: so, different structural codes and also different countries implementing the same one, e.g. the UE and EFTA countries using Eurocode 3 [2], can use different values - (in [2] a Nationally Determined Parameter (NDP) - although, all of them in their National Annex (NA) accepted the recommendation of the CEN official publication [5]). The aim of this study, a part of a more extended one conducted by the authors, is to define for a common connection in every component (materials, geometry, sections, etc.), how the variation of some parameters related to the bolts, influence their tension force distribution or their "effective design tension resistance", and in the same time to reach in any conclusion regarding the effective bending resistance of the connection. Other aspects like shear resistance, stiffeners and fillet welds adequacy, were excluded not affect the results.

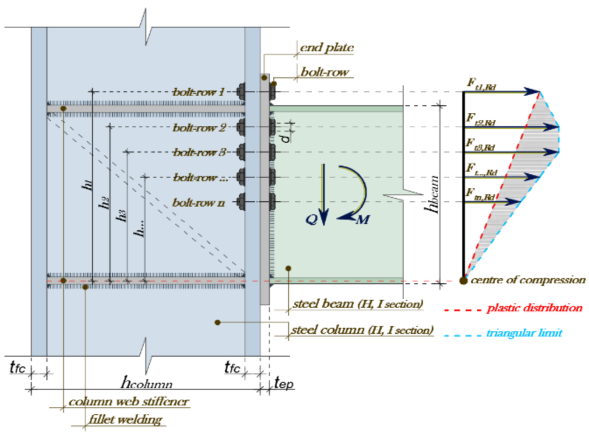


Fig -1: Beam-to-column end plate connection and bolt-rows tension force distribution

2. DESIGN PROCEDURE

The design procedure of beam-to-column end plate connection is iterative: a geometric configuration of bolts and, if necessary, stiffeners is selected; the resistance of that configuration is evaluated; the configuration is modified for greater resistance or greater economy, as appropriate; the revised configuration is re-evaluated until a satisfactory solution is achieved [1]. These can be summarized in 7 Steps as below - due to the extension of the procedure in a theoretical point of view, its full presentation was judged as impossible. Every necessary detail can be found in Section 6 of [2] or other literature related to this structural design code.

- Step 1: Calculate the effective design tension resistances of the bolt-rows ($F_{tr,Rd}$) in sequence, starting from bolt-row 1, the bolt-row furthest from the centre of compression, then progressing to bolt-row 2, etc. This involves calculating the bolts' resistance ($F_{t,Rd}$) (included in the others), the column web in tension ($F_{t,wc,Rd}$), the column flange in bending ($F_{t,fc,Rd}$), the end plate in bending ($F_{t,ep,Rd}$) andthe beam web in tension ($F_{t,wb,Rd}$).

$$F_{tr,Rd} = \min(F_{t,wc,Rd}; F_{t,fc,Rd}; F_{t,ep,Rd}; F_{t,wb,Rd}) \quad (1)$$

The effective resistance for any bolt-row may be that for the row in isolation, or as part of a group of rows, or may be limited by a "triangular" distribution from the compression flange level (the centre of rotation/compression) if the following is verified: Where the effective design tension resistance $F_{tx,Rd}$ of one of the previous bolt-rows *x* is greater than $1,9F_{t,Rd}$, then the effective design tension resistance $F_{tr,Rd}$ for bolt-row *r* should be reduced in order to ensure that:

$$F_{tr,Rd} \le F_{tx,Rd} \cdot h_r / h_x \quad (2)$$

h_x - is the distance from bolt-row x to the centre of compression; x - is the bolt-row furthest from the centre of compression that has a design tension resistance greater than $1,9F_{t,Rd}$, where $F_{t,Rd}$- single bolt tension resistance. In addition to this condition, National Annex BSEN 1993-1-8 [6], specifies that plastic distribution is in a certain level again possible, even if Equation (2) is verified, if:

$$t_{ep} \le (d/1.9)\sqrt{f_{ub}/f_{y,p}} \quad (3)$$

$$t_{fc} \le (d/1.9)\sqrt{f_{ub}/f_{y,fc}} \quad (4)$$

t_{ep} - is the end plate thickness; t_{fc} - is the column flange thickness; d - is the diameter of the bolts; f_{ub} - ultimate tensile strength of the bolts; $f_{y,p}$ - is the design strength of the end plate; $f_{y,fc}$ - is the design strength of the column flange (equal $f_{y,c}$ for rolled section columns→c-column). Plastic distribution corresponds to ductile failure Modes 1 or 2, respectively "Complete yielding of the flange" and "Bolt failure with yielding of the flange" (Mode 3 "Bolt failure" is not a ductile one).
The conclusion of this stage is a set of effective tension resistances, one value for each bolt-row, and the summation of all the bolt-rows to give the total resistance of the tension zone. (These resistances may need to be reduced in Step 4).

