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ADVANTAGES OF USING REDUCED CROSS-SECTIONS IN SEISMIC RESISTANT STEEL STRUCTURES

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Keywords**:** *ductility, plastic deformation control, eccentrically braced frames, concentrically braced frames, UACEG2017*

ABSTRACT

For eccentrically braced frames with long links, dog-bone configurations at the link ends ensure significant lateral stiffness of the frame and a better control of the plastic deformations along the links. Details with reduced cross-sections near the ends of upper storeys diagonals in concentrically braced frames lead to an adequate slenderness for the braces and to a proper tensile capacity of the diagonals. A favourable global plastic hinge mechanism can be sized by design for concentrically braced frames, by providing configurations with reduced cross-sections near the ends of frame girders. Details resembling the “dog-bone” near the base of bottom-storey columns appear to be safer from the point of view of ensuring the general stability of the first-storey columns during strong earthquakes.

1. Introduction

The present paper intends to illustrate some advantages of using configurations with reduced cross-sections in several seismic resistant steel structures equipped with different types of braced frames. All kind of structural elements of the analyzed centrically or eccentrically braced frames had built-up I-shaped cross-sections. The cross-sections of the braces of the considered centrically braced frames had the web orientated normally to the plane of the frame, in order to avoid out of plane buckling. The seismic forces used for the design of the analyzed

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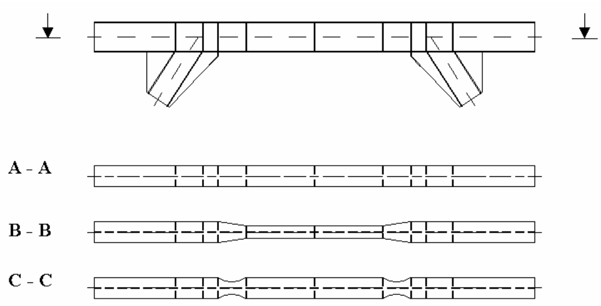
structural systems were evaluated according to the provisions of the European standard Eurocode 8 EN 1998-1:2004 [1] and the current Romanian seismic design code P100-1/2013 [2].

Dynamic nonlinear analyses were performed using Drain 2D+ computer software [8] and acceleration records of different Romanian Vrancea-earthquakes.

2. Configurations with Reduced Cross-Sections for Long Links

In a well-designed seismic resistant eccentrically braced frame, the greatest part of the energy induced in the structure by strong earthquakes is dissipated through plastic deformations concentrated in the links. To provide this, the links are sized for code specific lateral loads [1, 3, 6] and all the other structural members of the frames (columns, braces, beam segments outside the dissipative members) are designed for the forces generated by the fully yielded and strain hardened links [1, 3, 6].



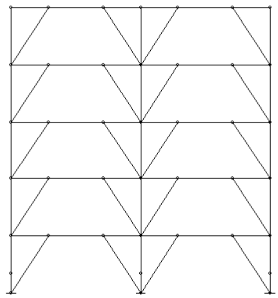


Figure 1. Detailing options for long links in an eccentrically braced frame (solution A-A was used for frame nr.2, solution B-B was used for frame nr.1, solution C-C was used for frame nr.3)

Making the link to be the weakest element of the frame, the designer can force the yielding to occur in the ductile link elements while preventing inelastic deformations in members with a non-ductile behaviour. Generally this design concept conducts to smaller cross-sections for the links than for the beam segments near them (see configuration B-B in Fig. 1).

Especially in eccentrically braced frames with long links the smaller cross-sections of the links lead to smaller values for the lateral stiffness of the structure. On the other hand, if the same cross-section is used for the dissipative members and for the beam segments outside the links (see configuration A-A in Fig. 1), the lateral stiffness of the frame increases but the plastic deformations may occur in other members than links, too (a favorable general plastic failure mechanism would be difficult to obtain, see Fig. 2). Many plastic hinges appeared in unwanted zones, mainly in the braces and beam segments outside the dissipative members.

A configuration with reduced beam flanges sections at the member ends is proposed (see configuration C-C in Fig. 1). We tried to outline the advantages of this solution on a designed structure. A five-storey eccentrically braced frame with two spans of 8,0 m and a storey height of 3,5 m was considered. The long links with a length of 3,4 m were placed in the central part of the frame girders, between two braces (see Fig. 1).

If the same cross-section is used for the whole flexural dissipative member, the positions of the plastic hinges along this element cannot be predicted exactly and so the maximum inelastic link deformations cannot be estimated exactly. The reduced cross-sections near the ends of the links ensure a better control of the positions where plastic hinges can occur along the link. As shown in Fig. 3*b*), a greater distance between the positions of plastic hinges along the dissipative member, reduces the link axis rotation angle [1].

