ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ СОФИЯ

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# A METHOD TO IMPROVE THE SEISMIC BEHAVIOUR OF ECCENTRICALLY BRACED FRAMES

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***Keywords*****:** *ductility, distribution of plastic deformations, favourable plastic failure mechanism, dynamic nonlinear analyses, UACEG2017*

**ABSTRACT**

The present paper is intended to enhance the inelastic response under severe seismic actions of some eccentrically bracing systems equipped with additional vertical connection elements (vertical truss elements between the ends of all dissipative members that are not connected directly to columns) compared to the seismic behaviour of traditional eccentric bracings. Each considered structural type (with and without additional vertical truss elements) is subjected to three dynamic nonlinear analyses, using Vrancea earthquakes acceleration records. The values of different response parameters recorded during nonlinear analyses are compared.

## 1. Introduction

The main objective of the present work is to compare the behaviour under seismic actions of two constructive systems: traditional eccentrically braced frames and eccentrically braced frames equipped with additional double-hinged vertical connection elements between the ends of the dissipative members from all storeys. Except for the bottom storey, these additional truss elements connect the ends of links that are not fixed directly to the columns.

Three eccentrically bracing systems were considered with and without additional truss elements, as indicated in Fig. 1. The analyzed frames had ten storeys of 3,5 m and two spans of

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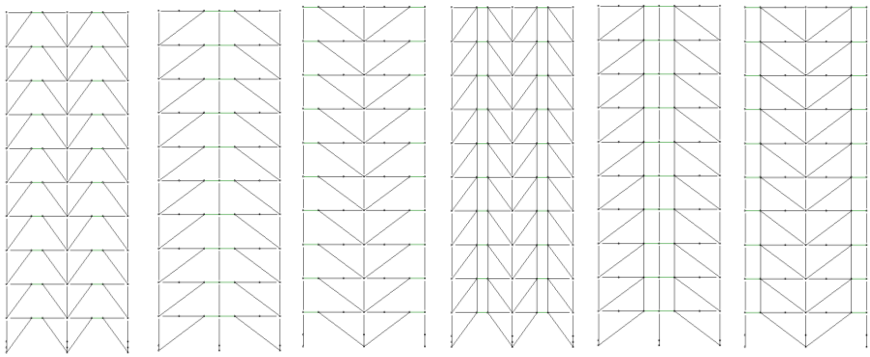
6,6 m [5]. All considered frames (with and without vertical truss elements) had short links with a length of 1,2 m. In the case of frame K the dissipative members are located in the central part of the frame girders, between to trusses. In the case of frame DC and frame DM the links are placed between a brace and a column (for frame DC the links are located on both sides of the central column, whilst for frame DM the dissipative elements are placed near the lateral columns).



a) Frame K b) Frame DC c) Frame DM d) Frame KP e) Frame DCP f) Frame DMP

**Figure 1. Analyzed frames**

The six analyzed frames were sized for the forces produced by the same horizontal seismic load, evaluated according to the prescriptions of the current Romanian seismic design code P100-1/2013 [6] and the provisions of the European standard Eurocode 8, EN 1998-1:2004 [3]. All kind of structural elements (columns, diagonals, vertical trusses, dissipative members and adjacent beam segments) had built-up I-shaped cross-sections, designed according to Eurocode 3, EN1993-1-1:2005 [2].

## 2. Numerical Evaluation of Seismic Response Based on Dynamic Nonlinear Analyses

Each considered structural type (with and without additional vertical truss elements) was subjected to dynamic nonlinear analyses using Vrancea earthquakes acceleration records [7]. The N-S components of the acceleration records of Vrancea earthquakes from 1977, 1986 and 1990 were considered, all recorded at the INCERC station in Bucharest. All accelerations records were calibrated for a peak ground value of about 0,3 times the acceleration of gravity. Rayleigh damping had taken into consideration mass and stiffness proportional damping factors, evaluated for the first and third eigenmodes [1, 7]. The dissipative members were modelled as finite elements that could plastify under the combined action of bending moment and axial force, while the columns, diagonals and beams segments outside the dissipative members could suffer inelastic deformations under the combined effect of bending moments and axial forces. The additional vertical truss elements were modelled to plastify, or to get out of work through buckling under the action of tensile, respectively compressive axial forces.

