Comments about Aseismic Diagonal Bracing Systems

H.Köber
Technical University of Civil Engineering Bucharest, Steel Structures Department, Romania

M.Stoian
Technical University of Civil Engineering Bucharest, Department of Construction Management, Romania

SUMMARY:
Four diagonal centrically bracing systems frequently used in seismic resistant structures were considered. Two frames with ten and six stories were analyzed for each considered bracing configuration. The distribution of the axial forces and bending moments among the different structural elements, the values of the lateral floor deformations and the estimated steel consumption were analyzed. Dynamic nonlinear analyses were performed with each frame. The history of the formation of plastic hinges was observed, the maximum inelastic deformations, the extreme values of the horizontal displacements and of the base shear forces were compared.

Keywords: diagonal bracings, member forces distributions, dynamic nonlinear analysis, inelastic deformations.

1. INTRODUCTION

The present paper is intended to point out some advantages and disadvantages of different diagonal bracing configurations used in centrically braced frames located in seismic areas.

1.1. Description of the analyzed frames

Eight centrically braced frames (four ten story frames and four six story frames) were sized for the same seismic action, evaluated according to the prescriptions of EN 1998-1 (Eurocode 8: Design of structures for earthquake resistance- Part 1: General rules, seismic actions and rules for buildings) and the in charge Romanian seismic design code.

The story height for each of the analyzed frames was 3.5m and the span length was 6.0m (see Fig. 1).

All structural members (braces, beams and columns) had built up I-shaped cross-sections sized according to the provisions of EN 1993-1-1 (Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings).

1.2. Comments about the seismic design procedure

An alternative seismic design procedure was used in order to size by design a favourable global plastic failure mechanism for the centrically braced frames with the compressed braces buckled mainly in the elastic range of behaviour, with yielding tensioned braces and with controlled inelastic deformations in the potentially plastic zones located near the bottom of the first story columns and in the girders in the neighborhood of the bolted spliced connections with the diagonals (see Fig. 2).

The cross-sections of the braces were designed for the forces generated by code seismic actions, F_{CODE}. The value of the code seismic lateral load was evaluated considering the prescriptions of the in charge Romanian Seismic Design Code, P100-2006 (Code for aseismic design - Part I - Design prescriptions for buildings, P100-1/2006).

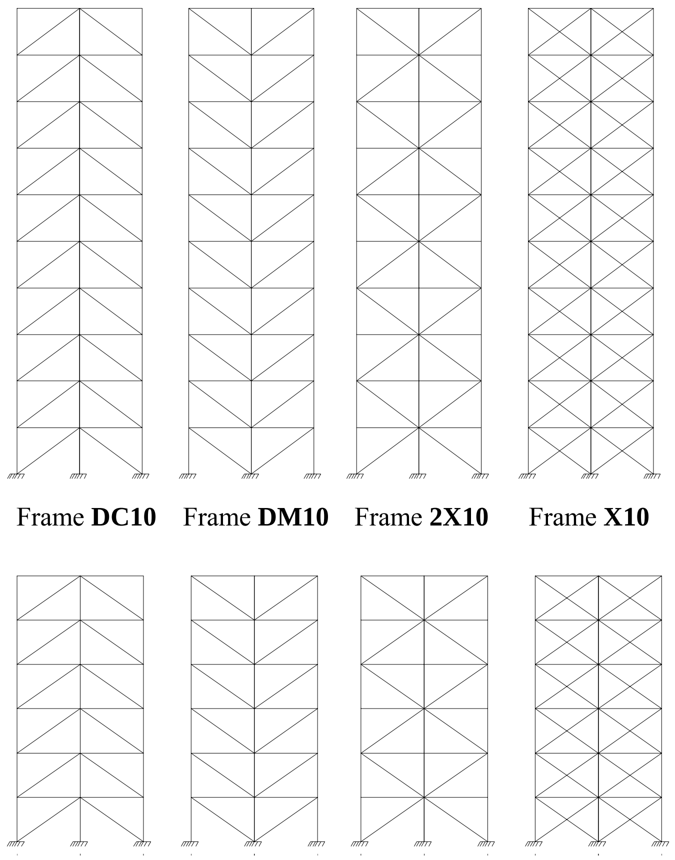
The cross-sections of the potentially plastic zones located in the girders were dimensioned for the forces generated by an increased seismic action $F_{FRAME}^{(N)}$. The potentially plastic zones in the girders are located near the connections with the diagonals (see Fig. 2). The columns and beam segments placed outside the potentially plastic zones were sized for the forces produced by a further amplified seismic load $F_{FRAME}^{(M,N)}$.

$$F_{FRAME}^{(N)} = 1.1 \cdot \gamma_{OV} \cdot \Omega^{(N)} \cdot F_{CODE} \quad (1.1)$$

$$F_{FRAME}^{(M,N)} = 1.1 \cdot \gamma_{OV} \cdot \Omega^{(M)} \cdot F_{FRAME}^{(N)} \quad (1.2)$$

