TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

DOCTORAL SCHOOL

RESEARCH REPORT NUMBER THREE
COMPARATIVE ANALYSES OF DIFFERENT CONSTRUCTIVE SOLUTIONS FOR CONCENTRICALLY BRACED FRAMES

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Content:

The present research report aims to point out through comparative analyses, the seismic behaviour of steel structures equipped with the concentrically braced frames with different constructive configurations.

In the first part of this research report, the influence of hinged and fixed connections for diagonals and girders have been analyzed comparatively on the same structural systems (a concentrically braced frame with six and ten storeys, provided whit the DM-bracing configuration, having descending diagonals from the lateral columns to the central column).

In the second part of this research report, the influence of the location of additional potentially plastic zones along the girders on the seismic behaviour of concentrically braced frames was analyzed. The location of potentially plastic zones along the girders were considered in two situations, located at approximately 1.0 m and respectively 2.0 m from de frame columns axes. Fixed connections were used among the elements of the analyzed concentrically braced frames.

1 Different connections solutions for diagonals and girders

Two structure with six and respectively ten storeys located in Bucharest, Romania were considered, having two spans and four bays of 6.0m, as indicated in Fig. 1.1.

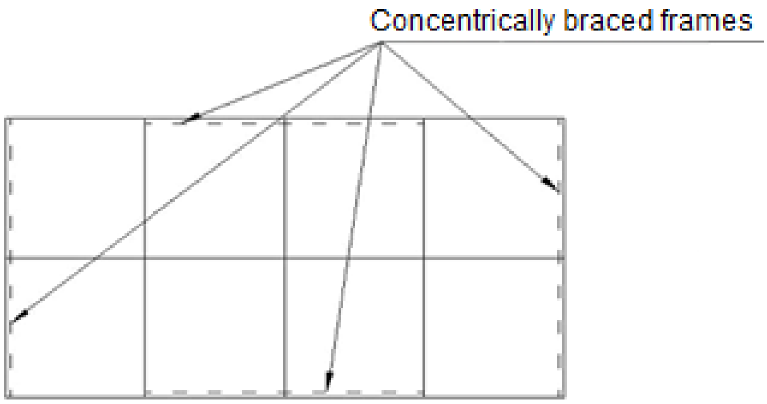


Fig. 1.1 Plan view of the structure with the location of the braced frames

The storey height for each of the analyzed frames was 3.5m.

All structural members (diagonals, girders and columns) had built up I-shaped cross-sections, sized according to the prescriptions of SR EN 1993-1-1 [3]. The webs of the braces cross-sections were rotated normally to the plane of the frame [6], in order to avoid out-of-plane buckling of the diagonals.

Each of the analyzed concentrically braced frames, was dimensioned in three constructive variants, depending on the connection type among the different categories of structural elements:

Variant A - the frames with hinged connections for diagonals and beams.

Variant B - the frames with hinged connections for diagonals and fixed connections for beams.

Variant C - the frames with fixed connections for diagonals and beams.

„Frame A" was configured according to variant A, „Frame B" was the one realized according to variant B and „Frame C" was configured according to variant C. A six storey and respectively a ten storey frame was considered for each of the three analyzed constructive variants.