### 2.1. Extreme Base Shear Forces and Horizontal Roof Displacements

Greater base shear forces could be noticed for the frames with additional trusses compared to the traditional eccentrically braced frames. The maximum differences between the values of the base shear forces were up to 18% (see Fig. 2). These can be explained by the greater lateral stiffness of the eccentrically braced frames equipped with vertical truss elements. Although a smaller lateral stiffness was noticed for the traditional eccentrically braced frames (up to 7%), greater horizontal displacements could be observed during dynamic nonlinear analyses (up to 5%) for the eccentrically braced frames equipped with additional vertical trusses (see Fig. 3). The values of the maximum positive and negative horizontal displacements are more balanced for the frames with vertical truss-elements, especially in case of the acceleration record of the Vrancea earthquake from 1977.

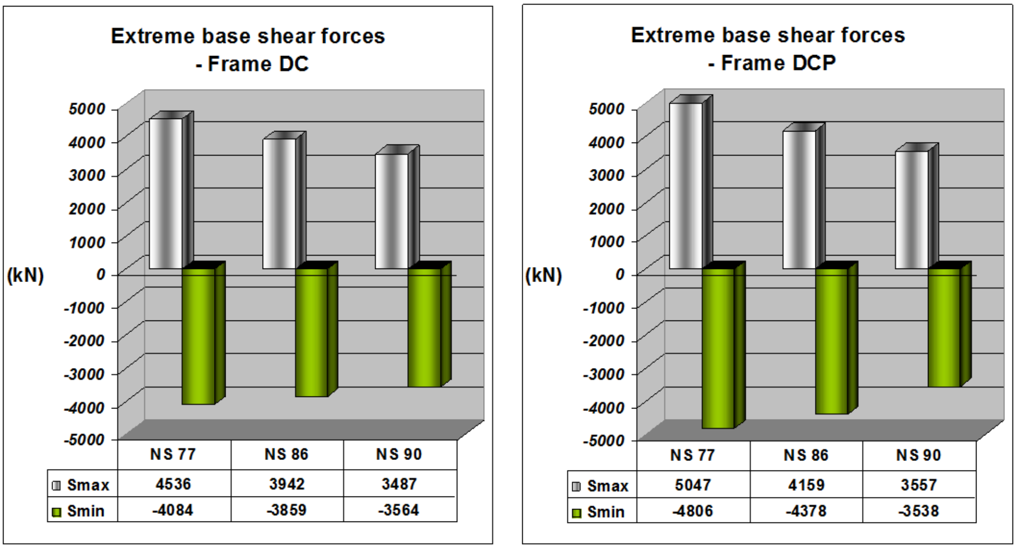



**Figure 2. Extreme values of the base shear forces recorded for frame DC and frame DCP**

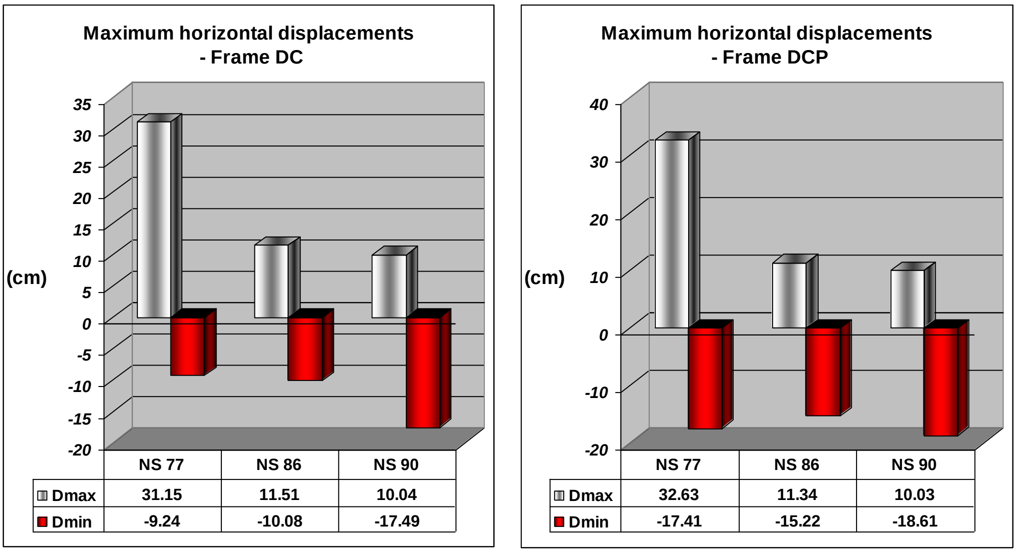



**Figure 3. Extreme values of the lateral roof displacements noticed for frame DC and frame DCP**

## 2.2. Plastic Deformations in the Dissipative Members

All considered structures had a favourable, predictable behaviour during dynamic nonlinear analyses. Inelastic deformations could be noticed only in the dissipative members and in the potentially plastic zones located near the bottom of first-storey columns.

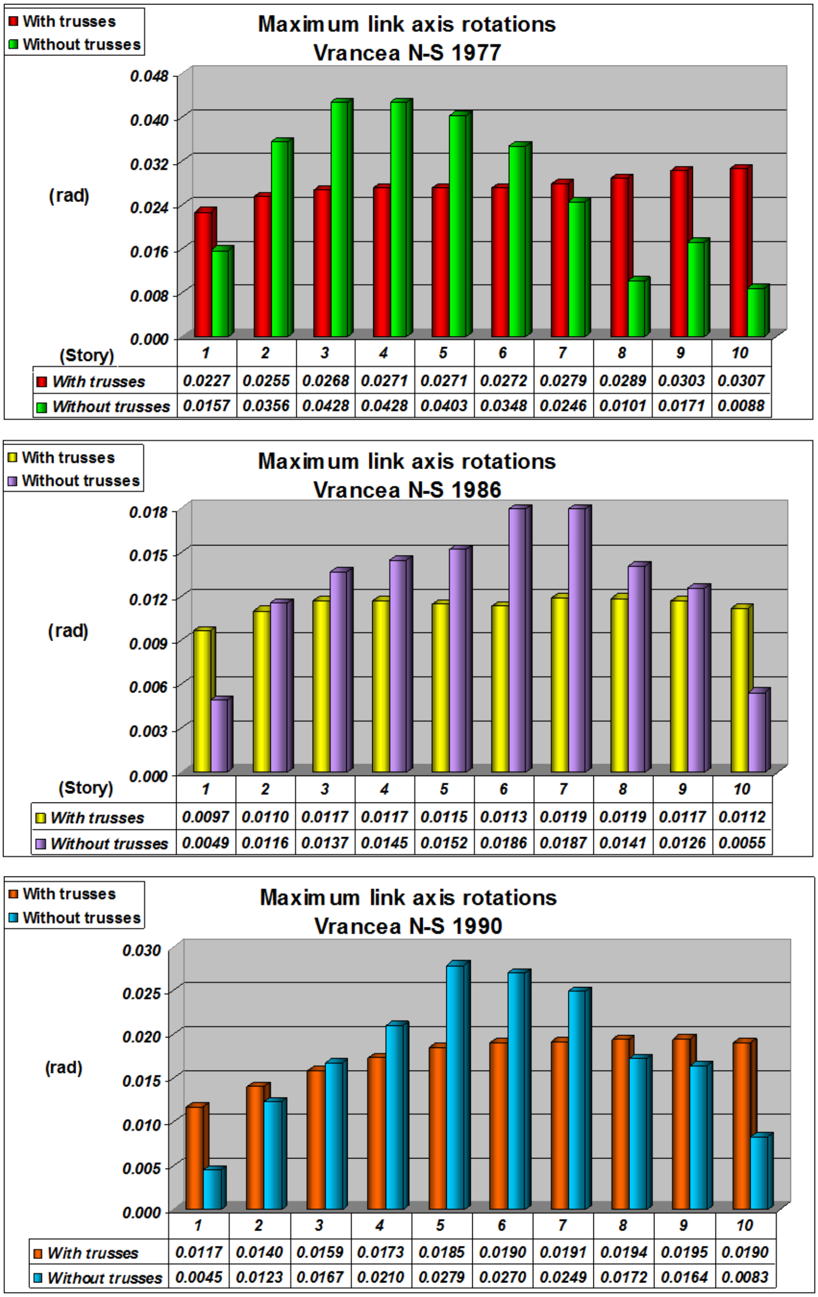
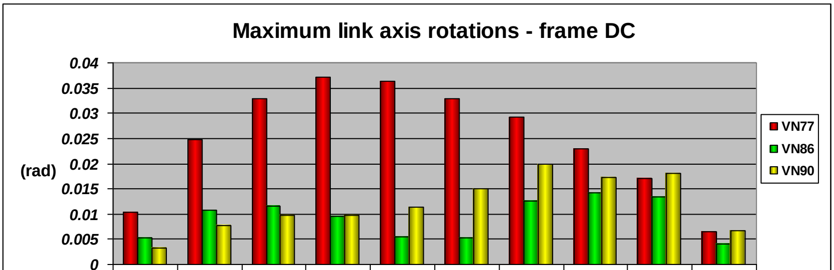