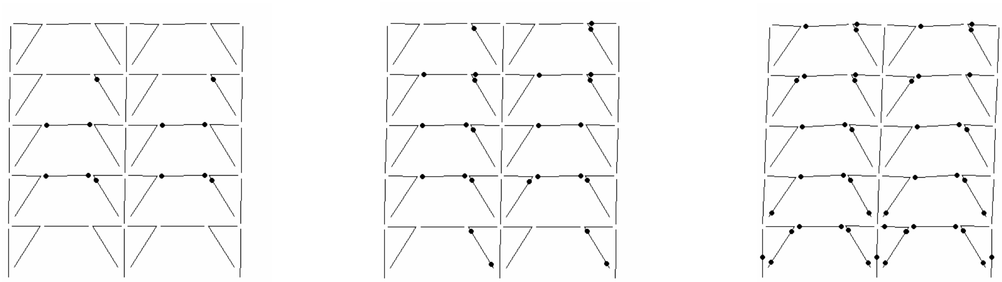
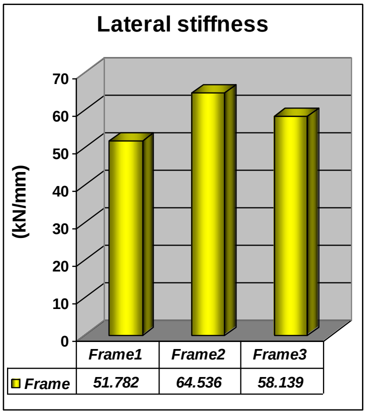
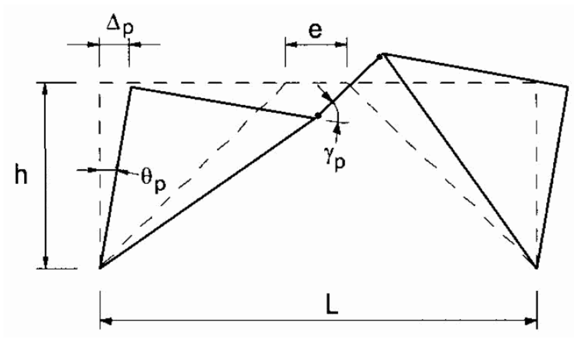


Figure 2. Some steps of the static nonlinear analysis of frame nr.2 (configuration B-B for links)

a) 

b) 

$$\gamma_p = \frac{L}{e}\theta_p$$

Figure 3.
a) Lateral stiffness values;
b) Influence of the distance between plastic hinges e on link axis rotation angle γ_p

Numerical tests showed a good behaviour of the structure with reduced beam flanges at the ends of long links. These structures have sufficient stiffness under lateral loads and they develop a favorable global plastic failure mechanism. They are also efficient from the point of view of material consumption.

3. Configurations Resembling the Dog-Bone for Braces

Configurations resembling the "dog-bone" near the ends of the upper-storey diagonals in concentrically braced frames (see Fig. 4) ensure on one hand, the abidance of the slenderness demand for the braces [3, 6] ($\bar{\lambda} \leq 2,0$) and on the other hand, small values of the over-strength ratio [3, 6] ($\Omega_i(N) = Npl_{Rd,i} / N_{Ed,i}$).

The reduced cross-section of the diagonal in the "dog-bone" detail zones ensures an adequate tensile capacity of the braces and small $\Omega_i(N)$-values. At the same time the buckling behaviour and slenderness of the braces is not significantly affected by the reduced cross-sections near the member ends and the slenderness demand of the braces will be satisfied.

A ten-storey concentrically braced frame is considered having two spans of 6,0 m and a storey height of 3,5 m (see Fig. 5*a*). The diagonals had built-up I-shaped cross-sections, placed with the web normally to the bracing plane (see Fig. 4). The same current cross-sections are used for the braces located at the storeys 1, 5-6; respectively 2-4; 7-8 and 9-10 (as indicated in Table 1). The non-dimensional slenderness limitation ($\bar{\lambda} \leq 2,0$) is satisfied in all cases.