- Step 2: Calculate the resistances of the compression zone of the joint, considering the column web ($F_{c,wc,Rd}$)and the beam flange and web in compression ($F_{c,fb,Rd}$).

- Step 3: Calculate the shear resistance of the column web ($V_{wp,Rd}$).The influence of the shear force in the column web on the resistances of the tension and compression zones have been taken into account in Steps 1 & 2.

- Step 4: Calculate the "final" set of tension resistances for bolt-rows, reducing the effective resistances (calculated in Step 1) where necessary in order to ensure equilibrium (if the total effective tension resistance exceeds the compression resistance calculated in Step 2) or to match the limiting column web panel shear resistance calculated in Step 3. Calculate the moment resistance as the sum of the products of the bolt-rows forces ($F_{tr,Rd}$) multiplied by their respective lever arm, referred to the centre of rotation/compression.

$$M_{j,Rd} = \sum_r h_r F_{tr,Rd} \quad (5)$$

h_r - is the distance from bolt-row r to the centre of compression.

- Step 5: Calculate the shear resistance of bot-rows. The resistance is taken as the sum of the full shear resistance of the bottom row (or rows) of bolts (which are not assumed to resist tension) and 28% of the shear resistance of the bolts in the tension zone (assuming, conservatively, that they are fully utilized in tension).

- Step 6: Verify the adequacy of any stiffeners in the configuration.

- Step 7: Verify the adequacy of the welds in the connection. (Note that welds sizes are not critical in the preceding Steps but they do affect some of the results achieved - so when it is necessary the values used in these Steps may be re-evaluated). Components in compression in direct bearing need only nominal weld, unless reversal must be considered.

As mentioned, the study is focused only in the first 4 Steps. For a better understanding of the results and conclusions, it is recommended to read the references listed in the end.

3. CASE STUDY

In order to fulfill the aim of the study, a common 90° beam-to-column end plate connection was discussed (Fig-2). Column section - HEM 600, S355; beam section - IPE 500, S235; end plate - width b_{ep}=250mm, height h_{ep}=650mm, thickness t_{ep}= 25mm, S275; bolts - w_b=120mm; column web stiffeners - thickness t_{st}=20mm, S275; fillet welding throat thickness (≥3mm): beam flange - end plate, $a_{w,f}$ =10mm; beam web - end plate, $a_{w,w}$ =7mm; bolts holes and their distance in compliance with the requirements of Eurocode 3 [2]. The strength grade of the bolts (non-preloaded), their diameter and intermediate distance were defined as parameters for each of the three cases of this study:

- 1st case: Variation of the bolts' strength grade: 4.6, 5.6, 6.8, 8.8 and 10.9 (first number is the ultimate tensile strength in MPa (f_{ub}/100), and the second is the ratio ($f_{y,b}/f_{u,b}\cdot 10$, where f_{yb} is the yield tensile strength in MPa).
- 2nd case: Variation of the bolts' grade 8.8diameter *d(M)*: M16, M18, M20, M22 …M36(diameter of holes d_o: d≤20mm → d_o=d+1mm, d>20mm → d_o=d+2mm).
- 3rd case: Variation of the bolts' intermediate distance or bolt-rows configuration (different values of Δ_i in Fig-2).

