Remarks about Seismic Resistant Eccentrically Bracing Configurations

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SUMMARY:
Six ten storied frames, having different eccentrically bracing configurations, were sized for the same seismic action. All frames were equipped with short links with the same length of 1.2m. Static and dynamic nonlinear analyses were performed with each frame. The history of the formation of plastic hinges was observed, the energy dissipated through inelastic deformations was analyzed. The maximum values of the bending moments, axial forces and plastic hinge rotations were compared. The distribution of the forces among the different structural elements, the values of the remaining floor deformations and the estimated steel consumption were analyzed.

Keywords: eccentrically bracing configurations, dynamic nonlinear analyses, plastic hinges, dissipated energy

1. INTRODUCTION

The present paper is intended to point out some features of different bracing configurations used in eccentrically braced frames located in seismic areas.

1.1. Description of the analyzed frames

A ten story structure was considered, having the eccentrically braced frames placed as shown in Fig. 1. The structure has two spans and six bays of 6.6m. The story height is 3.5m.

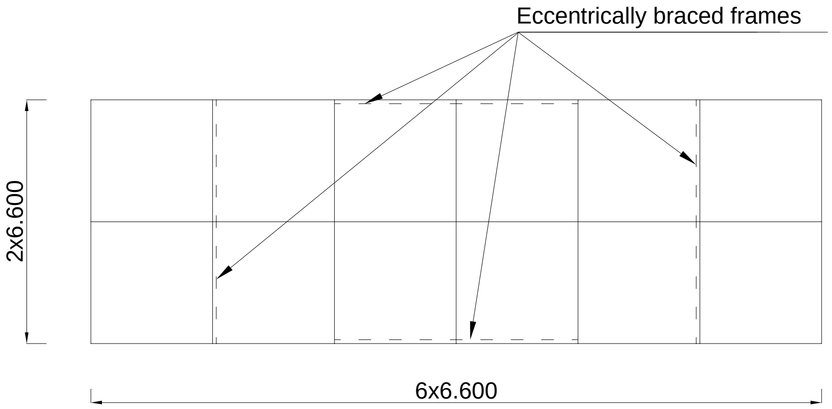


Figure 1. Position of eccentrically braced frames in the structure

The eccentrically braced frames were configured according to the provisions of the Romanian seismic design code and Eurocode 8. The eccentrically braced frames were designed in six different configurations (using six different bracing systems). Each solution used short links with a unique length of 1.2*m*. The six geometry types are presented in the Fig. 2.

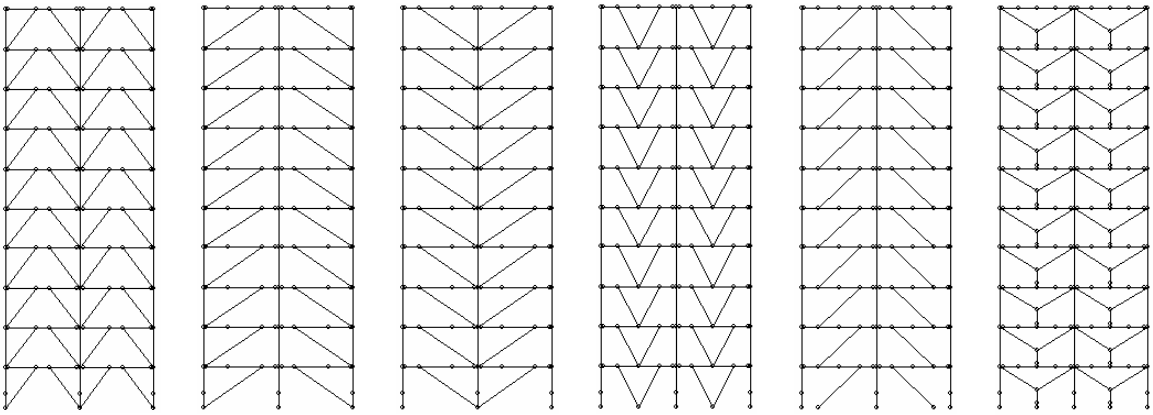

Frame **K** Frame **DC** Frame **DM** Frame **V** Frame **Z** Frame **Y**

Figure 2. Analyzed eccentrically braced frames

All structural elements (columns, braces, dissipative members, adjacent beam segments) had built up I-shaped cross-sections checked according to the prescriptions of Eurocode 3.

The six different braced frames were sized so that they have very close eigenperiods in order not to induce significant differences from this point of view in the behaviour of the structures during dynamic nonlinear analyses. The values of the first three eigenperiods of the six eccentrically braced frames are given in table 1.

Table 1. Eigenperiods (s)

Eigenperiod	Frame K	Frame DC	Frame DM	Frame V	Frame Z	Frame Y
T_1 (s)	1.125	1.111	1.067	1.104	1.109	1.112
T_2 (s)	0.405	0.401	0.366	0.385	0.406	0.390
T_3 (s)	0.226	0.227	0.207	0.223	0.242	0.227

1.2. Inelastic static and dynamic analyses

Each frame was subjected to a static nonlinear analysis in order to verify the successive formation of plastic hinges in the different structural elements of the analyzed frames (see Fig. 3). The computation consists in a biographical analysis under constant gravitational loads combined with monotonic increasing horizontal seismic loads.