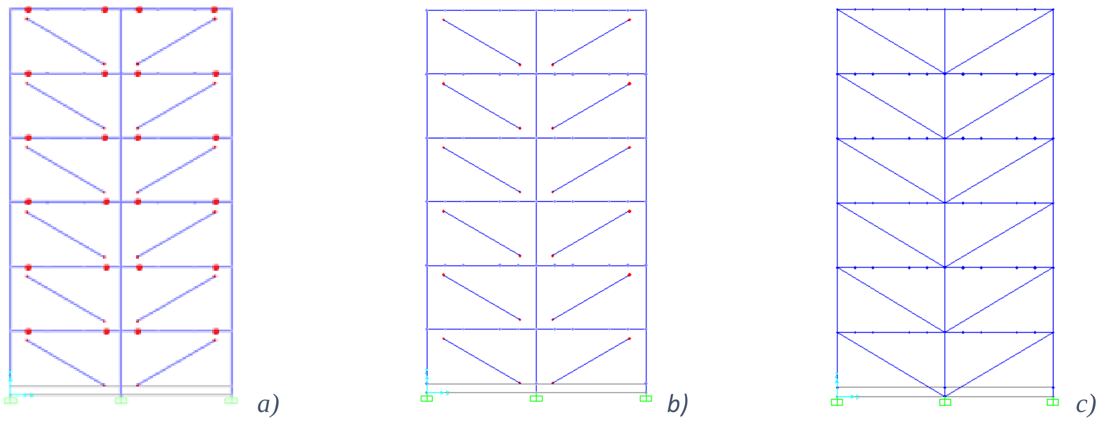


Fig. 1.2 Analyzed frames with six storeys: a) Frame A, b) Frame B, c) Frame C

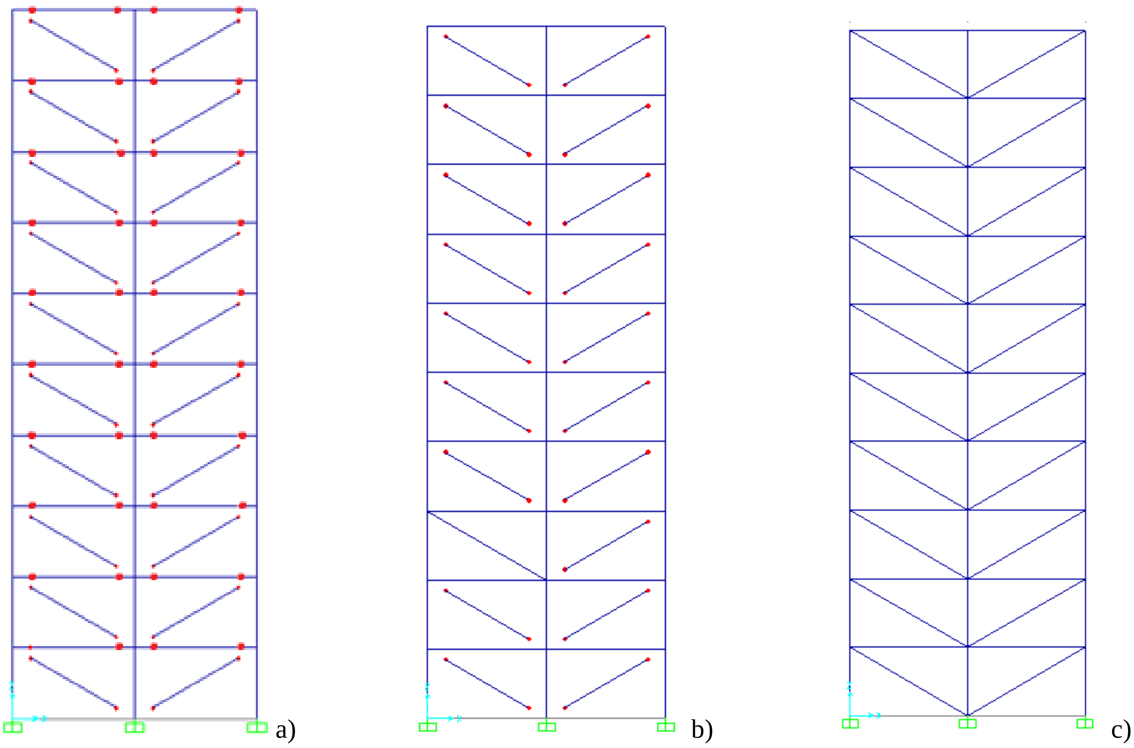


Fig. 1.3 Analyzed frames with ten storeys: a) Frame A, b) Frame B, c) Frame C

The seismic design procedure was as follows:

a) *For the Frames A (with hinged connections for diagonals and girders):*

– The diagonals of the concentrically braced frames were sized as primary dissipative elements for the forces generated by the non-amplified seismic design force (Scode). For these designed braces cross-sections an amplification factor of the seismic forces was evaluated (Ω^N).
$\Omega^N = \min\{\Omega^N{}_i\}$; $\Omega^N{}_i = N_{pl,Rd,i}/N_{Ed,i}$;