Where:

- $\gamma_{OV} =$ over strength factor; according P100-2006 and Eurocode 8: $\gamma_{OV} = 1.25$;
- $\Omega^{(N)} =$ minimum value of $\Omega_i^{(N)} = N_{pl,Rd,i} / N_{Ed,i}$ calculated for all the diagonals of the braced frame; $N_{pl,Rd,i} =$ the design resistance of diagonal „ i ”; $N_{Ed,i} =$ the design value of the axial force in the same diagonal „ i ” in the seismic design situation.
- $\Omega^{(M)} =$ minimum value of $\Omega_i^{(M)} = M_{pl,Rd,i} / M_{Ed,i}$ calculated for all potentially plastic zones located in the girders of the centrically braced frames; $M_{Ed,i} =$ design value of the bending moment in the potentially plastic zone „ i ” in the seismic design situation; $M_{pl,Rd,i} =$ the corresponding bending moment capacity.



Frame **DC06** Frame **DM06** Frame **2X06** Frame **X06**

Figure 1. Analyzed diagonal braced frames

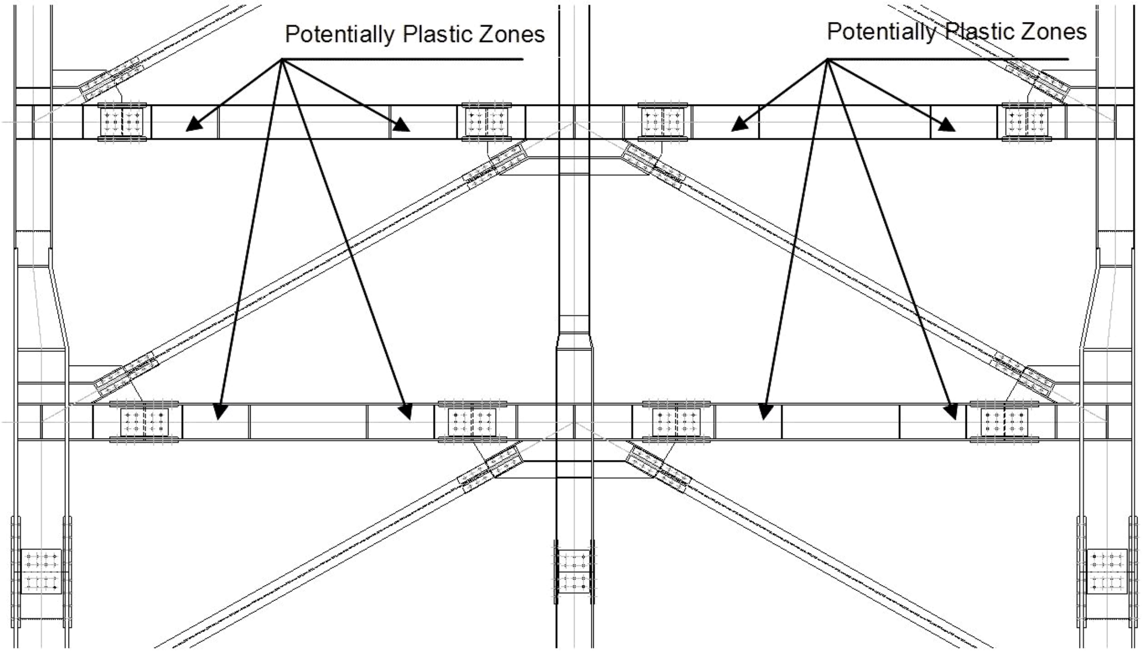


Figure 2. Location of the potentially plastic zones in the girders of a braced frame

The forces used for the design of the girders and columns are obtained from static linear analyses on a structure having the braces modeled with a reduced axial stiffness. The materials considered in the braces had reduced values for the modulus of elasticity: $E_1 \cong 0.5 \cdot E = 1.05 \cdot 10^5 N/mm^2$ for tensioned diagonals and $E_2 \cong \chi_{MEDIUM} \cdot E_1 \cong 0.335 \cdot E_1 = 0.35 \cdot 10^5 N/mm^2$ for the compressed diagonals. $E = 2{,}1 \cdot 10^5 N/mm^2$ is the Young modulus of steel and χ_{MEDIUM} is the average value of the buckling factors values obtained for all the diagonals of the braced frame.

1.3. Dynamic nonlinear analyses

A dynamic nonlinear analysis was performed with each frame using the same base excitations, namely the N-S component of the Vrancea earthquake from 04.03.2011. Drain 2D+ computer program was used for these analyses.

The peak ground acceleration of the record was calibrated to about 0.24 times the acceleration of gravity. 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. Damping was taken into account using the Rayleigh procedure, considering mass and stiffness proportional damping factors. These factors were calculated using the periods of the first and the third eigenmodes.