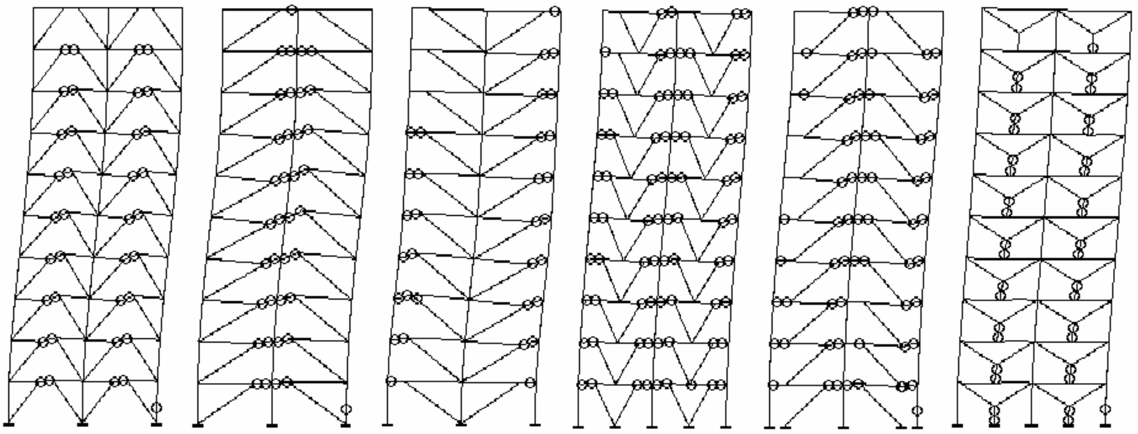


Figure 3. Stage during the static nonlinear analyses
corresponding to the occurrence of the first plastic hinge outside the dissipative members

Dynamic nonlinear analyses were performed with each frame using the same base excitation [1]. The excitation was taken from the Vrancea 04.03.1977 earthquake (the most severe earthquake in Romania in the last sixty years, with a magnitude of 7.2 on the Richter scale) and it consisted of the N-S component acceleration record. The peak acceleration for this record is about 0.2 times the acceleration of gravity. The first 20 seconds of this record were used since this period contains all the high acceleration peaks and nearly all inelastic activity is expected to occur during this period.

The acceleration record was calibrated to a peak ground acceleration value of $2.334 m/s^2$ (about 0.24 times the acceleration of gravity). Damping was not taken into account.

Gravitational loads, representing the characteristic values of permanent loads and also 40% of the characteristic values of the live loads acting on the floors, were taken into consideration as accompanying loads during the dynamic nonlinear analyses.

2. RESULTS, COMMENTS AND REMARKS

In a well-configured eccentrically braced frame, during strong earthquakes, inelastic deformations will occur mainly in the potentially plastic zones located in the dissipative members and eventually at the bottom of the first-story columns. To provide this, the cross-sections of the dissipative members are sized for code specific lateral loads. All other structural members are designed for increased values of seismic forces, comparative to those used for the design of the dissipative members.

2.1. Behaviour during dynamic nonlinear analyses

Although the six frames had very close eigenperiods, their behaviour during the dynamic nonlinear analyses was quite different. Except for frame Y, the behaviour of the eccentrically braced frames during the dynamic nonlinear analyses was favourable, inelastic deformations occurred mainly in the dissipative members.