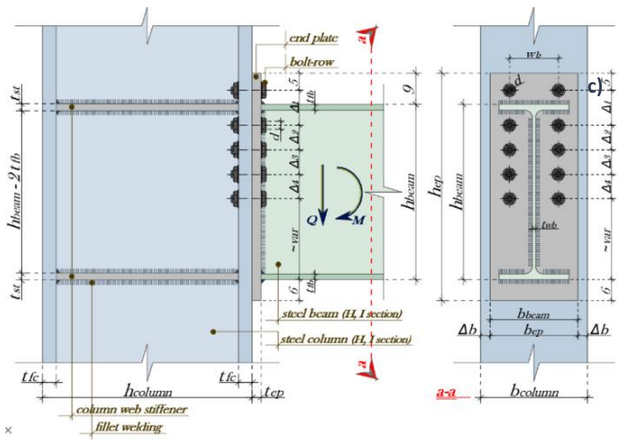
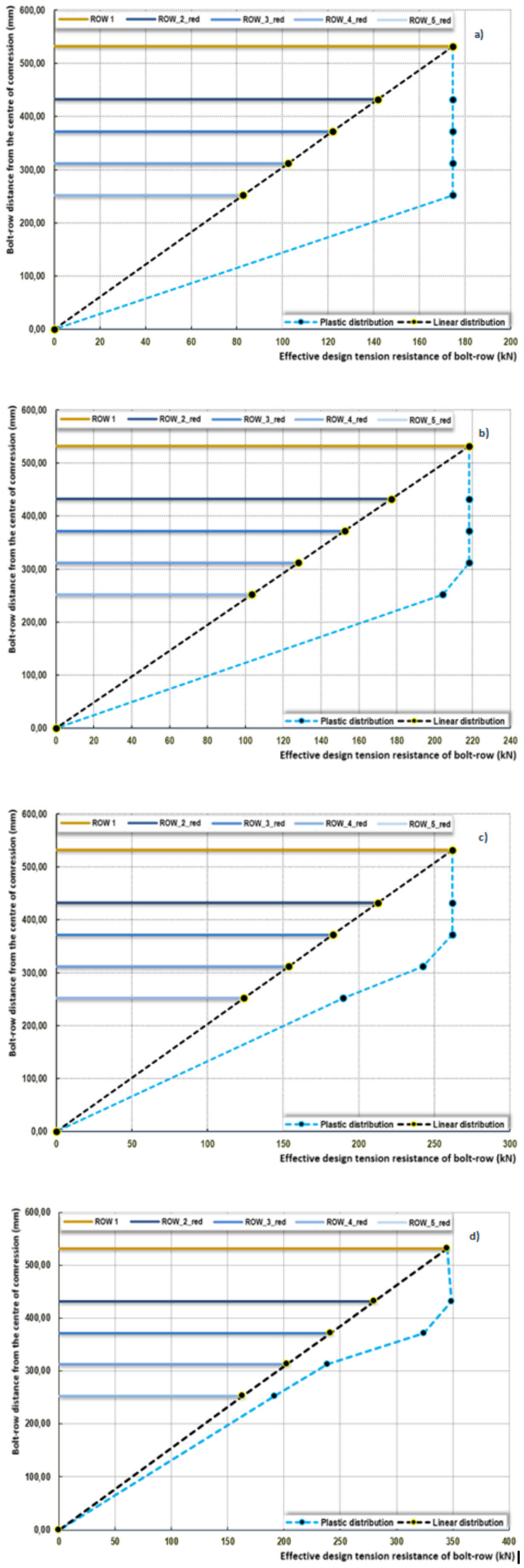


Fig -2: Beam-to-column end plate connection geometry

3.1 Influence of Bolts' Strength Grade

The most frequently used bolts in structural connections are non-preloaded bolts of strength grades 4.6 to 8.8 used usually in ≤2 mm clearance holes. These bolts are termed ordinary bolts and are specified in many standards like EN ISO 4014-4017. Precision bolts, manufactured to EN 3692-3for use in close tolerance holes are not widely used [7]. The bolts of strength grade 10.9 are classified as high strength, and most of the time are pre-loaded. Strength grades differ not only by the ultimate and yield tensile strength but by their ductility as well. This is a very important fact that must be taken into account when choosing a certain type of bolt - not the focus of this study. Assuming that there are no limitations, 5 strength grades were considered [2]:4.6, 5.6, 6.8, 8.8 & 10.9.The partial safety factors values are γ_{M0}=1.10 and γ_{M2}=1.25.