2. REMARKS AND COMMENTS

2.1. Axial forces in structural members caused by the horizontal seismic action

For both groups of analyzed frames (ten storey and six storey), the greatest values of the average axial forces caused by the seismic action in the lateral columns can be noticed in the case of the DM10 and DM06 frames, respectively, while the smallest ones are on the frames DC10 and DC06. This can be explained by the fact that the values of the axial forces generated by the horizontal seismic forces in the lateral columns are proportional to the values of the global bending moment (the overall bending moment which is acting on the whole frame).

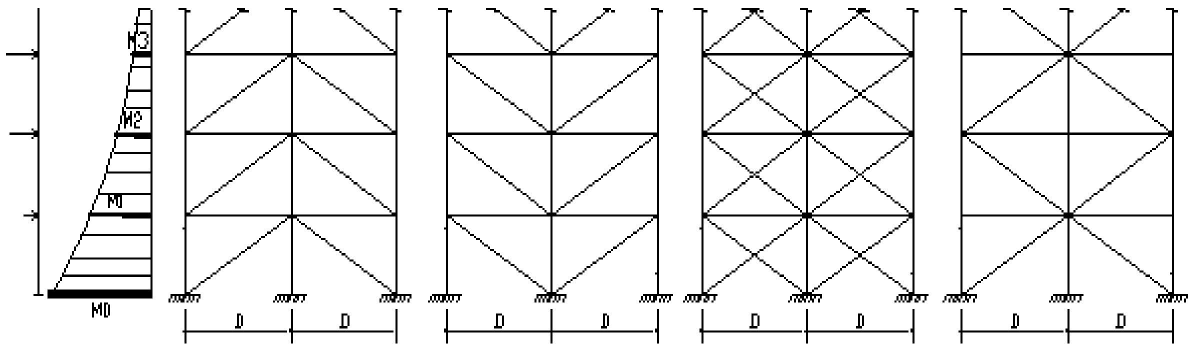


Figure 3. Lateral column axial forces caused by the horizontal seismic action

The following equilibrium relations can be written at the bottom of the lateral columns (see Fig. 3):

$$\left.\begin{array}{l} N_{bottom}^{DM} \cong \dfrac{M_0}{2 \cdot D} \\ M_0 > M_1 \\ N_{bottom}^{DC} \cong \dfrac{M_1}{2 \cdot D} \end{array}\right\} \Rightarrow N_{bottom}^{DM} > N_{bottom}^{DC} \quad (2.1)$$

Where: M_0 is the global bending moment at the bottom of the frame; M_1 is the global bending moment of the frame at the bottom of the first story; D is the span of the frame.

Table 1. (10pt bold) Data For Beams Under Dynamic Loading (10 pt regular)

Story	Frame							
	DC10	DM10	2X10	X10	DC06	DM06	2X06	X06
1	4117.03	4566.29	4109.47	4359.03	1422.92	1736.84	1418.56	1578.72
2	3470.42	4062.62	4076.53	3754.24	1022.81	1392.65	1397.01	1199.59
3	2839.67	3422.86	2824.59	3112.67	669.31	995.6	665.2	822.52
4	2217.19	2794.23	2794.73	2476.50	365.11	650.01	650.58	500.74
5	1669.24	2176.86	1661.14	1908.33	140.18	348.59	138.74	240.68
6	1165.47	1633.18	1635.55	1387.45	4.98	129.65	130.22	65.64
7	740.63	1131.64	735.90	924.18	-	-	-	-
8	393.17	718.12	718.84	547.83	-	-	-	-
9	147.05	374.64	145.51	256.77	-	-	-	-
10	5.19	135.77	136.40	68.67	-	-	-	-

Analyzing the values in Table 1, the following observations can be made about the values of the axial forces in the lateral columns generated by the horizontal seismic action:
- the values of the axial forces for the X-bracing configuration are smaller than those obtained for the DM-bracing, but greater than those noticed for the DC-bracing;
- for the uneven storey, the values of the axial forces are quite the same for the DC- and 2X- bracing systems (see the graphics in Fig. 4);
- in the case of the DM- and 2X-bracing configurations, the values of the axial forces are in the same range for the even storey;
- these values are more scattered in the case of six storey frames, as the difference between the values of the global bending moments on two consecutive storey is bigger in this case.

The axial forces caused in the braces by the conventional seismic action are quite similar for the DC10, DM10 and 2X10, respectively DC06, DM06 and 2X06 and they are greater than the ones for X10 and X06, respectively, by 45%. The greater number of diagonals in the case of the X-bracing system explains these smaller values.