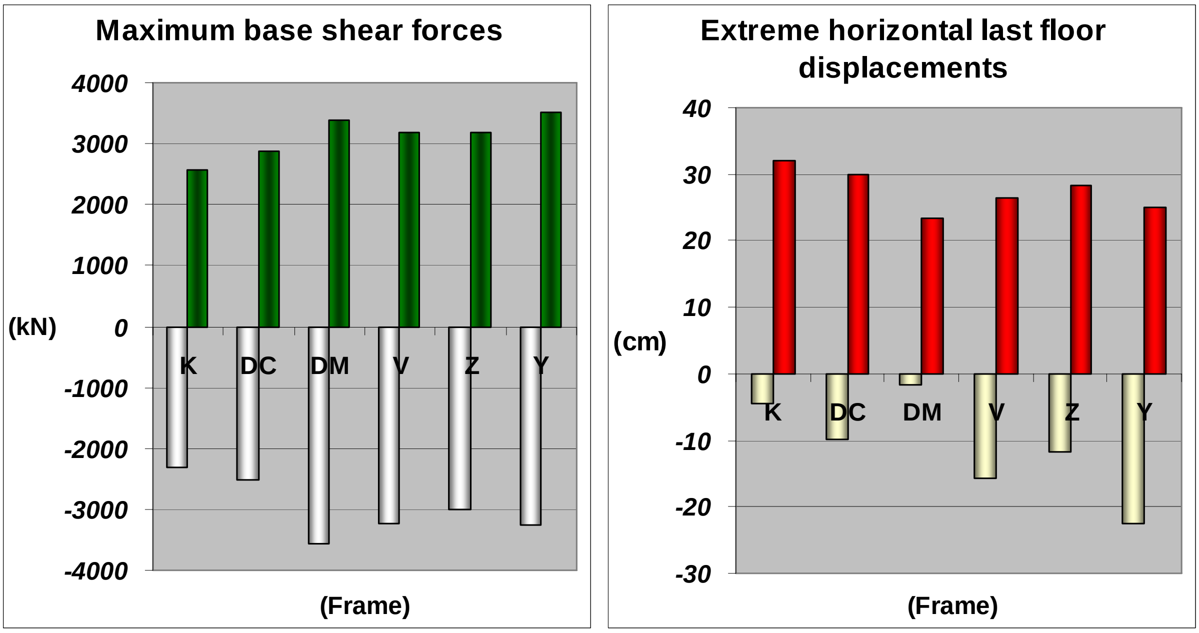


Figure 4. Maximum base shear forces and maximum last floor displacement recorded during dynamic nonlinear analyses

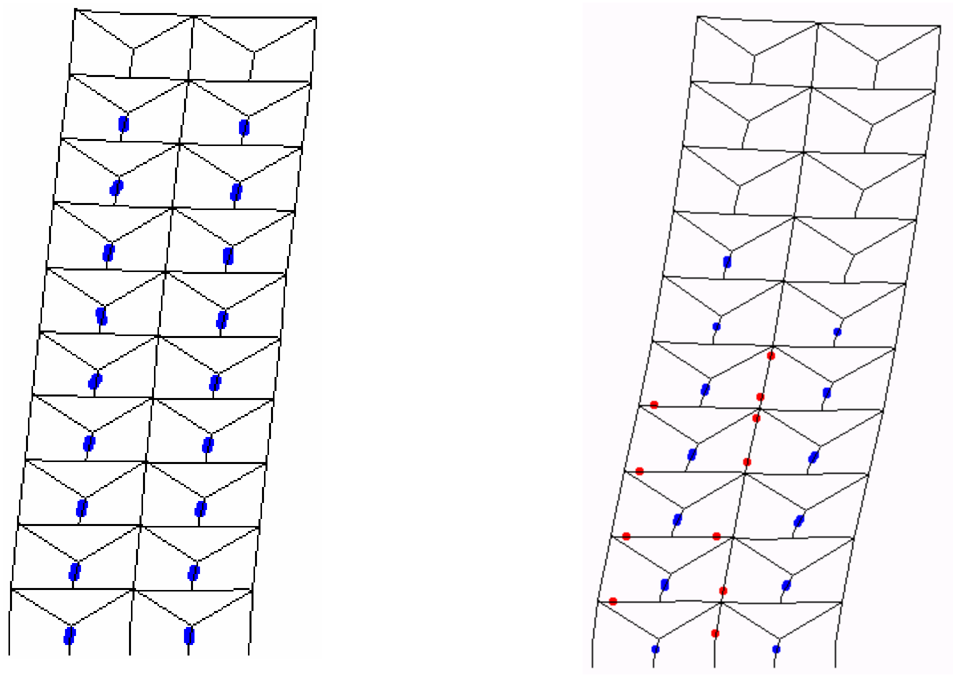
The larger shear capacity of the dissipative members of frame DM conducted to greater lateral forces. These potentially plastic zones suffered smaller inelastic deformations and the horizontal displacements of the frame were smaller. The greater base shear forces recorded for frame Y can be explained by the fact that, during a certain period of the dynamic nonlinear analysis, plastic hinges appeared in an uncontrolled way in all kind of structural elements (see Fig. 5).

The smaller cross-sections obtained for the dissipative members of frame K led to smaller base shear forces and greater horizontal floor displacements, compared to the values recorded for the other analyzed frames.

The cross-sections of the braces, columns and adjacent beam segments were in the same range in case of frame V and frame DM, only the dissipative members of frame DM had larger cross-sections. Greater base shear forces and smaller horizontal displacements were recorded in case of frame DM. As long as inelastic deformations appeared mainly in the dissipative members, the dimensions of the braces, columns and beam segments outside the potentially plastic zones seem to have a reduced influence on the lateral stiffness of the analyzed frames and on the behaviour of the structures during dynamic nonlinear analyses.

2.2. Inelastic deformations outside the potentially plastic zones for frame Y

Considering the fact, that during the dynamic nonlinear analysis plastic hinges appeared in many braces, girders and columns located in the first five stories of frame Y, the behaviour of this frame can be appreciated to be the poorest of all analyzed frames.



a) at 6.25 seconds from the analysis start

b) at 6.38 seconds from the analysis start

Figure 5. Plastic hinge distributions during dynamic nonlinear analysis of frame Y

This behaviour can be explained by the fact that a favourable global collapse mechanism was not sized by design in case of frame Y. As long as inelastic deformations were concentrated only in the dissipative members, frame Y had a favourable, predictable behaviour (see Fig. 5a). When the loading level increases and plastic deformations appeared in other type of members (braces, girders, columns) the behaviour of the frame was difficult to control (see Fig. 5b).

The less favourable behaviour of frame Y can be observed from the graphics in Fig. 6. Area (3) is much greater in the graphics for frame V and DM, than in the graphics for frame Y (see Fig. 6). In these graphics: area (1) = kinetic energy; area (2) = energy dissipated through plastic deformations in the dissipative members; area (3) = energy dissipated through plastic deformations in other structural members (columns and beam segments outside the dissipative members).