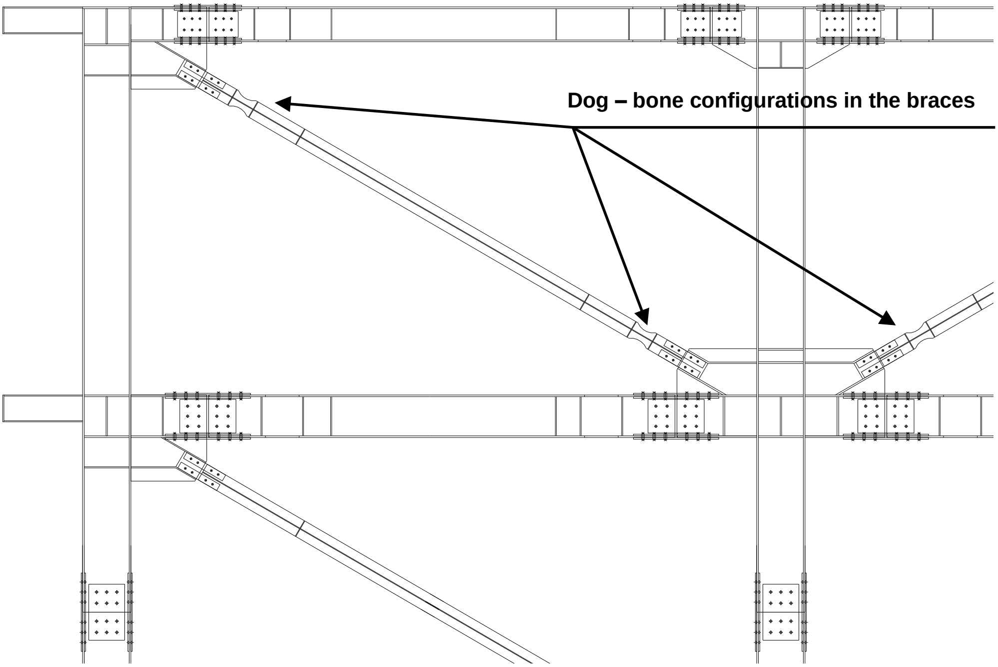


Figure 4. Details resembling the "dog-bone" for the top storey diagonals in a concentrically braced frame

Table 1. Reducing the values of the $\Omega_i^{(N)}$ ratios by using dog-bone details at the braces ends

Storey	Current brace cross-section				Reduced brace cross-section		
	Web	Flanges	$\Omega_i^{(N)}$ value	$\bar{\lambda}$ value	Web	Flanges	$\Omega_i^{(N)}$ value
1	230 x 8	260 x 15	$\Omega_1^{(N)}$ =1,249	1,178	-	-	-
2	250 x 9	280 x 16	$\Omega_2^{(N)}$ =1,075	1,102	-	-	-
3	250 x 9	280 x 16	$\Omega_3^{(N)}$ =1,091	1,102	-	-	-
4	250 x 9	280 x 16	$\Omega_4^{(N)}$ =1,144	1,102	-	-	-
5	230 x 8	260 x 15	$\Omega_5^{(N)}$ =1,067	1,178	-	-	-
6	230 x 8	260 x 15	$\Omega_6^{(N)}$ =1,178	1,178	-	-	-
7	200 x 8	220 x 12	$\Omega_7^{(N)}$ =1,031	1,435	-	-	-
8	200 x 8	220 x 12	$\Omega_8^{(N)}$ =**1,351**	1,435	200 x 8	160 x 12	$\Omega_8^{(N)}$ =**1,054**
9	160 x 5	170 x 10	$\Omega_9^{(N)}$ =1,067	1,809	-	-	-
10	160 x 5	170 x 10	$\Omega_{10}^{(N)}$ =**1,919**	1,809	160 x 5	90 x 10	$\Omega_{10}^{(N)}$ =**1,134**

Remark: The webs and flanges dimensions are given in mm!

It can be observed by analyzing Table 1, that the values of $\Omega_8^{(N)}$ and of $\Omega_{10}^{(N)}$ are greater than 1,25-times the minimum $\Omega_i^{(N)}$ value (which is equal to $\Omega_7^{(N)}$ = 1,031). If, in order to reduce the value of $\Omega_{10}^{(N)}$, a smaller cross-section is used for the braces placed at storey 8 and storey 10, the slenderness limitation ($\bar{\lambda} \leq 2,0$) will be not fulfilled. By providing dog-bone configurations for the diagonals from storey 8 and storey 10 (by reducing locally the width of the flanges of the braces cross-section at both ends of the diagonals or only at one end as indicated in 2005 by Piluso at al [7]), the values of $\Omega_8^{(N)}$ and of $\Omega_{10}^{(N)}$ will be reduced and the difference between the maximum and minimum $\Omega_i^{(N)}$-values will be smaller than 25% (see the values in the right part of Table 1). The slenderness demand of the braces will be also satisfied.