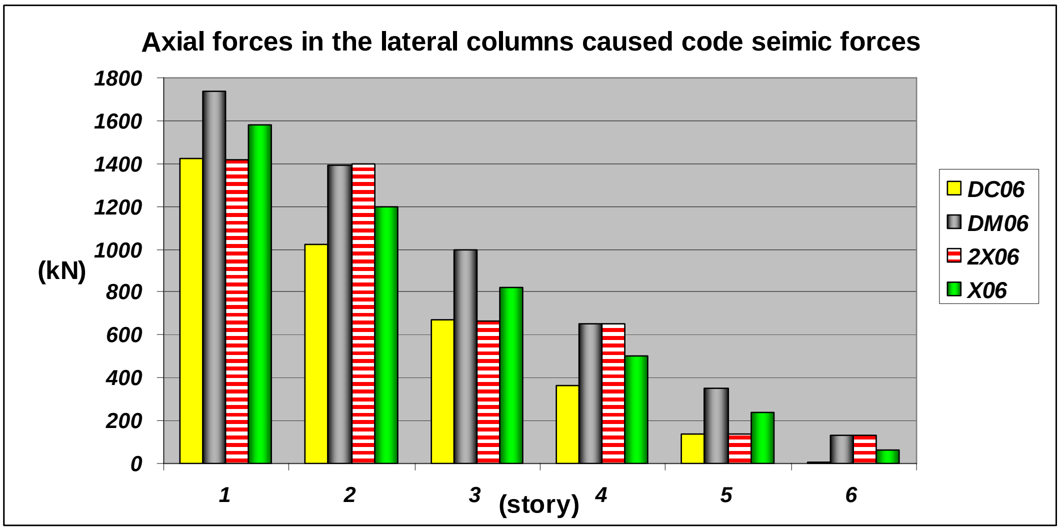
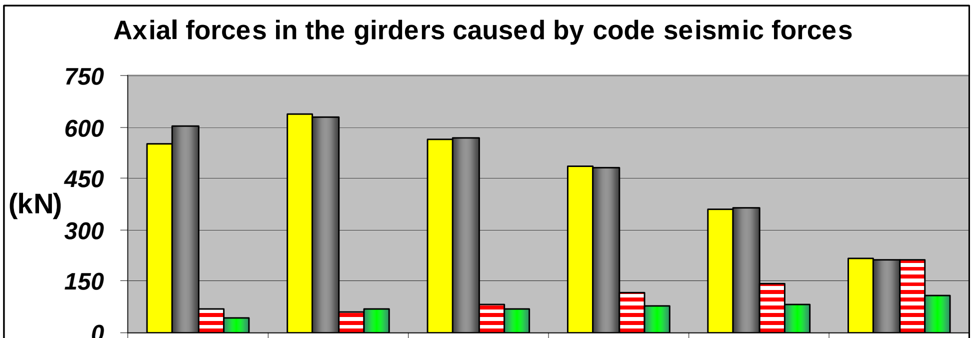


Figure 4. Axial forces in the lateral columns produced by code seismic forces

The greatest axial forces in the girders caused by horizontal seismic forces could be noticed for the DM and DC frames, whilst the smallest ones were noticed for the X braced frames. The values are (comparing to the X-braced frames) up to eight times greater for the ten storey frames and over six times bigger for the six storey frames. The axial forces in the girders of the 2X-braced frames are between 20÷50% greater than the ones noticed for the X-braced frames (see Fig. 5).

The shortening, respectively lengthening of the lateral columns caused by the horizontal seismic forces is affecting the values of the axial forces in the braces. If the “node isolation method” is applied in case of the DM- and DC-braced frames, it can be noticed that the horizontal components of the axial forces in the diagonals will be balanced by axial forces in the girders, whilst the vertical components will be balanced by the axial forces that appear in the columns.



	1	2	3	4	5	6
DC06	551.35	639.00	564.06	487.1	357.72	214.76
DM06	601.82	628.04	567.84	479.23	362.5	213.34
2X06	67.94	60.02	81.27	118.37	143.51	212.85
X06	45.32	68.66	70.71	77.05	81.48	108.07

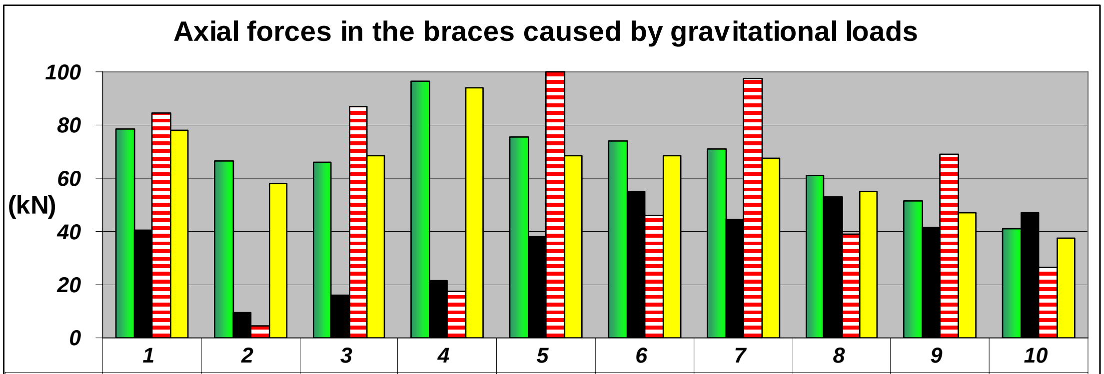
Figure 5. Axial forces in the girders generated by the horizontal seismic action

In the case of the X frames, on one hand, two braces are intersecting each other at each floor on the lateral columns and are carrying together the axial forces generated by the shortening or lengthening of the column. On the other hand, four braces are crossing each other at every floor level on the central column of the X-braced frames. The forces in all these braces, which are intersecting each other, are partially balancing each other directly and the girders have to carry a smaller horizontal component of the axial forces from the diagonals. For the 2X-braced frames this happens only at every second floor.