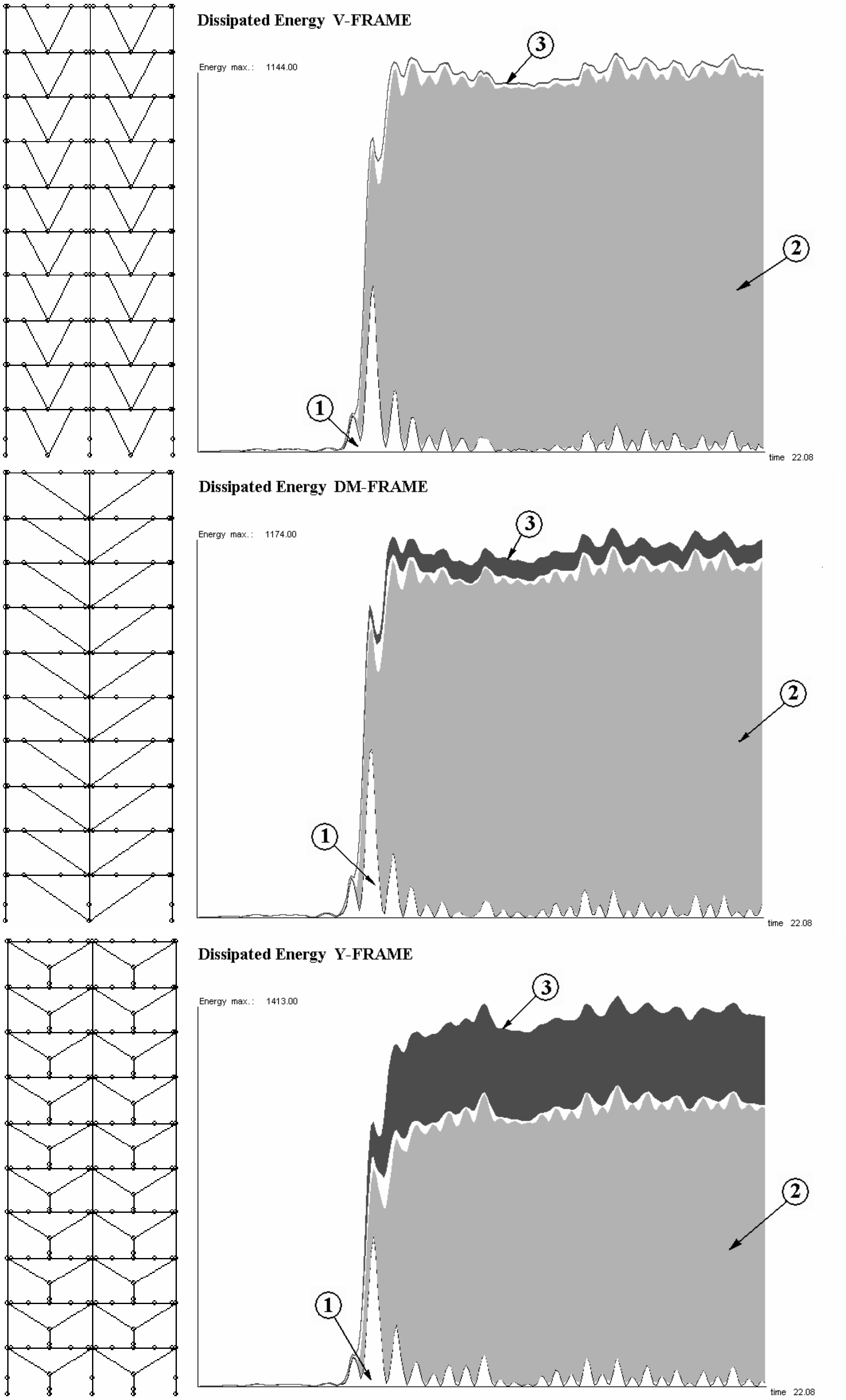


Figure 6. Dissipated (consumed) energy during dynamic nonlinear analyses

The uncontrolled inelastic deformations that appeared during the dynamic analysis in the braces, columns and adjacent beam segments of frame Y, conducted to a greater surface of area (3) in case of frame Y. The greater area (3) that can be observed in case of frame DM compared to frame V, can be explained by the fact that in case of frame DM larger inelastic deformations were recorded in the potentially plastic zones located near the bottom of the first story columns.

2.3. Maximum plastic deformations in the dissipative members

During dynamic nonlinear analyses, the smallest inelastic deformations were noticed in the dissipative members of the frames V and Z. This behaviour can be explained by the fact, that compared to the other considered bracing configurations, frame V and Z had a doubled number of dissipative members.