On the other hand, if greater cross-sections are provided for the diagonals located at storeys 1-9, the condition that the maximum $\Omega_i^{(N)}$-value does not differ from the minimum $\Omega_i^{(N)}$-value by more than 25% will be also fulfilled. But in this case, a homogeneous dissipative behaviour of all the diagonals will be ensured with much greater material costs. The estimated steel consumption for the diagonals would increase with about 48%, whilst the estimated material consumption for the whole frames will increase with about 14% (see Fig. 5*b*).

Situation 1 in Fig. 5*b* is the one when a homogeneous dissipative behaviour of all the braces is ensured by using dog-bone configurations for the 8- and 10-storey diagonals. Situation 2 is the one when greater cross-sections of the braces are provided for the storeys 1-9, in order to reduce the differences among the $\Omega_i^{(N)}$-values.

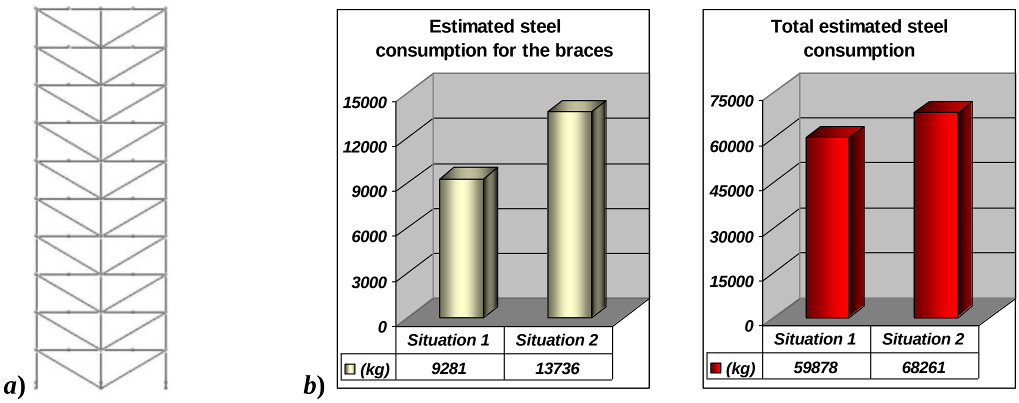


Figure 5.
a) Analyzed concentrically braced frame; b) Estimated steel consumption

Compared analyses led to the conclusion that the increase of labour cost due to the supplementary cuttings of the flanges at the ends of the braces is fully compensated by the reduction of overall material cost.

4. Reduced Cross-Sections in Girders of Concentrically Braced Frames

An explication for the poor behaviour of concentrically braced frames during dynamic nonlinear analyses [8] could lie in the fact that according to most seismic design procedures a global plastic failure mechanism is not sized clearly by design for this kind of seismic resistant structures [1, 3, 6].

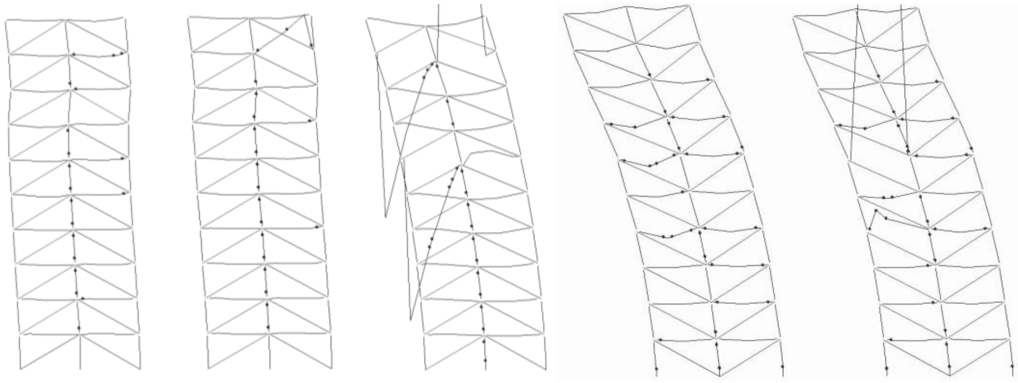


Figure 6. Unfavourable plastic hinges distributions in CBF during dynamic nonlinear analyses

Generally, as long as inelastic deformations are concentrated only in the diagonals, the centrically braced frames have a predictable behaviour. When the loading level increases and plastic deformations appear in other type of members (columns and girders), the behaviour of a centrically braced frame is difficult to control. Unfavourable distributions of plastic hinges may lead to the appearance of several local plastic mechanisms (see Fig. 6).

In order to size a favourable global plastic failure mechanism for a centrically braced frame, potentially plastic zones are provided along the girders [5]. A configuration with reduced beam flanges sections (resembling the dog-bone detail) near the connections with the braces can be adopted for the girders of the centrically braced frames, as indicated in Fig. 7.