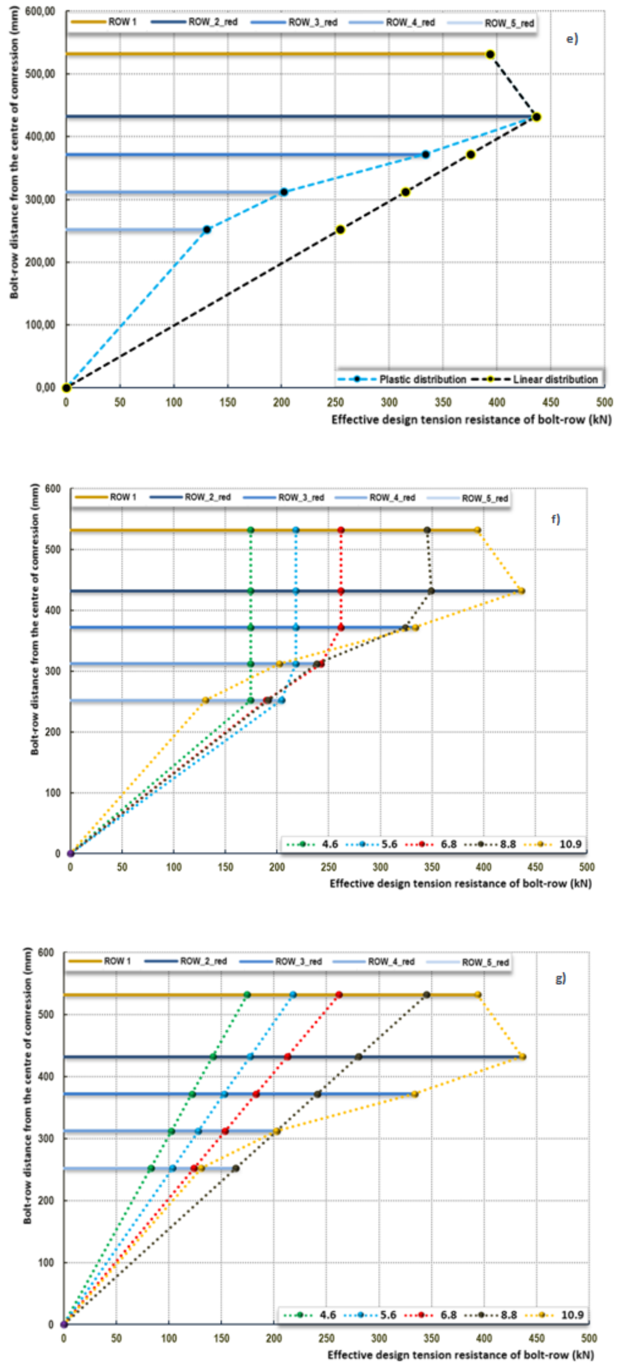


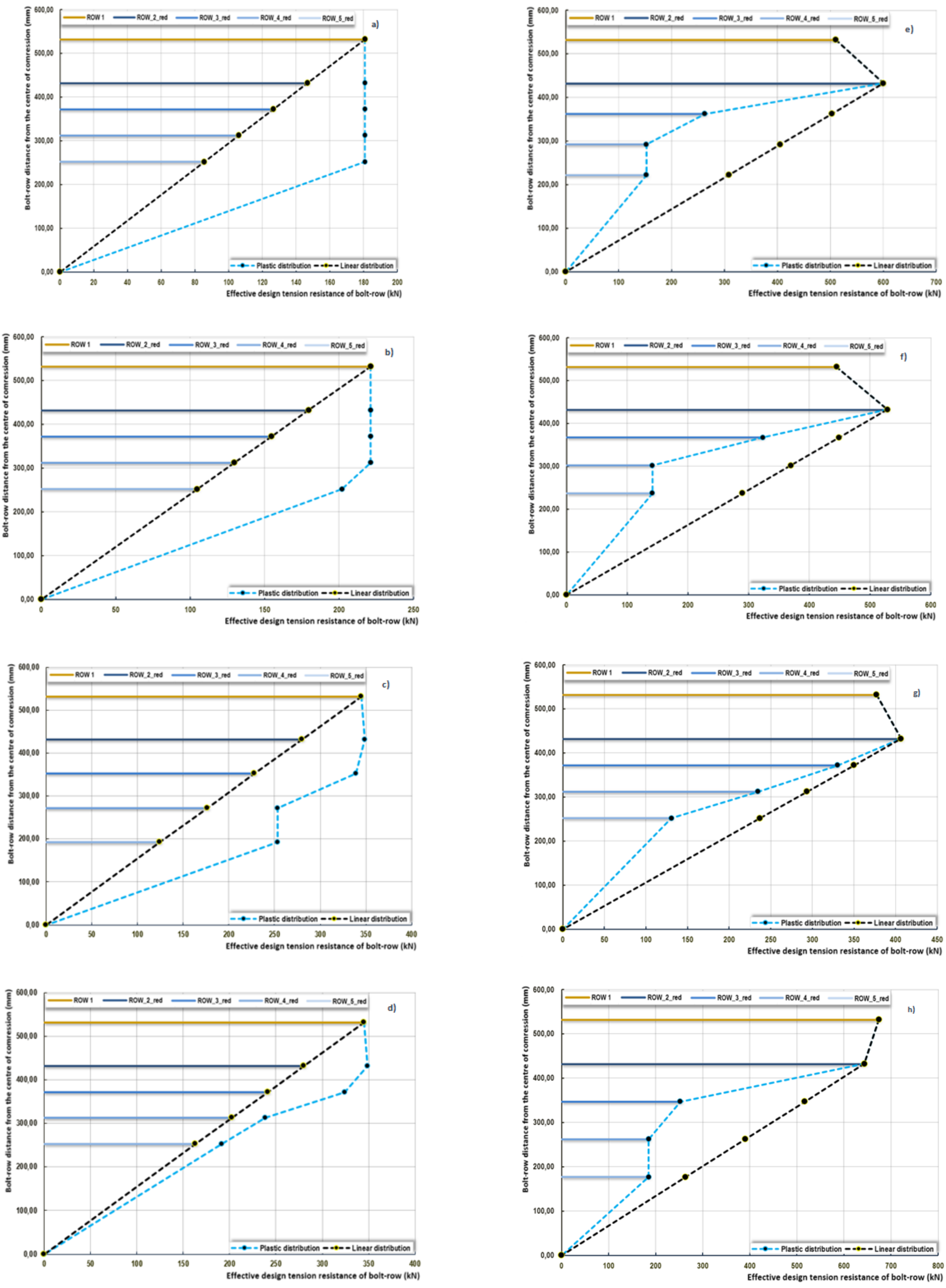
Chart -1: Effective design tension resistance of bolt-rows for different strength grades - a) 4.6; b) 5.6; c) 6.8; d) 8.8; e) 10.9; f) plastic distribution; g) modified distribution(triangular limit)