**Figure 4. Maximum plastic deformations in the dissipative members of frame K and KP**

For the frames without vertical trusses [5], the distribution of plastic deformations in the dissipative members along the height of the building is quite different from a dynamic analysis to the other (see Fig. 4 and 5). For the frames equipped with additional truss elements, more uniform distributions of inelastic deformations in the links along the height of the frames could be noticed in case of all considered acceleration records (as shown in Fig. 4 and 6).

For example, for frame K (see Fig. 4), maximum inelastic deformations could be observed in the dissipative members of storey 3 and 4 (in the case of the dynamic nonlinear analysis using the acceleration record of the Vrancea 1977 earthquake), in the links of storey 6 and 7 (for the Vrancea 1986 earthquake) and in the dissipative members of storey 5 (in the case of the Vrancea 1990 earthquake).

In the case of frame KP, as shown in Fig. 4, the maximum plastic deformations in the dissipative members were noticed in storeys 7, 8 and 9 for the Vrancea 1977 and Vrancea 1990 earthquakes, whilst in the case of the Vrancea 1977 earthquake the maximum deformations were observed in the links from the last two storeys. Compared to frame K, a much more uniform distribution of the plastic deformations along the height of the structures could be observed for frame KP (compare the values in the graphics of Fig. 4).



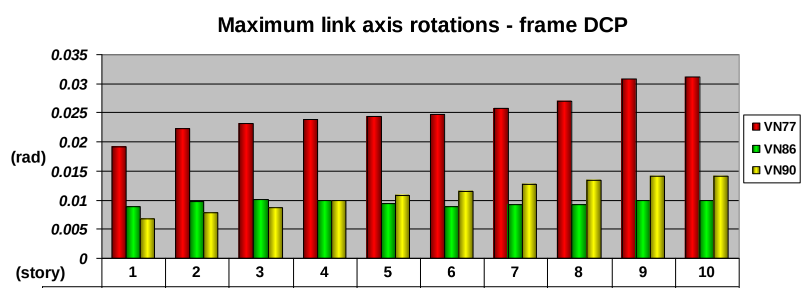

| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| VN77 | 0.01044 | 0.02473 | 0.03293 | 0.03712 | 0.03629 | 0.0328 | 0.02914 | 0.02295 | 0.01699 | 0.00644 |
| VN86 | 0.00524 | 0.01079 | 0.01157 | 0.00945 | 0.00545 | 0.00518 | 0.01255 | 0.01419 | 0.01331 | 0.00413 |
| VN90 | 0.00334 | 0.00764 | 0.00971 | 0.00982 | 0.01142 | 0.01507 | 0.01984 | 0.01729 | 0.01814 | 0.00672 |

**Figure 5. Maximum plastic deformations in the dissipative members of frame DC**

For frame DC the greatest inelastic deformations were recorded as shown in Fig. 5: in the links of storeys 4 and 5 (Vrancea 1977), in the dissipative members of storeys 8 and 9 (Vrancea 1986) and in the links of storey 7 (Vrancea 1990). For frame DM the greatest plastic deformations could be noticed: in the dissipative members of storeys 3 and 4 (Vrancea 1977), in the links of storey 3 (Vrancea 1986) and in the dissipative members of storey 6 (Vrancea 1990). It can be observed that the values of the plastic deformations are quite different along the height of the frames without additional truss-elements.