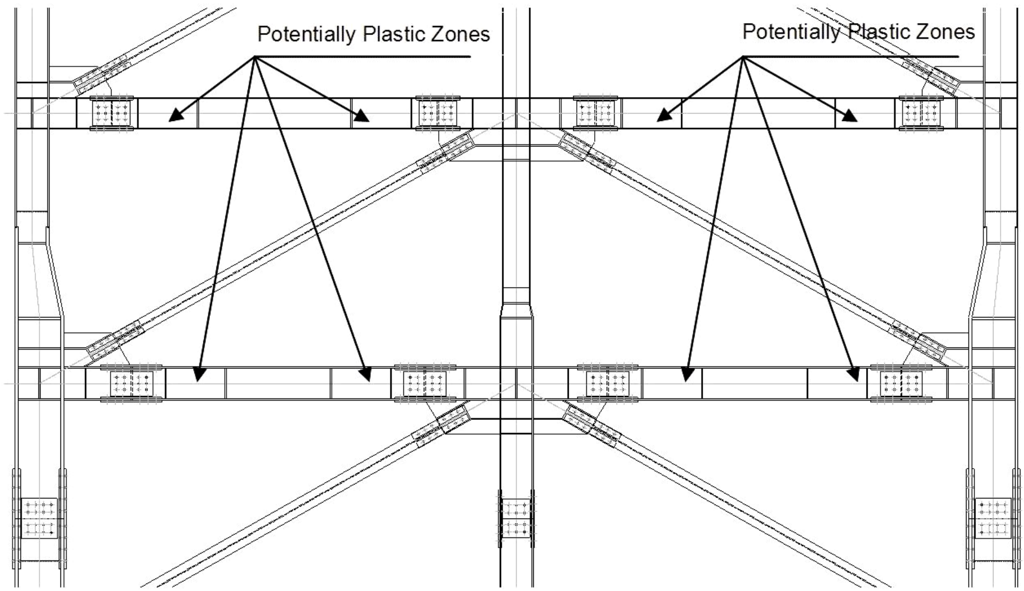


Figure 7. Location of the potentially plastic zones in the girders of a braced frame

So concentrically braced frames accepting plastic deformations in the diagonals at the bottom of first-storey columns and in the potentially plastic zones located along the frame girders (near the connections with the braces) can ensure a global plastic failure mechanism.

Also a better control of the positions of plastic hinges along the girders of the concentrically braced frames is provided [5].

The same concept can be used for designing a favourable global plastic mechanism for frames equipped with buckling restrained braces.

5. Details with Reduced Cross-Sections for First-Storey Columns

When a braced steel frame is subjected to strong earthquakes, inelastic deformations can appear also near the bottom of the first-storey columns. Several structural details were analyzed for the potentially plastic zones located near the bottom end of the columns considering [4]: reduced flanges cross-sections and/or transverse and longitudinal stiffeners for the columns bottom zone (as shown in Fig. 8 and 9).

Configuration I is the reference analysis detail and is shown in Fig. 8*a*. The column has the same cross-section on the entire height of the first-storey column. Transverse web stiffeners (P3) were used to avoid early local buckling in the potentially plastic zone.