In the case of the DM- and DC-bracings, the forces in the braces on two consecutive storeys are not conditioning each other directly and the horizontal forces in the girders will be greater.

2.2. Axial forces in structural members caused by gravitational loads

Under the action of gravitational loads all columns and braces are subjected to compression axial forces. The axial forces caused in the braces by the gravitational loads are up to ten times smaller in each case compared to the ones caused by code seismic loads.



	1	2	3	4	5	6	7	8	9	10
DC10	78.32	66.28	66.11	96.65	75.74	73.93	71.25	61.25	51.36	41.06
DM10	40.65	9.55	16.19	21.48	37.81	54.84	44.35	52.93	41.43	46.80
2X10	84.73	4.70	86.84	17.58	99.98	46.20	97.37	38.90	68.80	26.50
X10	78.05	58.16	68.38	93.80	68.75	68.67	67.75	55.17	47.00	37.67

Figure 6. Compression forces in the braces caused by gravitational loads

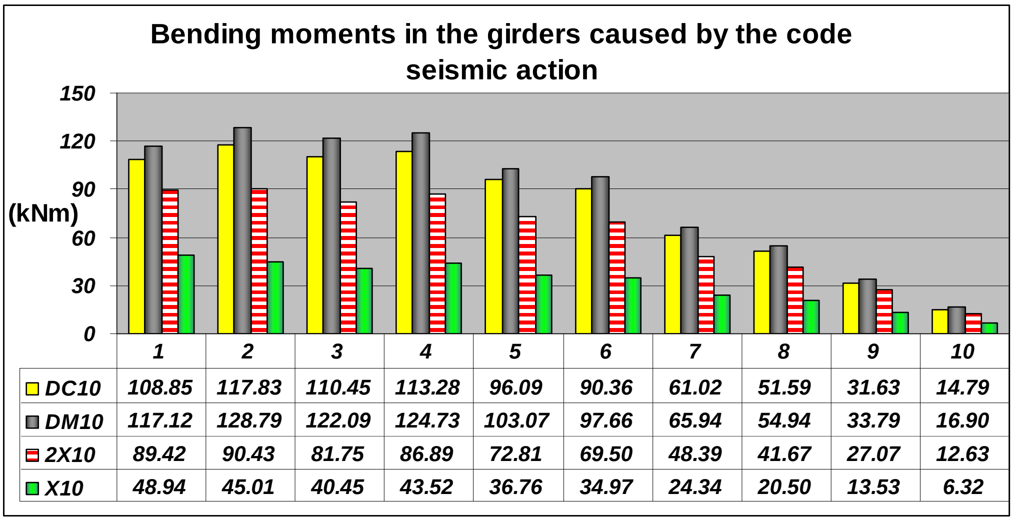
The more important shortening of the central column (when subjected to gravitational forces), compared to the one of the lateral columns, increases the compression in the braces for the DC-braced frames, and reduces the value of the axial compression forces in the braces of DM-braced frames.

The differenced shortening of the columns under gravitational loads explains the following remarks made by analyzing the values of the axial forces in the braces (see the graphics in Fig. 6):
- the forces in the diagonals of the DC-braced frames are smaller than the ones in the DM-frames;
- for the uneven storey, the greatest axial forces in the braces are obtained for the 2X frames;
- for the even storey, the smallest axial forces are noticed in the braces of the 2X-braced frames.

2.3. Bending moments in structural members caused by the horizontal seismic action

The greater number of braces, in the case of X10 and X06 frames, reduces the deformability of these frames when subjected to horizontal loads. Following this, the seismic action causes the smallest bending moments in the columns and girders of the X-braced frames among the four types of analyzed configurations.

The greatest bending moments caused by the seismic action can be noticed in most cases in the members on DM10 and DM06 frames. Only in some inferior storey columns the greater values of the bending moments were recorded for the DC-braced frames. The lateral stiffness is smaller for the frames DC10 and DC06 than for 2X10 and 2X06, respectively, which leads to smaller values of the bending moments in all kind of structural members.