For the frames equipped with vertical trusses, the maximum observed inelastic deformations are 25 ÷ 35% smaller compared to the one noticed for the traditionally eccentrically braced frames. In most cases the maximum plastic link deformations could be noticed in the upper storey of the frames with additional truss elements. The situation with smaller inelastic deformations in the upper two storeys of the traditionally eccentrically braced frames is avoided (compare the graphics in Fig. 5 and 6).

For all the eccentrically braced frames with additional trusses, a more uniform distribution of the plastic deformations along the height of the structures could be observed. The plastic deformation demand of all dissipative members is in the same range and so the links placed at different storeys participate in a comparable manner at the dissipation of energy through plastic deformations.

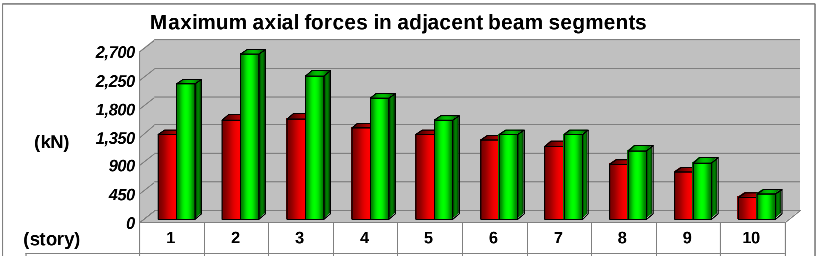



| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| VN77 | 0.01923 | 0.02222 | 0.02321 | 0.02394 | 0.02446 | 0.02474 | 0.0258 | 0.02691 | 0.03075 | 0.03111 |
| VN86 | 0.00896 | 0.00982 | 0.01012 | 0.00993 | 0.00945 | 0.00884 | 0.00917 | 0.00917 | 0.00992 | 0.00989 |
| VN90 | 0.00682 | 0.00782 | 0.00878 | 0.00985 | 0.01084 | 0.01156 | 0.01264 | 0.01334 | 0.01411 | 0.01414 |

**Figure 6. Maximum plastic deformations in the dissipative members of frame DCP**

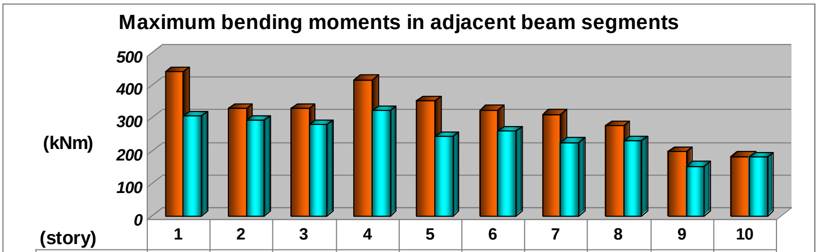
## 2.3. Maximum Values for Axial Forces and Bending Moments

For the adjacent beam segments, compared to traditional eccentric bracings (see Fig. 7), providing additional truss elements led to greater axial forces (about 34% for frame DCP and up to 26% for frame DMP) and to smaller values for the bending moments (up to 27% in the case of frame DCP and about 21% for frame DMP). Compared to frame K, in the case of frame KP, an average increase of the axial forces with about 28% combined with an average decrease of the bending moment with about 25% could be observed for the beam segments placed outside the dissipative members.




| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Frame DM | 1335.49 | 1570.72 | 1586.84 | 1433.07 | 1335.92 | 1242.84 | 1146.65 | 858.72 | 740.18 | 341.47 |
| Frame DMP | 2131.61 | 2605.67 | 2267.29 | 1910.07 | 1559.27 | 1333.18 | 1328.27 | 1077.24 | 891.82 | 387.76 |