– The cross-sections of the beams were dimensioned for the forces produced by an amplified seismic load: $1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot$ Scode or by the forces generated by the fundamental combinations of actions;

– The cross-sections of the columns were dimensioned for the forces produced by an even more amplified seismic load: $1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot 1.1 \cdot \gamma_{ov} \cdot 1.05 \cdot$Scode (in order to ensure an over-strength of the columns compared to the beams when subjected to severe seismic actions).

b) For the Frames B and C:

– At first the diagonals were sized as primary dissipative elements for the forces generated by the non-amplified seismic design load (Scode). Then an amplification factor (Ω^N) was evaluated for the designed cross-sections of the diagonals.
$\Omega^N = \min\{\Omega^N_i\}$; $\Omega^N_i = N_{pl,Rd,i}/N_{Ed,i}$;
– Secondary dissipative elements (potentially plastic zones with reduced cross-sections [6], located along the frame girders) were sized for the forces produced by an amplified seismic load: $1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot$ Scode [7]. For the cross-sections of these potentially plastic zones an additional amplification factor (Ω^M) was evaluated.
$\Omega^M = \min\{\Omega^M_i\}$; $\Omega^M_i = M_{pl,N,Rd,i}/M_{Ed,i}$;
– The cross-sections of the columns and beam segments outside the potentially plastic zones were dimensioned for the forces produced by an even more amplified seismic load [8]: $1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot 1.1 \cdot \gamma_{ov} \cdot \Omega^M \cdot$Scode.

1.1 Seismic behaviour of the concentrically braced frames with six storeys

In the following figure the first three modal periods for the analysed frames are shown:

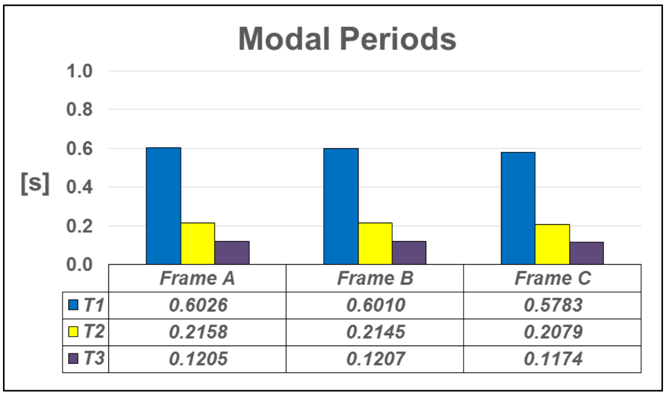


Fig. 1.4 The modal periods for the frames with six storeyed

It can be seen that the smallest modal periods were obtained for the Frame C, this frame being the most rigid. The Frame A proves to be the most flexible because the largest values of modal periods have been recorded (see Fig. 1.4).

For each considered constructive variant, the following cross-sections resulted from the design process frames for the main categories of structural elements:

	DIAGONALS		GIRDERS		CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	160 x 5	170 x 10	280 x 9	220 x 18	650 x 20	500 x 40	800 x 25	600 x 40
2	190 x 6	220 x 14	350 x 12	250 x 20	650 x 20	500 x 40	800 x 25	600 x 40
3	190 x 6	220 x 14	350 x 12	250 x 20	500 x 15	400 x 25	500 x 15	400 x 25
4	180 x 6	210 x 12	330 x 10	220 x 20	500 x 15	400 x 25	500 x 15	400 x 25
5	160 x 5	170 x 10	280 x 9	220 x 18	500 x 15	400 x 25	400 x 12	400 x 20
6	150 x 5	160 x 9	260 x 8	200 x 18	500 x 15	400 x 25	400 x 12	400 x 20