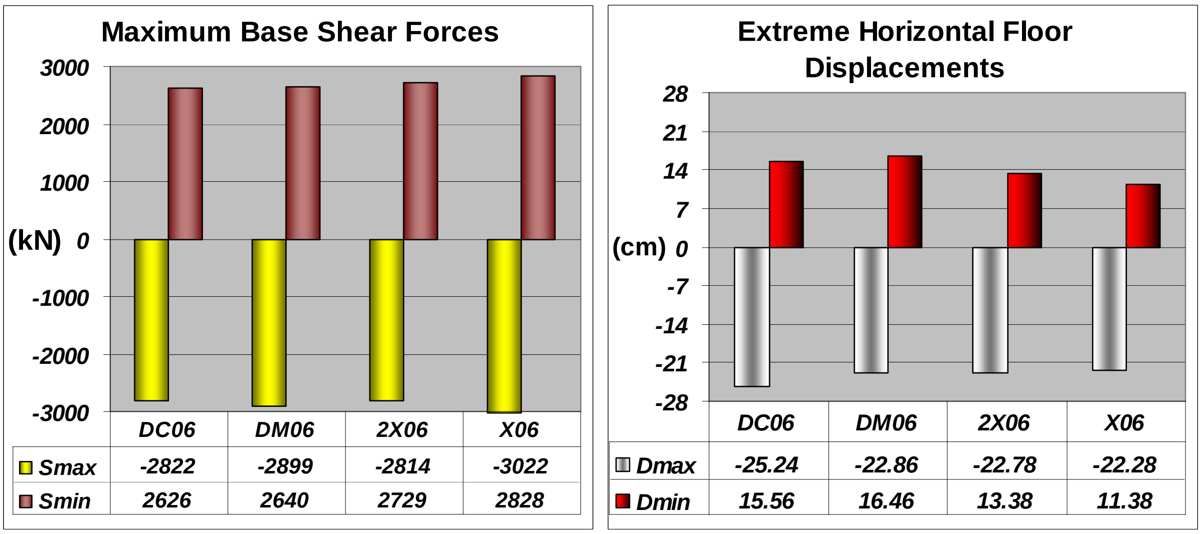


	1	2	3	4	5	6	7	8	9	10
DC10	108.85	117.83	110.45	113.28	96.09	90.36	61.02	51.59	31.63	14.79
DM10	117.12	128.79	122.09	124.73	103.07	97.66	65.94	54.94	33.79	16.90
2X10	89.42	90.43	81.75	86.89	72.81	69.50	48.39	41.67	27.07	12.63
X10	48.94	45.01	40.45	43.52	36.76	34.97	24.34	20.50	13.53	6.32

Figure 7. Bending moments in the girders caused by the horizontal seismic action

3. BEHAVIOUR DURING DYNAMIC NONLINEAR ANALYSES

Greater base shear forces and smaller horizontal floor displacements were recorded during the dynamic nonlinear analyses for the X-braced frames, compared to the values recorded for the other analyzed frames.



	DC06	DM06	2X06	X06
Smax	-2822	-2899	-2814	-3022
Smin	2626	2640	2729	2828

	DC06	DM06	2X06	X06
Dmax	-25.24	-22.86	-22.78	-22.28
Dmin	15.56	16.46	13.38	11.38

Figure 8. Extreme values for base shear forces and horizontal floor displacements recorded during the dynamic nonlinear analyses

All the analyzed structures had a favourable behaviour under the dynamic nonlinear analyses. No plastic deformations could be observed in unwanted areas. Inelastic deformations appeared only in the braces and in the potentially plastic zones located in the girders and near the bottom of the first story columns (see Fig. 9).

The maximum plastic deformations recorded in the braces during dynamic nonlinear analyses were observed in the lower storey of frame DC10 and frame X10, respectively in the upper storey of frame DM10 (see the values and graphics in Fig. 10).

All the I-shaped cross-sections of the diagonals where placed whit the web orientated normally to bracing plane in order to avoid out of plane buckling of the diagonals. The values of the braces slenderness factors were sized so that the in plane buckling of the diagonals would occur mainly in the elastic range of behaviour. The braces were modeled for the nonlinear analyses as elements that could yield under tension and buckle under compression in the elastic range. So the diagonals did not suffer any plastic deformations when subjected to compression, only inelastic deformations under tension were recorded for the braces.