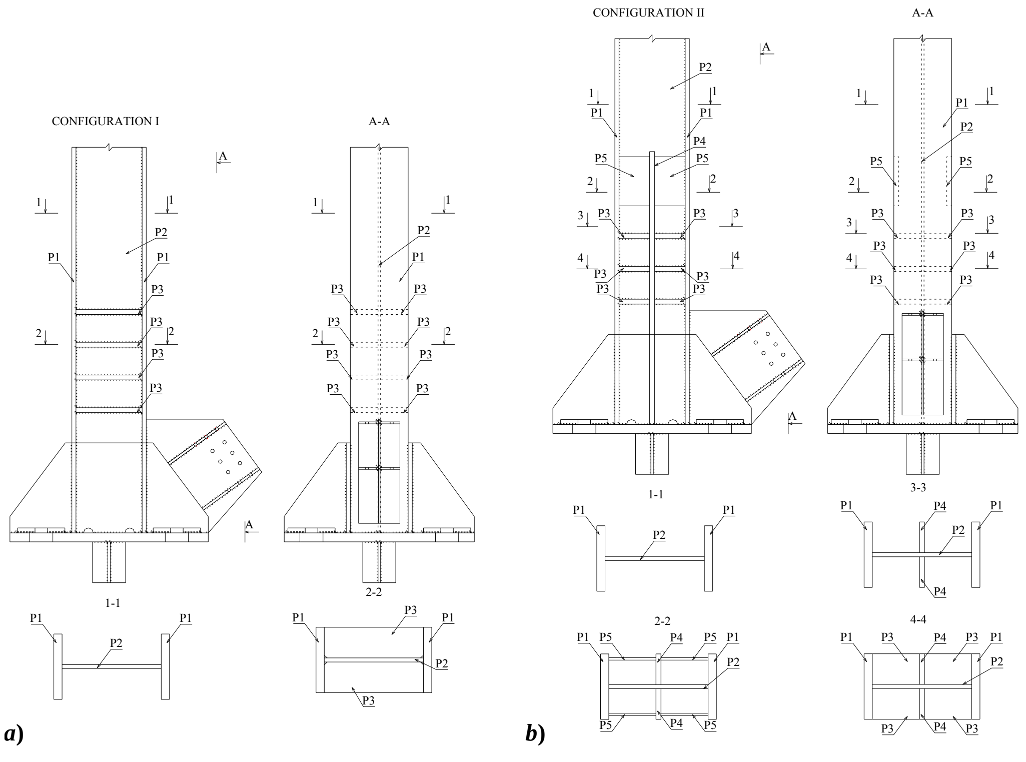


Figure 8.
a) Configuration I; b) Configuration II

Compared to configuration I, in the second considered detail an additional pair of longitudinal stiffeners (P4) was placed on the web (see Fig. 8*b*). These longitudinal stiffeners (P4) were provided in order to reduce the axial loading level in the flanges, to make room for stresses generated by bending moment. The pair of stiffeners (P4) is placed in the middle of the web in order to not increase significantly the flexural capacity of the potentially plastic zone cross-section. Plates P5 were used to facilitate the axial load transfer from the column flanges (P1) to the longitudinal web stiffeners (P4) reducing at the same time load concentration effects.

Transverse web stiffeners (P3) are kept in all configurations to reduce the risk of local buckling in the potentially plastic zone (as shown in Fig. 8 and 9).

The third configuration has a reduced flange cross-section in the potentially plastic zone (resembling the dog-bone detail) as shown in Figure 9*a*. The reduced flanges cross-sections ensure a better control of the position of plastic hinges along the first-storey column. If the same cross-section is used along the whole member, the positions of the plastic hinges cannot be predicted exactly. The longitudinal web stiffener is kept to assure quite the same axial capacity all along the first-storey column height. In configuration 3 the reduced width of the flanges in the potentially plastic zone is about 25% smaller than the flanges width in the rest of the first-storey column.

In the fourth considered detail, the first configuration column cross-section was kept for the potentially plastic zone, whilst the rest of the column has larger flanges cross-sections in order to increase the buckling capacity of the first-storey column (see Fig. 9*b*). The reduced flange width in the potentially plastic zone is also about 25% smaller than in the rest of the first-storey column.

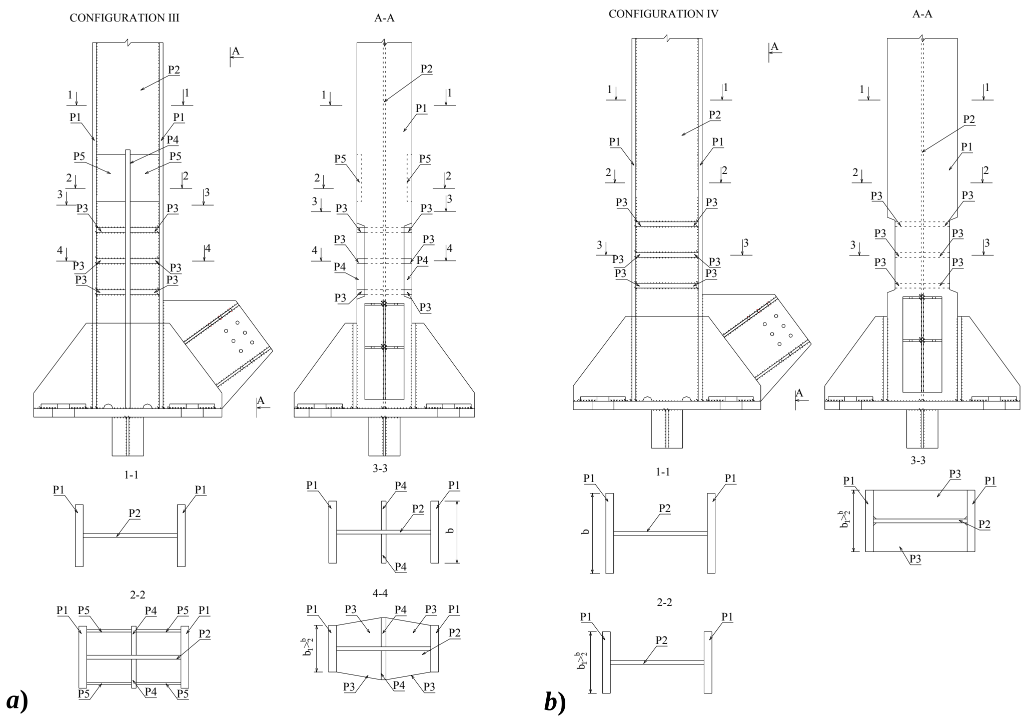
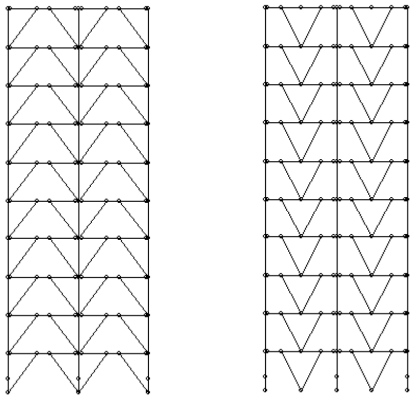