Tab. 1.1 Sections for Frame A

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	180 x 6	160 x 10	400 x 10	340 x 20	180 x 20	650 x 20	450 x 40	800 x 25	550 x 40
2	180 x 6	190 x 12	400 x 12	360 x 25	190 x 25	650 x 20	450 x 40	800 x 25	550 x 40
3	180 x 6	160 x 12	400 x 12	360 x 20	180 x 20	450 x 14	400 x 25	500 x 15	400 x 30
4	180 x 6	160 x 12	360 x 10	340 x 20	180 x 20	450 x 14	400 x 25	500 x 15	400 x 30
5	150 x 5	150 x 9	300 x 9	260 x 16	130 x 16	400 x 12	400 x 20	400 x 12	400 x 20
6	150 x 5	150 x 9	220 x 7	180 x 14	100 x 14	400 x 12	400 x 20	400 x 12	400 x 20

Tab. 1.2 Sections for Frame B

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	180 x 6	180 x 12	400 x 10	330 x 20	180 x 20	600 x 20	450 x 40	750 x 25	550 x 40
2	190 x 6	220 x 12	400 x 12	350 x 25	180 x 25	600 x 20	450 x 40	750 x 25	550 x 40
3	180 x 6	180 x 12	400 x 12	350 x 20	180 x 20	400 x 14	400 x 25	550 x 15	400 x 30
4	180 x 6	180 x 12	360 x 10	330 x 20	180 x 20	400 x 14	400 x 25	550 x 15	400 x 30
5	150 x 5	160 x 9	310 x 9	240 x 16	120 x 16	400 x 12	350 x 20	400 x 12	350 x 20
6	150 x 5	160 x 9	220 x 7	160 x 14	100 x 14	400 x 12	350 x 20	400 x 12	350 x 20

Tab. 1.3 Sections for Frame C

1.1.1 Extreme values for base shear forces and horizontal displacements

In most situations, the largest horizontal floor displacements during dynamic nonlinear analyses were recorded in case of Frame A, while the smallest values were observed in case of Frame C. The maximum differences were up to 30% (see Figure 1.6). The biggest horizontal displacement was obtained for frame A, during dynamic nonlinear analysis with the Vrancea 77 acceleration record.