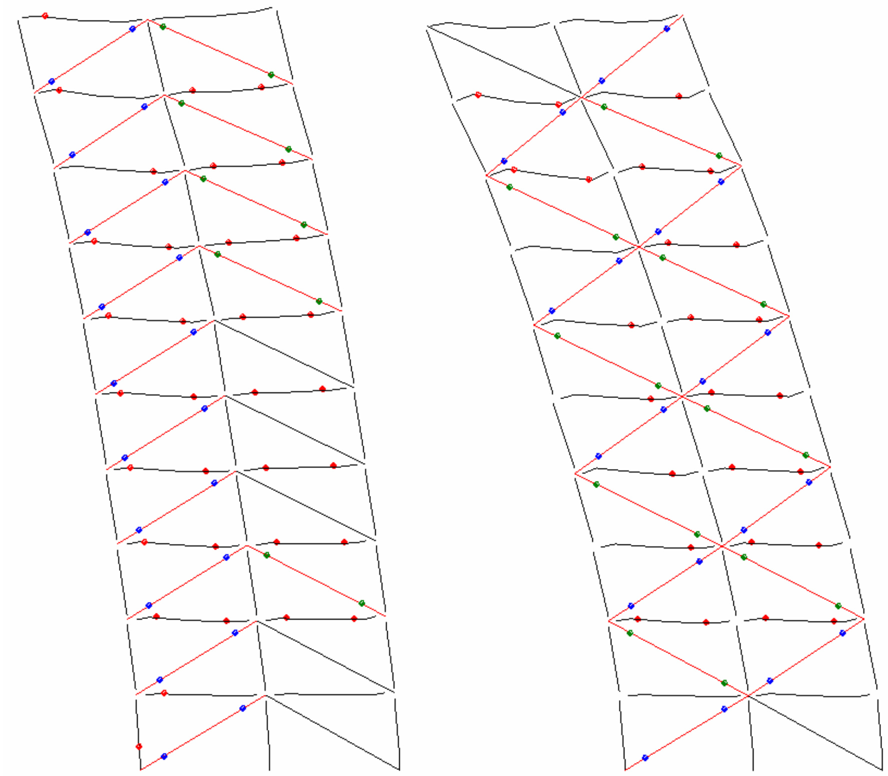
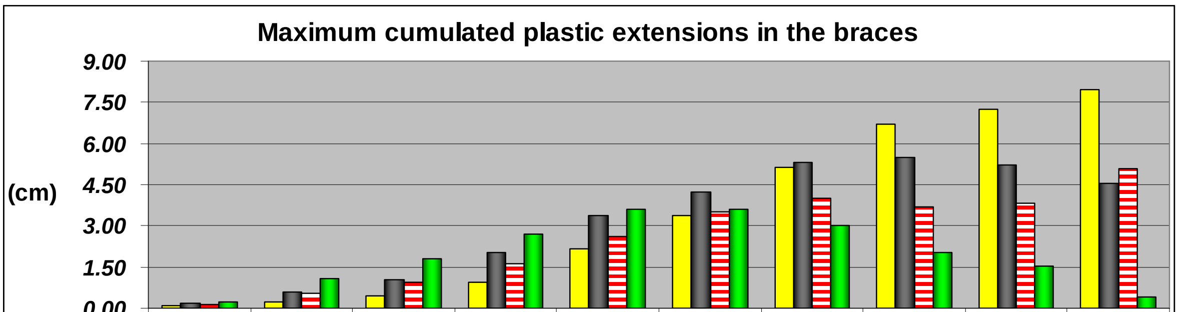


Figure 9. Plastic hinge distributions at 7.02 seconds from the start of the dynamic nonlinear analyses



(Story)	1	2	3	4	5	6	7	8	9	10
DM10	0.08	0.21	0.46	0.94	2.15	3.36	5.11	6.69	7.23	7.96
DC10	0.16	0.59	1.04	2.01	3.39	4.25	5.33	5.49	5.24	4.53
2X10	0.13	0.55	0.94	1.63	2.62	3.51	4.00	3.71	3.83	5.08
X10	0.22	1.09	1.81	2.69	3.59	3.61	3.00	2.01	1.55	0.39

Figure 10. Maximum cumulated inelastic lengthening of the braces recorded after the dynamic nonlinear analyses

The girders and columns of the frames where modeled as elements that could yield/ buckle under the combined action of the bending moment and axial force. The greatest plastic hinge rotations recorded in the potentially plastic zones located in the girders (see Fig. 11) were noticed in the lower storey of frame X10 and in the upper storey of frame DM10.

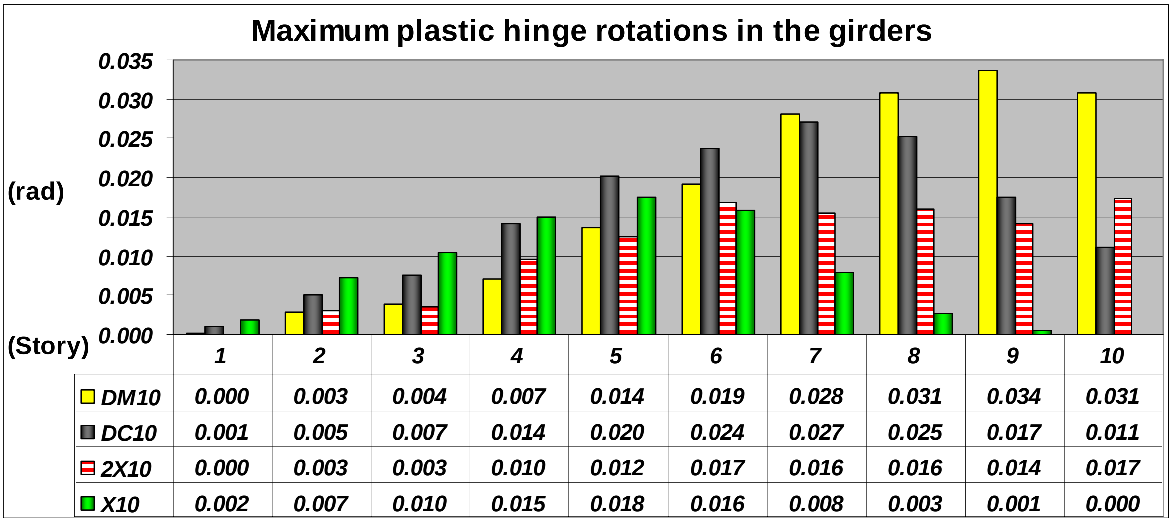


Figure 11. Maximum plastic hinge rotations in the girders recorded during the dynamic nonlinear analyses