Figure 9.

a) Configuration III; b) Configuration IV

Two ten-storey eccentrically braced frames with short dissipative members of 1,2 m are considered. The frames had two spans of 6,6 m and a storey height of 3,5 m (see Fig. 10).



Frame **K** Frame **V**

Figure 10. Analyzed frames

Compared to the other considered construction details, configuration 3 leads to smaller bending moments and greater plastic hinges rotations at the bottom of the columns (see Fig. 11). The smaller bending moment values lead to smaller anchor bolts for the columns. The maximum bending moments recorded during the dynamic nonlinear analyses [4] at the bottom of first-storey columns in the other considered configurations are nearly the same. Compared to these values, the bending moments recorded for configuration 3 are about 20 ÷ 26% smaller.

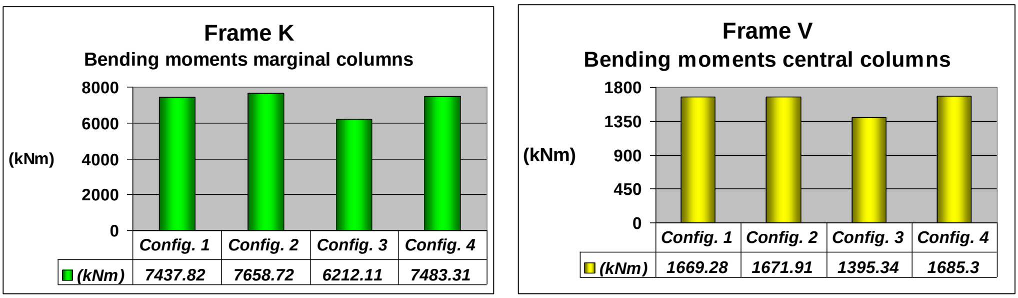


Figure 11. Maximum bending moments at the bottom of the first-storey columns

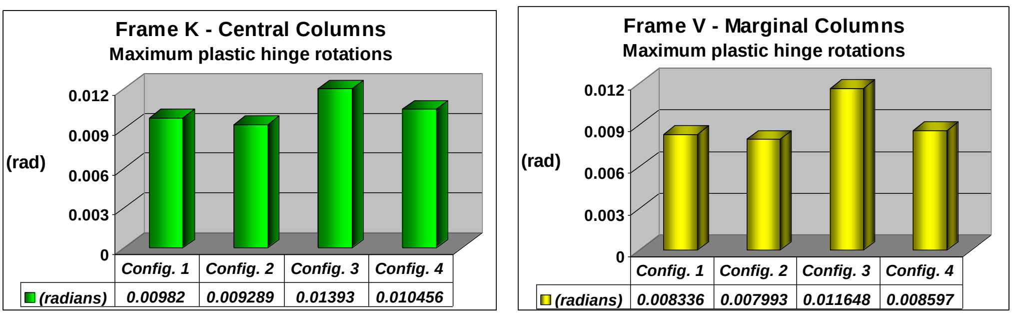


Figure 12. Maximum plastic hinge rotations noticed at the bottom of the first-storey columns

The greatest plastic hinge rotations in the potentially plastic zones of the first-storey columns were recorded during dynamic nonlinear analyses [8] for configuration 3. The values of the maximum plastic hinge rotations at the bottom of the columns for the other considered configurations were in the same range. Compared to these values, the plastic rotations for configuration 3 were about 37 ÷ 45% greater (see Fig. 10*b*).