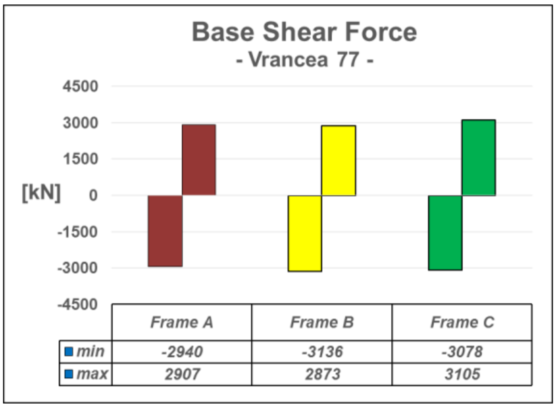


Fig. 1.5 Maximum values for the base shear force - Vrancea 77 -

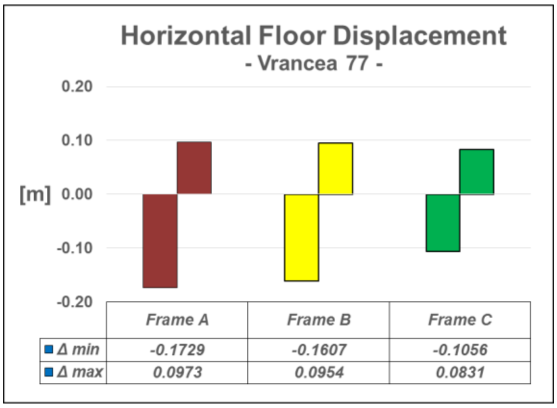


Fig. 1.6 Maximum values of horizontal floor displacements - Vrancea 77 -

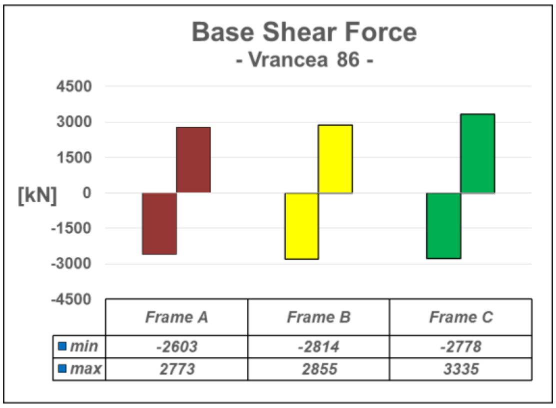


Fig. 1.7 Maximum values for the base shear force - Vrancea 86 -

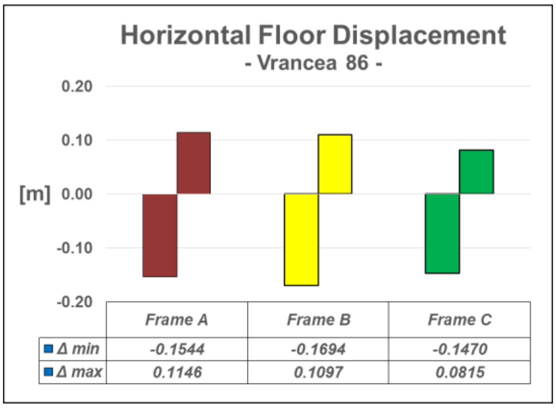


Fig. 1.8 Maximum values of horizontal floor displacements - Vrancea 86 -

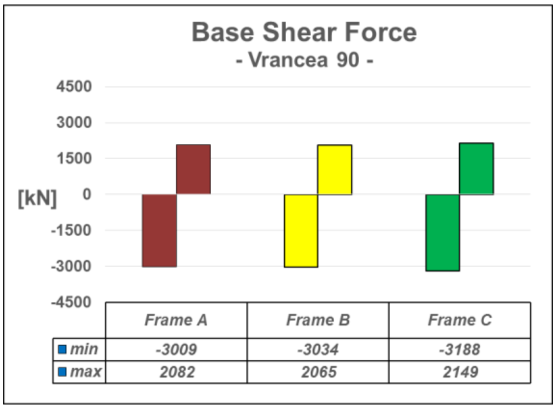


Fig. 1.9 Maximum values for the base shear force - Vrancea 90 -

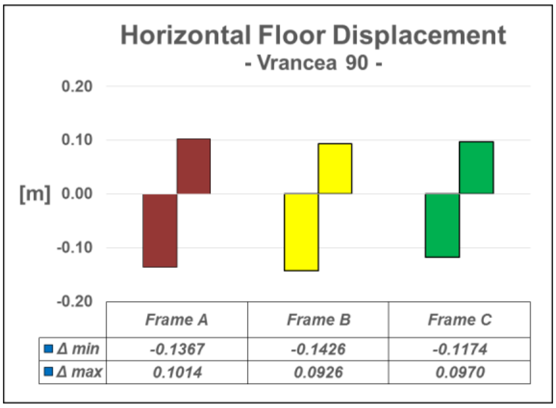


Fig. 1.10 Maximum values of horizontal floor displacements - Vrancea 90 -

Generally, the smallest values for base shear forces were obtained in case of frame A for all considered acceleration records. The highest base shear force values for the six storeyed frames were obtained for Frame C during the dynamic nonlinear analysis with the Vrancea 86 acceleration record. The differences among the extreme values were up to 16.9% for one sense of motion, respectively about 7.5% for the opposite sense of motion, during dynamic nonlinear analysis using the Vrancea 86 acceleration record (see Fig. 1.7).