The greatest inelastic deformations in the braces and girders were noticed in the upper storey for frame DM10, in the middle part for frame DC10 and in the lower storey for frame X10. The inelastic deformations observed for the frames equipped with 2X-bracings are in most situations greater than those recorded for the X-braced frames, but smaller than the one noticed for the DM- and DC-frames.

Comparing the maximum values, the greatest plastic deformations where noticed for the DM-braced frames, whilst the smallest where recorded for the frames with an X-bracing configuration.

4. ESTIMATED MATERIAL CONSUMPTION

The two families of frames were sized for similar values of the seismic action. When determining the loading state, similar cross-sections were used for each type of structural member in a family, to avoid the influence of the sizing skill of the designer.

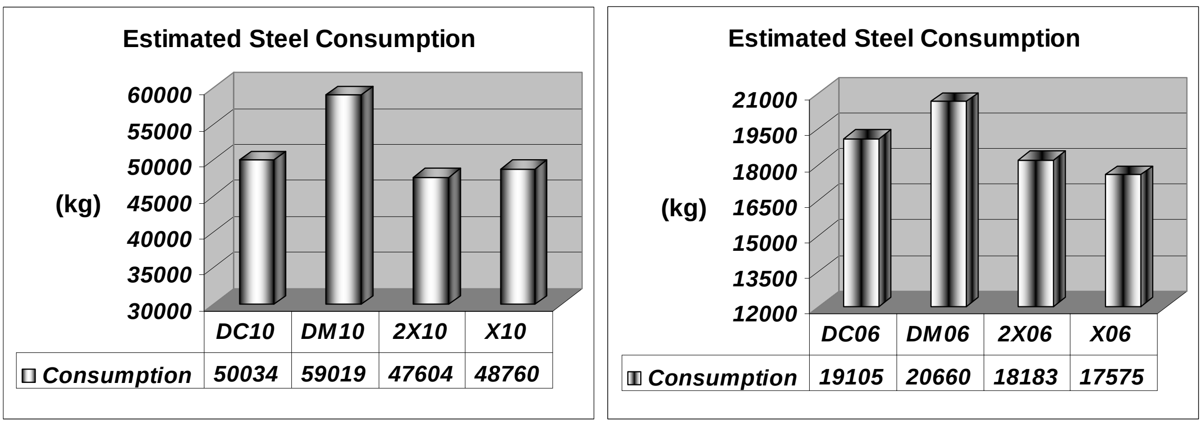


Figure 12. Estimated material consumption

The smallest material consumption was obtained for the 2X (2X10 and 2X06) and for the X (X10 and X06) frames, whilst the greatest one was noticed for the DM (DM10 and DM06) frames. In the case of the 10 storey frames, frame DM10 requires about 24% more material than 2X10 and X10, whilst DC10 requires 17% more (than 2X10 and X10). For the 6 storey frames, DM06 uses about 17% more steel and DC06 requires about 8% more than 2X06 and X06.

The smaller material consumption obtained for the X- and 2X-braced frames can be explained by the smaller member forces and smaller cross-sections obtained for the girders and columns of the frames having X or 2X-bracings, compared to those equipped with a DC- or DM-bracing system.

4. GENERAL CONCLUSIONS

The smallest inelastic deformations are recorded in most the girders and diagonals of the X-braced frames. Taking into account the smaller axial forces and bending moments obtained in most cases for all kind of structural members the X-bracing system appear to be the most advantageous for the distribution of forces among the different structural components. The main disadvantage of the X-bracing configuration consists in the difficulty of the emplacement of door and window openings.

In most cases the greatest inelastic deformations recorded in the braces and girders were noticed for the frames equipped with a DM- or DC-bracing configuration. These two bracing systems lead to greater values of the estimated steel consumption.

The bracing configuration of the DC-frames is more favorable than the one of the DM-frames, because it conducts, in most cases, to smaller axial forces and bending moments in the frame girders and lateral columns. The axial forces in the diagonals of the DC-braced frames are greater than those obtained for the DM- braced frames. On the other hand smaller axial forces were recorded in the central column of the DC-frames compared to the one noticed in case of the DM-frames.

The 2X-bracing configuration combines somehow the advantages of the DC- and DM-bracing systems regarding the distribution of member forces and avoids the disadvantage of the X-bracing configuration concerning the emplacement of door and window openings.

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 X- and 2X-bracing configurations appear the most favourable.

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