The buckling resistance of first-storey columns was evaluated using relations (6.61), (6.62) and annex B from EN 1993-1-1:2005 [2]. The general stability was verified taking into consideration the most unfavourable loading situations that were recorded in the first-storey columns [5] (pairs of bending moment values at the ends of the first-storey columns and compressive axial forces that were recorded in the verified element at the same time during the dynamic nonlinear analysis). Generally, these unfavorable loading situations occurred when plastic hinges were developed near the bottom of first-storey columns [4].

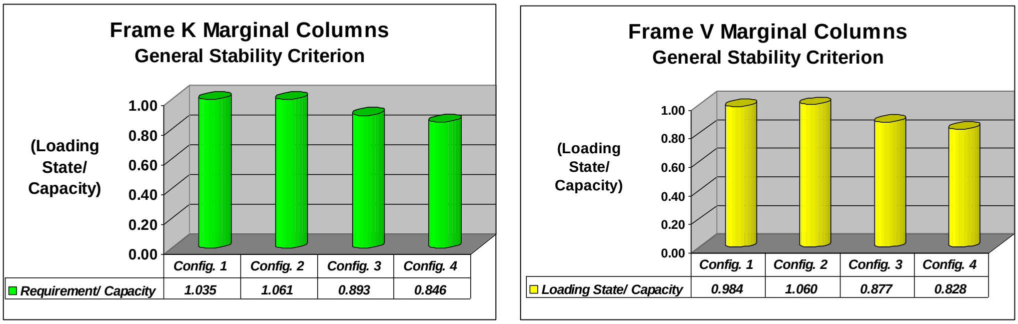


Figure 13. Buckling resistance of first-storey columns

It can be observed from the graphics in Fig. 13, that configuration 4 provides the greatest buckling resistance for the situations when inelastic deformations appear in the potentially plastic zones at the bottom of the columns. The general stability criterion is not satisfied in many situations (up to 6%) especially for the marginal first-storey columns in case of configuration 1 and 2. Configuration 4 appears to be the safest from the point of view of assuring the general stability of the first-storey column in the situation when plastic deformations occur in the potentially plastic zone at the bottom of the column.

6. Conclusions

Constructive details with reduced cross-sections (resembling the “dog-bone”-detail can be used in several situations in order to improve the behaviour of seismic resistant structures during strong earthquakes:

1. In case of eccentrically braced frames with flexural links, a dog-bone configuration at the link ends ensures significant lateral stiffness for the eccentrically braced frame and a favourable global plastic hinge mechanism.

2. Details with reduced cross-sections near the ends of the upper storey diagonals in concentrically braced frames lead to an adequate slenderness for the braces and to a proper tensile capacity of the diagonals, with small over-strength ratio values.

3. Providing configurations with reduced cross-sections for potentially plastic zones along the frame girders, a favorable global plastic hinge mechanism can be sized by design for concentrically braced frames.

4. Configurations with “dog-bone” details near the base of bottom-storey columns appear to be safer from the point of view of ensuring the general stability of first-storey columns in the situations when plastic deformations occur in the bottom storey columns.

5. Using reduced cross-sections in different kind of structural elements in seismic resistant structures ensure a better control of the distribution of inelastic deformations along the structural members.

REFERENCES

1. AISC, Seismic Provisions for Structural Steel Buildings, American Institute of Steel Construction AISC - 2010.

2. Eurocode 3. EN 1993-1-1:2005, Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings, 2005.

3. Eurocode 8. EN 1998-1:2004, Design of Structures for Earthquake Resistance, Part 1: General Rules, Seismic Actions and Rules for Buildings, 2004.

4. *Köber, H., Ştefănescu, B.* Dog-bone Details for Potentially Plastic Zones in First Storey Columns. Congress on Recent Advances in Earthquake Engineering and Structural Dynamics, Vienna, Austria, 2013.

5. *Köber, H., Stoian, M.* Remarks about the Seismic Design of Centrically Braced Frames According to Eurocode 8. National Symposium on Steel, Timber and Composite Structures, Sofia, Bulgaria, 2010.

6. Ministry of Transportations, Public Works and Territory Planning. Code for Aseismic Design – Part I – Design prescriptions for buildings, P100-1/2013, Bucharest, Romania, 2013.

7. *Piluso, V, Longo, A, Montuori, R.* An Innovative Conception for Bracing Members: The Reduced Brace Section Solution, 4th European Conference on Steel and Composite Structures – Eurosteel 2005, Maastricht, Netherlands, 2005.

8. *Tsai, K. C., Li, J. W.* Drain2D+ A General Purpose Computer Program for Static and Dynamic Analyses of Inelastic 2D Structures, 1994.