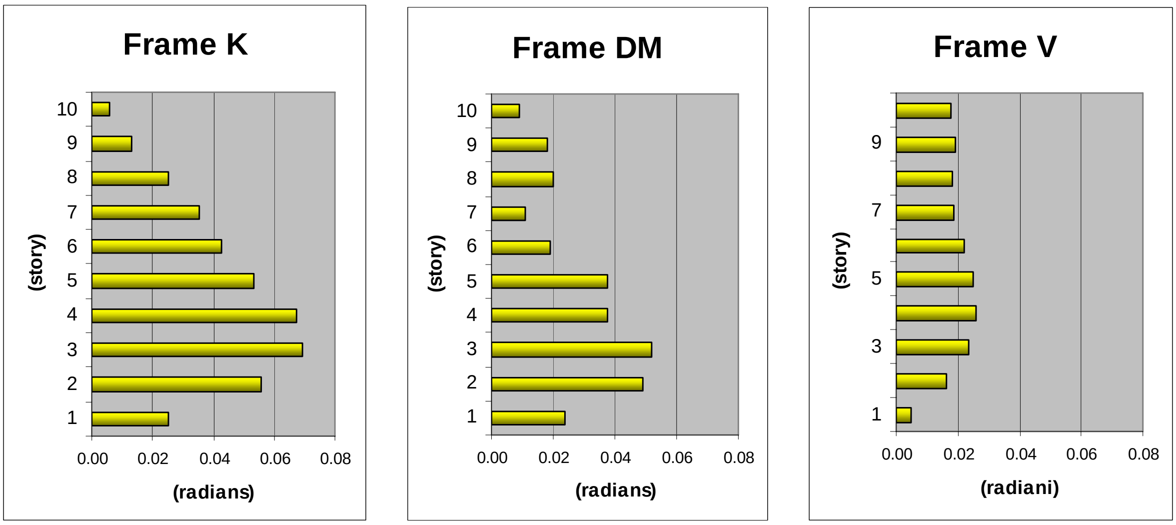


Figure 7. Maximum plastic link axis rotations noticed during dynamic nonlinear analyses

2.4. Remaining relative floor deformations

The main disadvantage of frame V and Z, which did not have the braces directly attached to the columns, consists in the greater remaining relative vertical deformations registered by the floors.

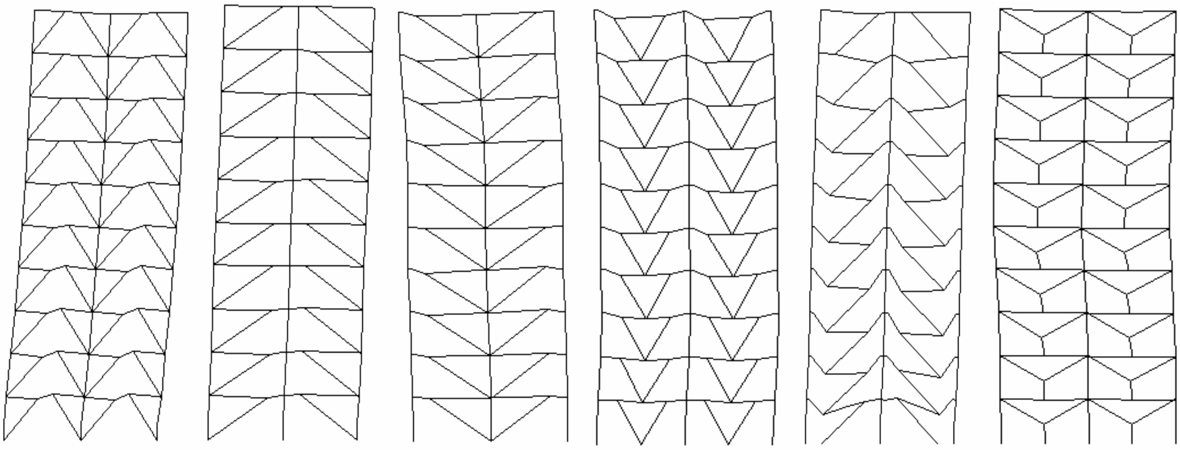


Figure 8. Deformed shapes of the frames at the end of the dynamic analyses

The deformed shapes of the frames at the end of the dynamic analyses are shown in Fig. 8. Greater remaining relative floor deformations can be observed at the higher stories of frame V and at the lower stories of frame Z.

In case of frame V and Z, the braces were not connected directly to the columns and the vertical loads of the floors were supported together by the columns and by the system formed by the braces and the adjacent beam segments. This braces/beam segments system is more flexible under the action of vertical loads than the columns, which explains why the parts of the floors supported by the braces suffered larger vertical deformations than the parts of the floors supported by the columns.