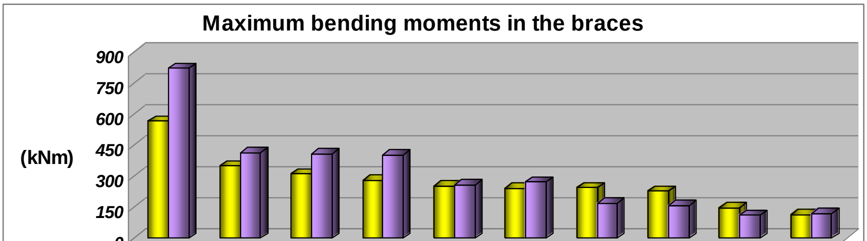
**Figure 7. Maximum axial forces in the adjacent beam segments of frame DM and DMP**




| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Frame DC | 440.92 | 329.93 | 328.96 | 417.07 | 353.27 | 324.84 | 310.73 | 275.84 | 197.57 | 182.25 |
| Frame DCP | 307.02 | 292.37 | 278.63 | 323.45 | 244.07 | 259.83 | 224.83 | 229.96 | 152.78 | 179.71 |

**Figure 8. Maximum bending moments in the adjacent beam segments of frame DC and DCP**

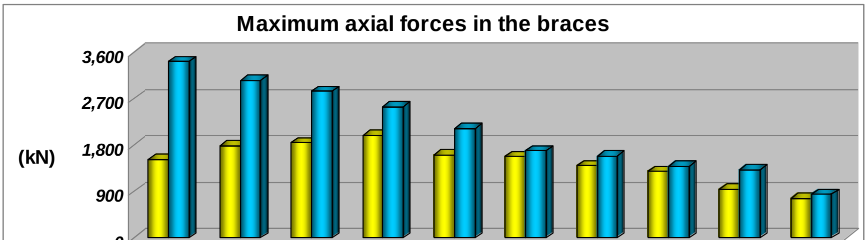
Greater axial forces were noticed in the braces of the frames with additional trusses (see Fig. 10). An average increase up to 35% was observed for frame DMP, up to 32% in the case of frame DCP and an increase of about 17% for frame KP (compared to the frames without vertical trusses). In addition, greater bending moments were recorded in the diagonals of the frames equipped with vertical trusses (see Fig. 9): about 25% greater in the case of frame DMP, respectively about 6% greater in the case of frame KP. In the case of frame DCP and DC the bending moment values in the diagonals were quite the same, except for the first storey. For the bottom-storey braces, a big increase of the values of bending moments and axial forces (sometimes greater than 100%) could be noticed for all analyzed bracing systems. In the absence of the vertical truss-elements at the first storey, the bottom-storey diagonals had to balance the greatest part of the axial forces from the trusses from the storey above. At other storeys (excepting the bottom storey), the axial force from a vertical truss element from a storey above is balanced mainly by the axial force in the truss from the storey below.




| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Frame DM | 565.84 | 350.91 | 310.65 | 280.65 | 253.54 | 242.01 | 244.63 | 227.73 | 145.93 | 114.22 |
| Frame DMP | 821.32 | 415.28 | 407.02 | 403.06 | 260.18 | 273.18 | 169.70 | 157.34 | 112.15 | 121.02 |

**Figure 9. Maximum bending moments in the braces of frame DM and DMP**

The greater axial forces and bending moment values led to greater cross-sections for the diagonals of the frames with additional truss-elements, compared to one without vertical trusses.




| (story) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Frame DM | 1524.15 | 1786.85 | 1846.11 | 1993.51 | 1610.20 | 1573.93 | 1399.41 | 1292.72 | 948.20 | 770.31 |
| Frame DMP | 3422.38 | 3049.08 | 2843.25 | 2543.44 | 2123.92 | 1693.28 | 1584.32 | 1382.60 | 1321.17 | 841.75 |

**Figure 10. Maximum axial forces in the diagonals of frame DM and DMP**

Greater axial forces were noticed in the marginal columns of the frames equipped with vertical trusses, compared to the ones without trusses. The average axial force increase was between 14% in the case of frame DCP and 8% in the case of frame KP. Except for the first storey, smaller bending moments were recorded in the frames with additional trusses. The average bending moment reduction was about 32% for frame DCP, about 26% in the case of frame DMP and over 17% for frame KP. At the bottom storey of the frames equipped with additional trusses, the absence of vertical truss-elements, led to a big increase of the bending moment values in the columns (sometimes greater than 75%) for all considered bracing systems.