1.1.2 Maximum inelastic deformations along diagonals and girders

All frames had a favourable behaviour during the dynamic nonlinear analyses, having all inelastic deformations concentrated only in the diagonals and in the potentially plastic zones placed along the frame girders.

In most cases, during the dynamic nonlinear analyses using the three acceleration records, the largest plastic hinge rotations values were recorded in the potentially plastic zones along the girders of Frame B, and the smallest values could be noticed in case of frame C (see Fig. 1.12, Fig. 1.14 and Fig. 1.16).

On average, for the dynamic nonlinear analysis using the Vrancea 86 acceleration record, the differences between the two frames were about 15%. For the first storey of Frame B no inelastic deformations along the girders were obtained, for any of the performed dynamic nonlinear analyses using the three considered acceleration records.

For the dynamic nonlinear analysis performed with the Vrancea 86 acceleration record, the largest values of inelastic deformations along diagonals could be observed at the upper storeys of Frame A and at the lower storeys of Frame B (see Fig. 1.13). The smallest values of the inelastic deformations along the diagonals resulted for the first four storeys of Frame A, respectively for the last two storeys of Frame C.

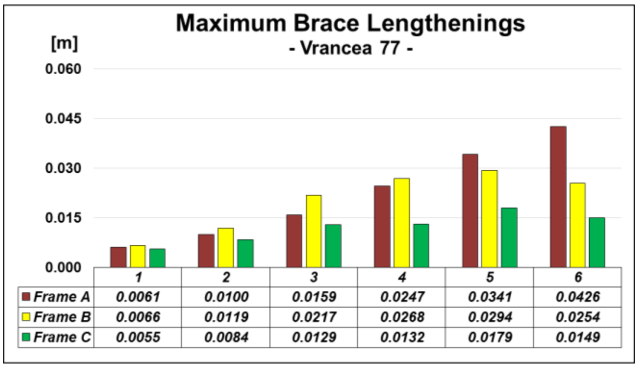


Fig. 1.11 Maximum Brace Lengthenings
- Vrancea 77 -

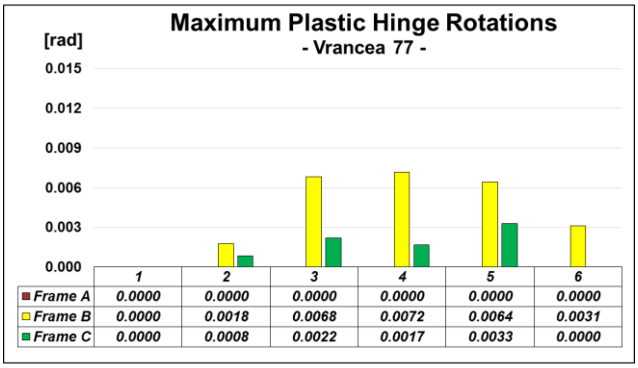


Fig. 1.12 Maximum Plastic Hinge Rotations
- Vrancea 77 -

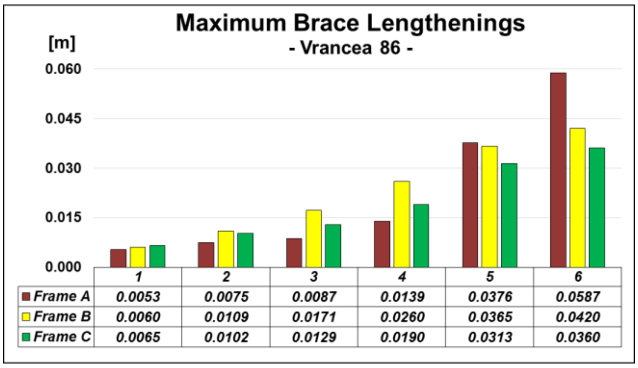


Fig. 1.13 Maximum Brace Lengthenings
- Vrancea 86 -

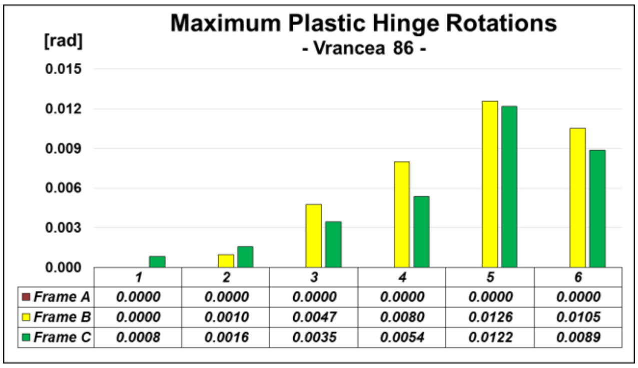


Fig. 1.14 Maximum Plastic Hinge Rotations
- Vrancea 86 -

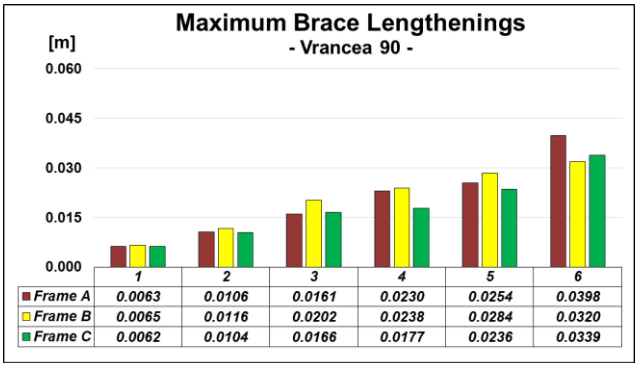


Fig. 1.15 Maximum Brace Lengthenings – Vrancea 90

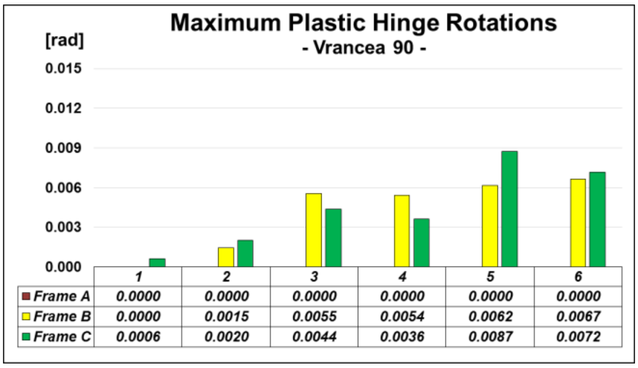


Fig. 1.16 Maximum Plastic Hinge Rotations – Vrancea 90

The maximum values of the deformations along the diagonals were on average up to 45.5% smaller in case of Frame C compared to the values recorded for Frame A for the dynamic nonlinear analysis with the Vrancea 77 acceleration record. In case of the analyses using the Vrancea 86 acceleration record the maximum values for brace lengthenings were on average about 16% larger for Frame B compared to the ones obtained in case of Frame C.

1.1.3 Maximum member forces

1.1.3.1 Maximum forces along girders

In almost all situations for the six storeys frames, the largest values of the different member forces were registered during the dynamic nonlinear analyses with the Vrancea 86 acceleration record.