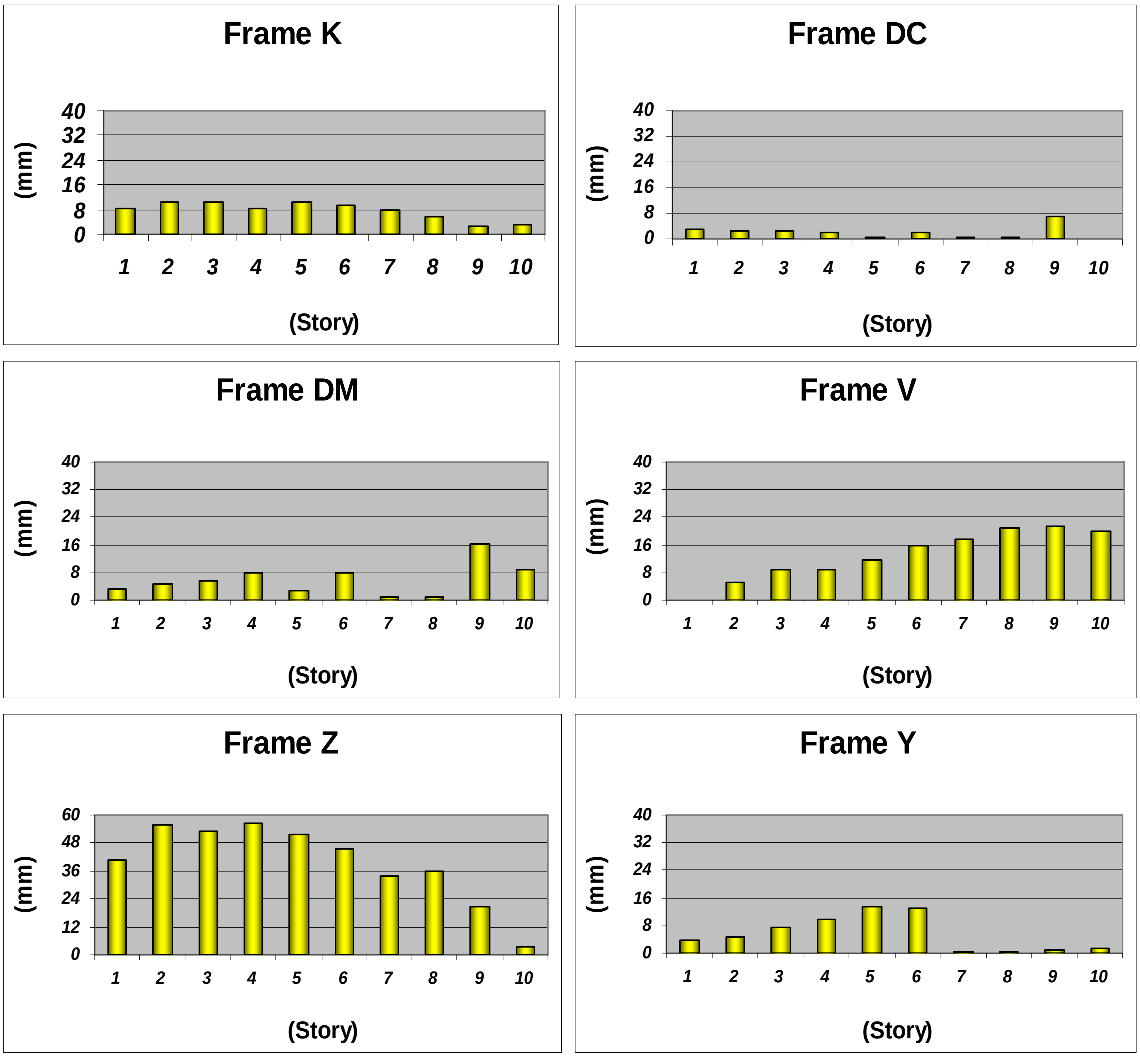


Figure 9. Maximum remaining relative floor deformations at the end of the dynamic analyses

In case of the other analyzed frames (bracing configurations K, DC, DM and Y) the braces were connected directly to the columns and the columns carried the whole vertical loads of the floors. For these frames the values of the remaining relative floor deformations were much smaller compared to those noticed in case of frame V and Z.

The smallest remaining floor deformations were noticed for frame DC.

2.5. Bending moment values in the columns

The smallest bending moments during the dynamic nonlinear analyses were noticed in case of the columns that were placed far away from the dissipative members. The placement of the links near the columns conducts to greater bending moment values in those columns (compare the values in graphics of Fig.10 and 11). Greater bending moments appeared in the central column of frame DC, compared to the one recorded for frame K and DM (see Fig.10).