Except for the first storey, smaller bending moments were noticed in the central columns of the frames with vertical truss-elements, compared to the frames without trusses. The average axial force reduction was about 24% in the case of frame KP, 23% for frame DMP and about 16% in the case of frame DCP. In addition, for frame DCP and frame KP smaller axial forces were recorded, compared to traditional eccentric bracings (about 4% in the case of frame DCP and about 3% for frame KP). The axial forces in the columns of frame DCP and frame DC were in the same range.

Providing additional vertical trusses in eccentrically braced frames increases the axial forces in most structural elements. The frames equipped with vertical trusses start to behave more like a vertical truss-girder, which explains the smaller recorded bending moment values observed in most structural elements (except for the diagonals).

## 3. Inelastic Deformations in the Bottom-Storey Columns

During the dynamic nonlinear analyses with the Vrancea N-S77 acceleration record, inelastic deformations could be noticed in all potentially plastic zones located near the bottom of the first-storey columns of all analyzed frames [4].

The presence of the vertical truss elements leads in most cases to greater inelastic deformations in the potentially plastic zones located near the bottom of first-storey columns.

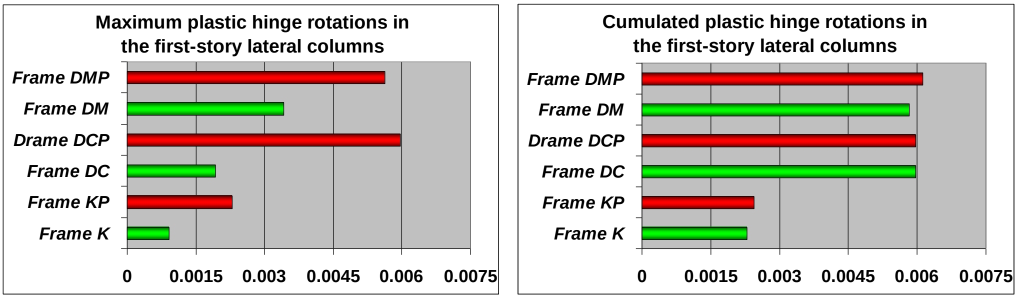



**Figure 11. Maximum plastic deformations recorded in the bottom-storey lateral columns**

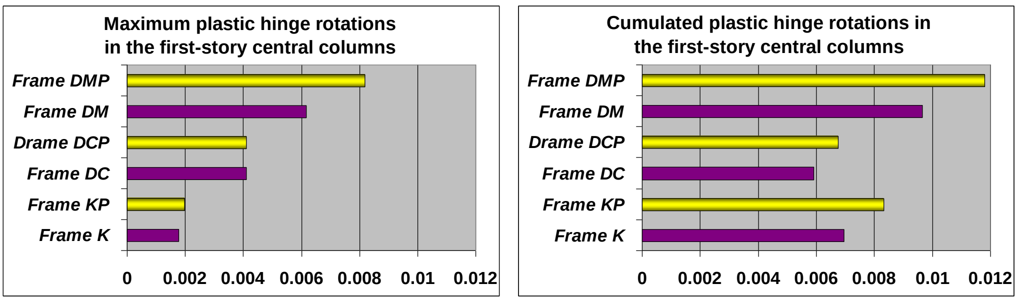



**Figure 12. Maximum plastic deformations recorded in the bottom-storey central columns**

In the case of the lateral (marginal) columns the maximum plastic hinge rotations were up to 3-times larger for frame DCP, compared to frame DC, while the values of the cumulated plastic hinge rotations were in the same range for all the three pairs of frames (K and KP, DC and DCP, respectively DM and DMP), as shown in Fig. 11.