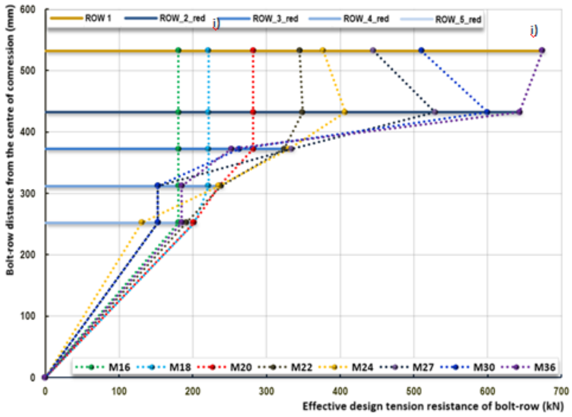
The results are presented in a graphical form (Chart -1(a-g)). It can be noticed that the potential tension resistance of the bolt-rows for lower steel grades (up to 6.8) is mainly governed by the tensile strength of the bolts (Mode 3 of failure). This can be ideally confirmed in the case of 4.6 bolts (see the line defined as "plastic distribution" in Chart -1(a)). On the other hand, the ductility of the joint for the given configuration is not satisfactory, and as a consequence a triangular distribution must be accepted (see the line defined as "linear distribution"). The difference between the two surfaces limited by these lines represent the difference between the theoretical bending resistance and the possible one (shaded are in Fig -1), and it is less noticeable for higher strength grades. For 10.9 bolts, the plastic distribution can be achieved, while the triangular limit is theoretical- there is no problem with the lack of ductility but with the strength that cannot be provided by the parts of the connections in the same level or proportional to the top rows. It is very important to understand that these effective design tension resistances, not only in this case study but also in the other two, may not develop due to equilibrium conditions - this topic is included in the procedure for the determination of the moment resistance and due to space reason it will not be discussed in details (see paragraph 2.4 below).The variation of the plastic distribution, in a comparative optic for all the cases (Chart -2(f)), is quite difficult to explain in simple terms because of the complexity of the equivalent tension T-stub model where the design method is based and the interaction in group of bolt-rows [1-2]. Although, it can be concluded that when the bolt's tension strength increases with the strength grade, the top rows can develop a good part of it (or completely), and the remaining, closer to the centre, are limited by the behaviour of the mechanism in its all components - when this does not happen, than the triangular distribution sets the limit.

3.2 Influence of Bolts' Diameter Variation

The designer, depending on the overall geometric configuration of the connection, can choose bolts with different diameters, but not smaller than M12 [8]. This choice does not affect only their intermediate distance and those related to other connection's components like beam's height, end plate dimensions, column's flange width, but also the bending resistance. As presented in the introduction part of this paragraph, 8 different values were considered, covering almost all of the possible design practice range: M16, M18, M20, M22, M24, M27, M30 and M36. The intermediate distances Δ_i(i=2, 3, 4) are $\Delta_i \geq 2.2d_o$: for diameters up to M24, Δ_i=60mm; for M27, Δ_i=65mm; for M30, Δ_i=70mm; for M36, Δ_i=85mm; Δ_1=100mm is a constant value, but $\Delta_1 \geq 2.2d_o$. The results are presented in Chart -2(a-h); the differences in distance between bolt-rows for diameters≥ M27wereneglectedand not shown in the resultant charts (Chart -2(i-j) in order to make their reading easier.