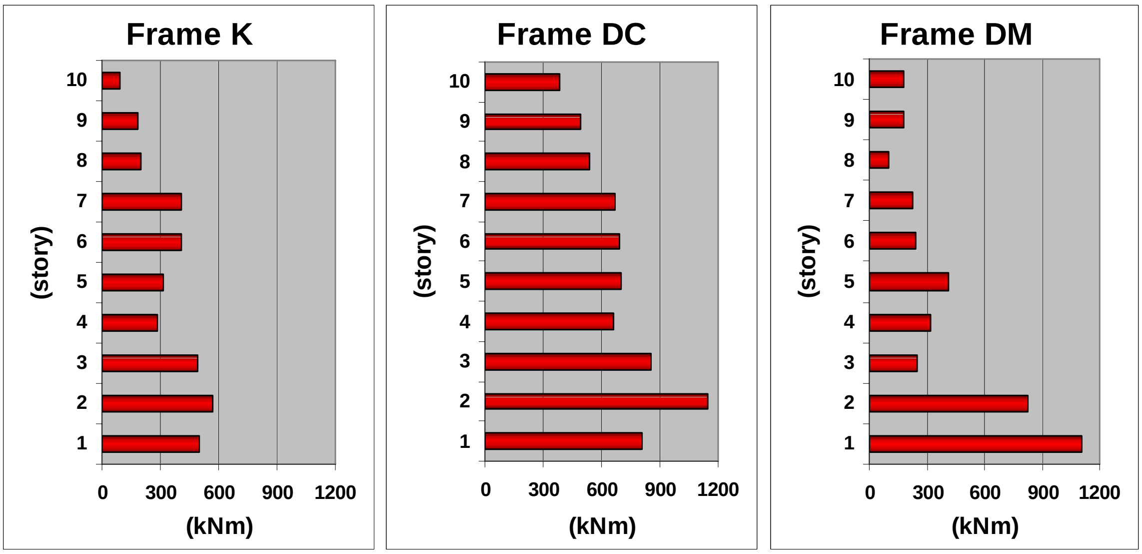


Figure 10. Maximum bending moment values recorded in the central columns

Greater values for the bending moments were noticed in the marginal columns of frame DM, compared to the values obtained in the marginal columns of frame K and DC (see Fig. 11).

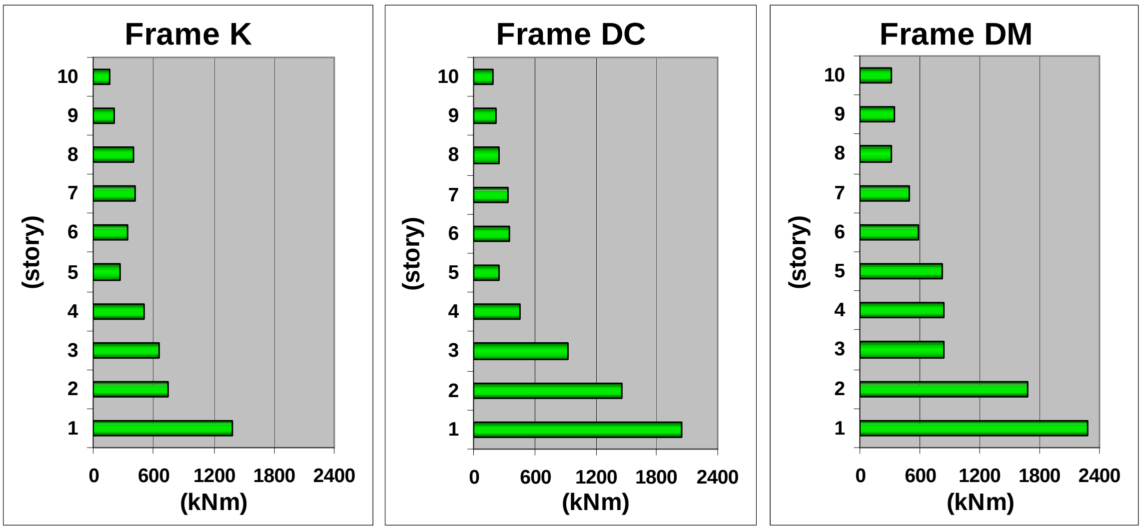


Figure 11. Maximum bending moment values recorded in the marginal columns

It seems that the placement of the dissipative member away from the column, between two braces in the central part of the frames span is favourable for the bending moment stress distribution in the columns. The bending moment values in the columns of frame K were the smallest and frame K had the smallest columns cross-sections from all considered bracing configurations.

In case of frame V and Z with dissipative members located both near the central and marginal columns the maximum bending moment values in the columns are quite in the same range with values recorded for the central columns of frame DC and the lateral columns of frame DM.

2.6. Axial forces in the members of frame DC and frame DM

The bracing configuration of frame DM conducts to greater axial forces in the braces and columns compared to those recorded for frame DC (see Fig. 12). These greater axial forces combined with the greater bending moment values conducted to greater cross-sections for the braces and marginal columns of frame DM, compared to those of frame DC.