For the central columns on the other hand, the maximum plastic hinge rotations and the cumulated plastic hinge rotations had up to 22% greater values for the frames equipped with vertical trusses (see Fig. 12).

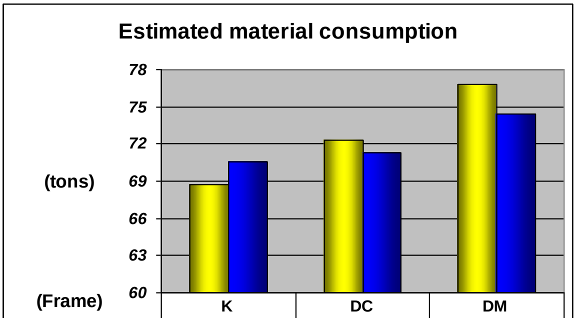
The columns of the frames were modelled as finite elements that could plastify under the combined action of bending moments and axial forces. The cumulated plastic hinge rotation at the end of a dynamic nonlinear analysis represents the sum of all the inelastic deformations recorded in a plastic hinge for one sense of rotation, during the dynamic nonlinear analysis [7].

## 4. Estimated Steel Consumption

The estimated steel consumption for the two considered structural types is indicated in Fig. 13. The same design value for the seismic force was used for the six analyzed frames (the dissipative elements of all the analyzed frames were sized for the forces produced by the same design seismic force, evaluated according to the current Romanian seismic design code [6]).

The presence of the additional truss elements had no significant influence on the overall steel consumption of the eccentrically braced frames. The differences among the values of the estimated steel consumption for the frames equipped or not with additional truss elements are smaller than 3% (as shown in Fig.13).

In the case of the frames equipped with vertical truss elements, smaller steel consumptions were noticed for the lateral and central columns, whilst greater consumption values were obtained for the diagonals. Almost the same material consumption values could be noticed for the frame girders (dissipative members and adjacent beam segments) for both frame types.




| (Frame) | K | DC | DM |
|---|---|---|---|
| Without trusses | 68.69 | 72.33 | 76.77 |
| With trusses | 70.57 | 71.33 | 74.45 |

**Figure 13. Estimated material consumption for the six analyzed frames**

The constructive solution with additional vertical truss elements led to a smaller material consumption in the case of the DC- and DM-bracing systems (with about 1,7% and respectively 3,5%). For these two bracing configurations only one end of the dissipative members is connected to a brace.

For the K-bracing system, with the dissipative members placed between two braces in the central part of the frame girders, traditional eccentric bracing proved to be more economic (with about 2,7%). This fact can be explained by the greater number of diagonals and additional truss elements used in case of the K-bracing system compared to the DC- or DM-bracing configurations.

## 5. Conclusions

The main differences in the behaviour under seismic actions of the two analyzed constructive systems (traditional eccentrically braced frames and eccentrically braced frames equipped with additional double-hinged vertical connection elements between the ends of the dissipative members from all storeys) are:

1. The main advantage of the eccentrically braced frames with vertical truss elements consists in the more uniform distribution of inelastic deformations along the height of the structure; the plastic deformation demand of all dissipative members is in the same range and so the dissipative members placed at different storeys participate in a comparable manner at the dissipation of energy through plastic deformations.

2. The main disadvantage of providing additional vertical trusses in eccentrically braced frames consists in the difficulty of the emplacement of door and window openings in the braced bays and spans.

3. The additional truss elements lead to a greater lateral stiffness compared to traditional eccentric bracing.

4. For the frames with vertical trusses, generally greater axial forces were recorded in all kind of structural elements and smaller bending moments could be noticed in the columns and beam segments placed outside the dissipative members.

5. Providing additional truss elements on the whole height of the building except for the first storey, increases the values of the axial forces and bending moments in the columns and braces of the bottom storey.

6. Greater inelastic deformations were recorded in most cases in the potentially plastic zones located near the bottom of first-storey columns for the frames equipped with vertical trusses, compared to traditional eccentrically braced frames.

7. The values of the estimated steel consumption are quite the same for the eccentrically braced frames equipped or not with vertical truss elements.

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