In this case study, as in the previous, for diameters up to M22, the potential tension resistance of the bolt-rows for lower steel grades is mainly governed by the tensile strength of the bolts (Mode 3 of failure), but now due to the reduced cross-sectional area - triangular distribution is necessary. Plastic distribution can be achieved for the remaining part. Resultant charts (Chart -2(i-j)) show a fast increase of the effective tension resistance in the top bolt-rows, with a bigger gradient than in the first case - more effective due to their distance from the centre of rotation/compression. This means that when big diameters are used the bending resistance of the connection will mainly depend on their contribution and the other bolts closer to the defined centre may not develop their potential strength due to discussed reasons, meaning at the end that they are in a sense "useless" or unnecessary or at least a diameter reduction can be made.


a)
b)
c)
d)
e)
f)
g)
h)
ROW 1
ROW_2_red
ROW_3_red
ROW_4_red
ROW_5_red
Plastic distribution
Linear distribution
Bolt-row distance from the centre of compression (mm)
Effective design tension resistance of bolt-row (kN)



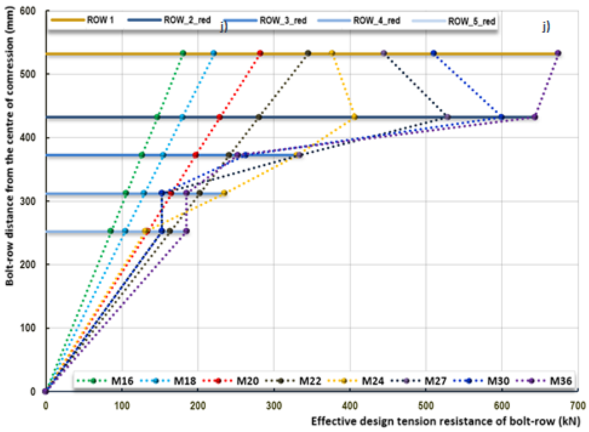


Chart -2: Effective design tension resistance of bolt-rows for different diameters - a) M16; b) M18; c) M20; d) M22; e) M24; f) M27; g) M30; h) M36; i)plastic distribution; j) modified distribution(triangular limit)

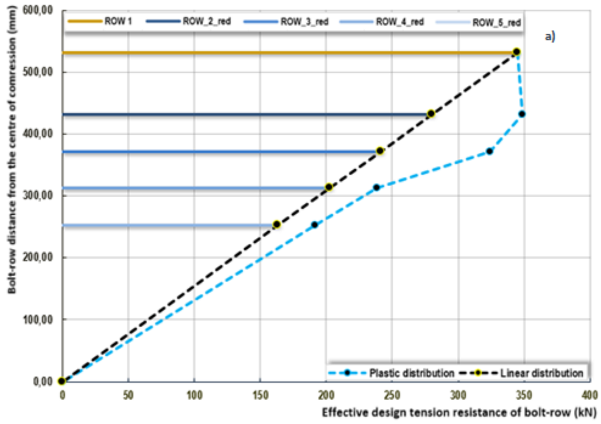
3.3 Influence of bolts' configuration

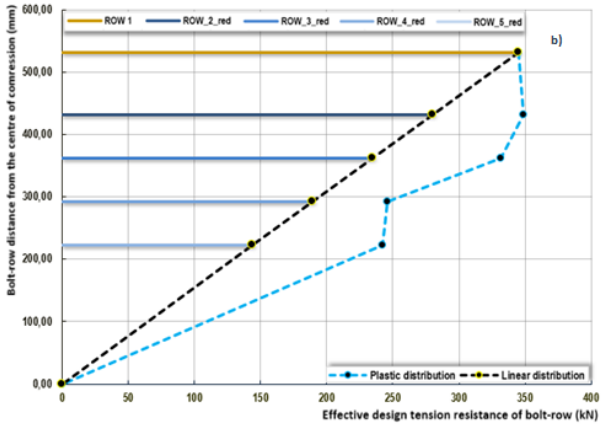
Variation of the bolts' intermediate distances or bolt-rows configuration is the last "parameter" chosen to be discussed (for diameter M22). The results, due to the previous interpretations, are somehow expected in qualitative terms. To have a better understanding even numerically, 8 different configuration were considered, as shown in Table -1.