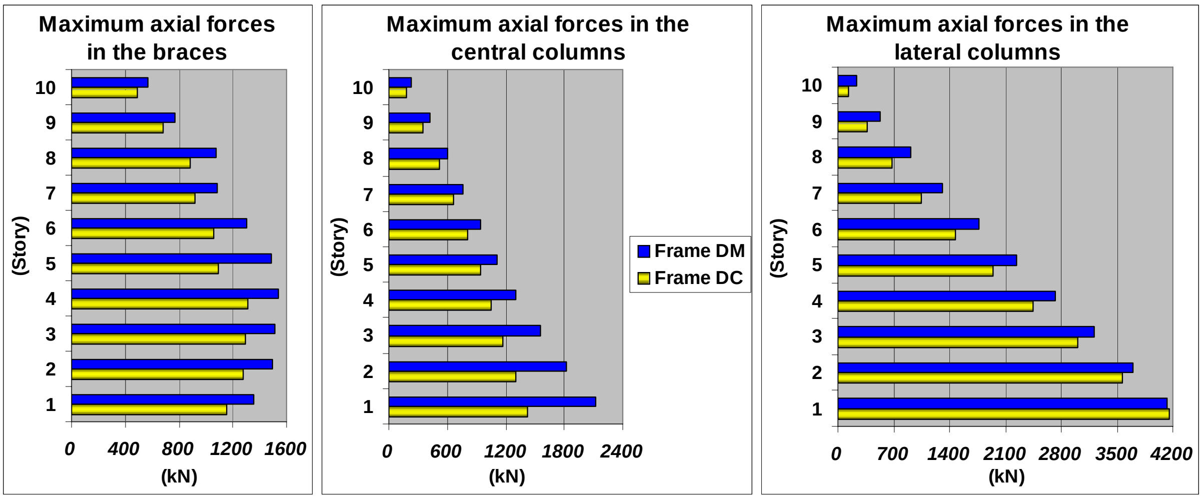


Figure 12: Maximum axial forces recorded during the dynamic nonlinear analyses

2.7. Estimated material consumption

Table 2 contains the values of the estimated steel consumption for all the analyzed frames, taking into account the cross-sections obtained after the dimensioning of the different types of structural elements.

Table 2. Estimated steel consumptions (*kg*)

Element type	Frame K	Frame DC	Frame DM	Frame V	Frame Z	Frame Y
Dissipative members	1686	1782	2184	4446	4386	4736
Adjacent beam segments	10809	11547	14065	10353	10682	20537
Braces	12882	9569	9776	12680	9524	14206
Marginal columns	14815	16243	18441	17719	16276	18793
Central columns	5616	6638	6380	6572	6242	7068
TOTAL	45808	45780	50846	51769	47111	65341

The greatest estimated material consumption was obtained for frame Y, whilst the smallest values did result for frame K and frame DC. The differences of steel consumption between frame Y and frame DC or frame K are in the range of 42%.

Frame K had the smallest cross-sections for the different types of structural elements from all the considered frames, which explains the reduced value of the overall steel consumption. Compared to frame K, in case of frame DC, greater cross-sections were obtained for all kind of structural elements. The smaller number of braces in case of frame DC, conducted to quite the same value of the overall steel consumption as for frame K (see Fig. 13).

The smaller number of braces also explains the smaller material consumption estimated for frame Z, compared to frame V (about 10%).

The estimated steel consumption value for frame DM was about 11% greater than the one calculated for frame DC. Compared to frame DM, in case of frame DC greater cross-sections were obtained only for the central columns., in most cases greater values of bending moments and axial forces were recorded in the braces, marginal columns and adjacent beam segments of frame DM (compared to frame DC). So the cross-sections and the steel consumption were greater for all these elements of frame DM, compared to the corresponding values that were obtained for frame DC.

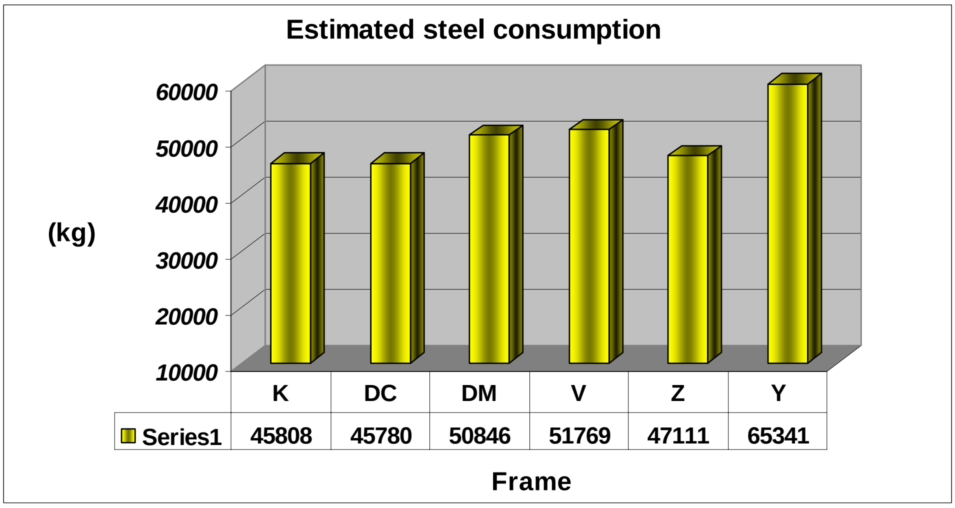


Figure 13: Estimated material consumption

3. GENERAL CONCLUSIONS

Excepting frame Y, all the others considered bracing systems conducted to eccentrically braced frames with a favourable behaviour during the dynamic nonlinear analyses, having the inelastic deformations concentrated only in the potentially plastic zones located in the dissipative members and near the bottom of the first-story columns.

The absence of a favourable global collapse mechanism, conducts after the plastic deformation of the most dissipative members to an unpredictable behaviour of frame Y.

The DC and DM bracing configurations led to the smallest remaining floor deformations after the dynamic nonlinear analyses. The smallest inelastic deformations were recorded in case of frame V.

The placement of the dissipative members near the columns leads to greater values of the bending moments in the columns. The bracing configuration of frame K (with the dissipative members placed away from the columns, in the middle of the girders span) conducts to the smallest member forces and to smaller cross-sections for all kind of structural elements (columns, braces, dissipative members and adjacent beam segments).

Taking into consideration the behaviour during the dynamic nonlinear analyses, the material consumption and the stress distribution among the different types of structural elements the bracing configurations of frame K and DC appear the most advantageous.

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