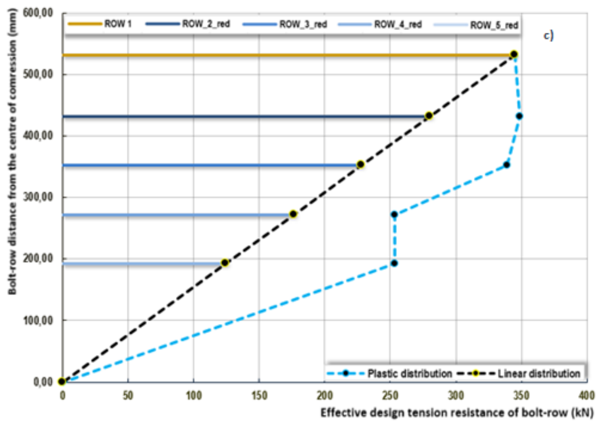
Table -1: Bolts'intermediatedistancesforeachconfiguration

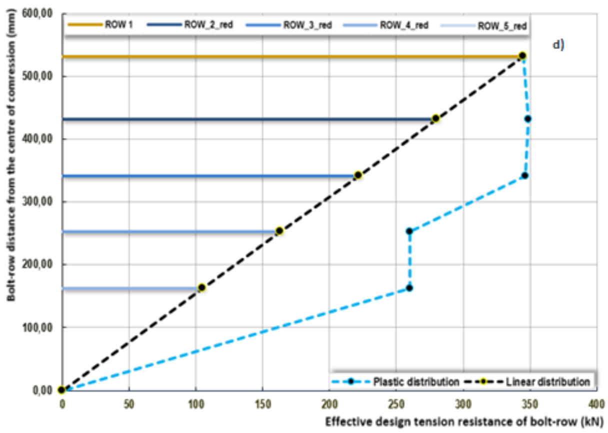
Δi	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8
Δtop	50	50	50	50	50	50	50	50
Δ1	100	100	100	100	100	120	100	100
Δ2	60	70	80	90	100	120	100	240
Δ3	60	70	80	90	100	120	210	70
Δ4	60	70	80	90	100	120	70	70

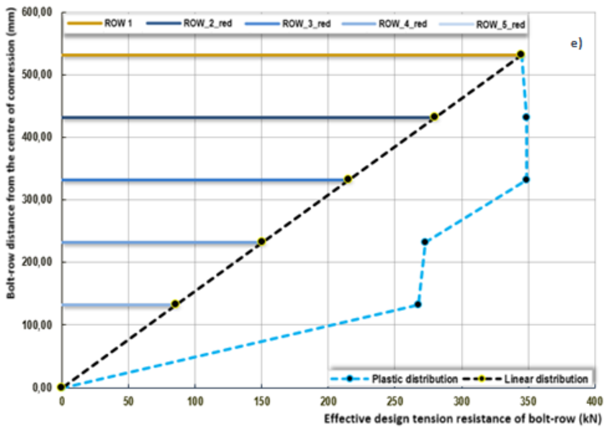
This variation can be noticed in each of the specific charts (Chart -3(a-h)) - see the position of the horizontal lines that represents the bolt-rows tensile strength related to the ordinate axis. No resultant chart will be presented due to the complexity of data that would make very difficult its interpretation. Any increase of the intermediate distance between bolt-rows results in a reduction of their effective tension resistance and as a consequence in a modification of the plastic distribution - more evident in those closer to the centre of rotation (e.g. configuration C-7 and C-8). Although, the potential tension resistance of the latter, especially in these two configurations, can be higher than in some other, it is only theoretical due to ductility conditions. The overall configuration of the connection dictates in each case a triangular distribution, however in efficiency terms, configuration C-1 is the best (see Table -4).

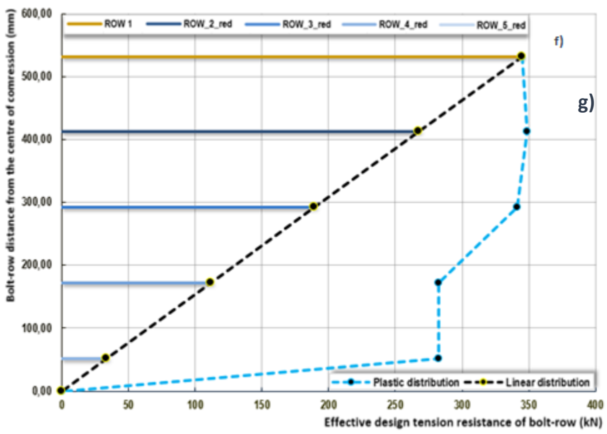


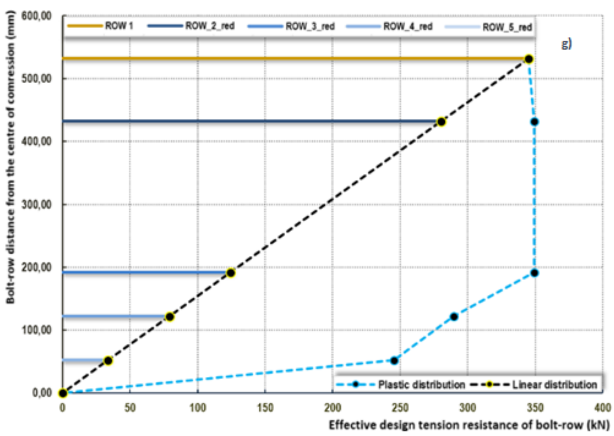












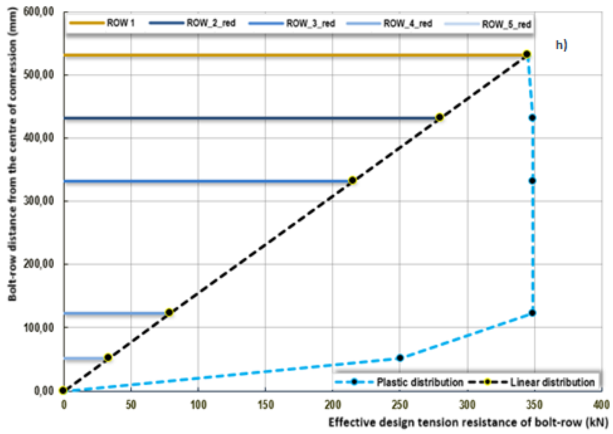


Chart -3: Effective design tension resistance of bolt-rows for different configurations - a) C-1; b) C-2; c) C-3; d) C-4; e) C-5; f) C-6; g) C-7; h) C-8

3.4 Moment Resistance Calculation

The moment resistance of the connection was calculated according to the following procedure [1-2]:

- Step 1: Calculate the plastic or elastic moment of the beam section framing into the connection depending on the cross-section class of resistance [2];
- Step 2: Calculate the compression resistance of the connection as the minimum of the beam flange effective strength using the Flange Only Method [2], and the shear resistance of the column web panel, including the effects of the stiffeners.
- Step 3: Calculate the difference between the sum of the effective tension resistances of all the bolt-rows and the compression resistance defined above.
- Step 4: Redistribute the forces on the bolt-rows starting from top to bottom/ centre of rotation, in order to satisfy the equilibrium conditions (tension = compression).
- Step 5: Calculate the moment resistance according to Equation (5) in this study - Table -(2-4).These tables summarize numerically the discussions made previously.

Table -2: Moment resistance $M_{j,Rd}$ for different bolts' strength grades [kNm]

Strength grade	**4.6**	**5.6**	**6.8**	**8.8**	**10.8**
$M_{j,Rd}$	252.24	315.30	378.36	426.22	449.43

Table -3: Moment resistance $M_{j,Rd}$ for different diameters of bolts [kNm]

d [mm]	**16**	**18**	**20**	**22**
$M_{j,Rd}$	261.40	319.67	397.94	426.22
d [mm]	**24**	**27**	**30**	**36**
$M_{j,Rd}$	445.01	462.87	469.39	485.78

Table-4: Moment resistance $M_{j,Rd}$ for different configurations of bolts (Bolts' conf.) [kNm]

Bolts' conf.	**C-1**	**C-2**	**C-3**	**C-4**
$\mathbf{M_{j,Rd}}$	426.22	421.32	416.30	411.14
Bolts' conf.	**C-5**	**C-6**	**C-7**	**C-8**
$\mathbf{M_{j,Rd}}$	405.85	370.09	387.70	340.10

4. CONCLUSION

Bolted beam-to-column end plate connection behaviour is quite complex and as a consequence similarly can be defined its design procedure, chosen according to Eurocode 3. This behaviour is a function of many aspects starting from the materials, configuration, geometry, bolts, welding, etc. These aspects may in turn depend by certain parameters. In this study, the parameters related to the bolts were discussed: their strength grade, diameter and position.

It can be concluded that for different strength grades different effective design resistances can be achieved in the bolt-rows, so different distributions that most of the time were limited due to the ductility conditions. Of course, for higher strength grades, a higher moment resistance can be achieved.

Any variation of the diameter of the bolts causes a redistribution of the effective design tension resistances, however, the exact variation is a function of the behaviour of all the components of the connection and due to the model where the design method is based, is difficult to be described in simple manner. Due to the lack of ductility, in every case a triangular distribution is necessary. Again, moment resistance increases with the increase of the bolt tension strength - in this case because of the cross-section and not the strength grade.

In the end, a very important conclusion is the one regarding the configuration of the bolt-rows. It is not recommended to accommodate them closer to the centre of rotation due to their low efficiency, no matter the theoretical potential strength.

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BIOGRAPHIES

Esmerald Filaj: Structural engineer/ academic staff of Faculty of Civil Engineering, UPT, Tirana. Area of interest: Steel structures, Reinforced concrete structures, FEM analysis.