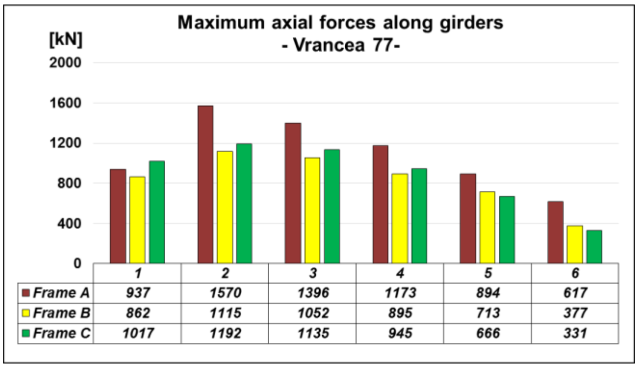


Fig. 1.17 Maximum axial forces along girders
-Vrancea 77-

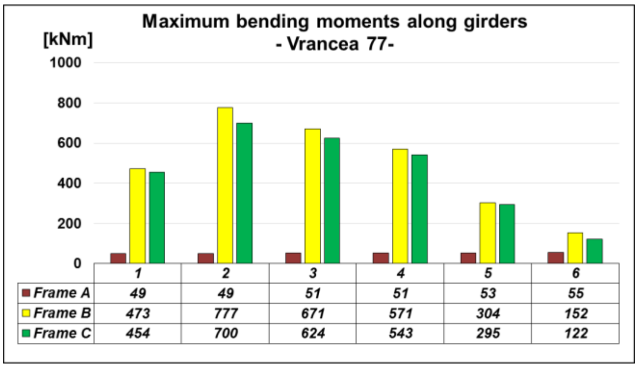


Fig. 1.18 Maximum bending moments along girders
– Vrancea 77 -

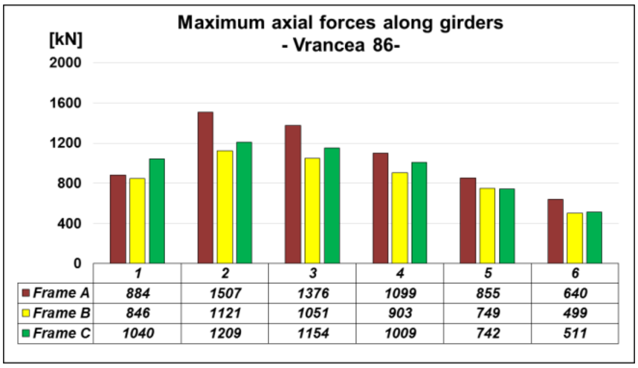


Fig. 1.19 Maximum axial forces along girders
-Vrancea 86-

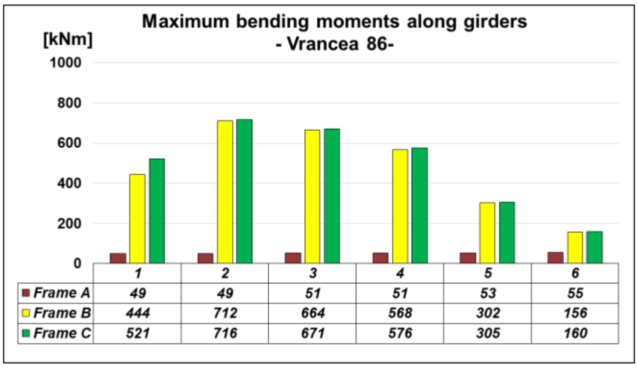


Fig. 1.20 Maximum bending moments along girders
-Vrancea 86-

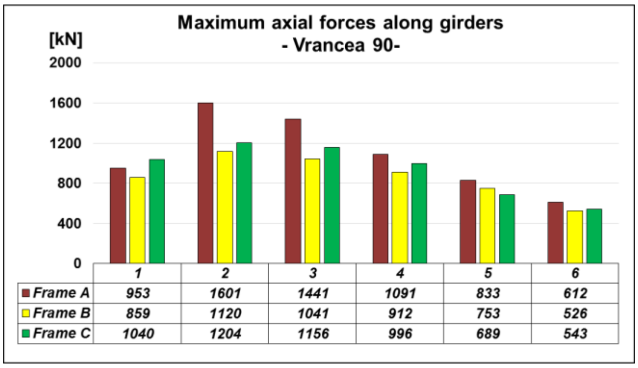


Fig. 1.21 Maximum axial forces along girders
-Vrancea 90-

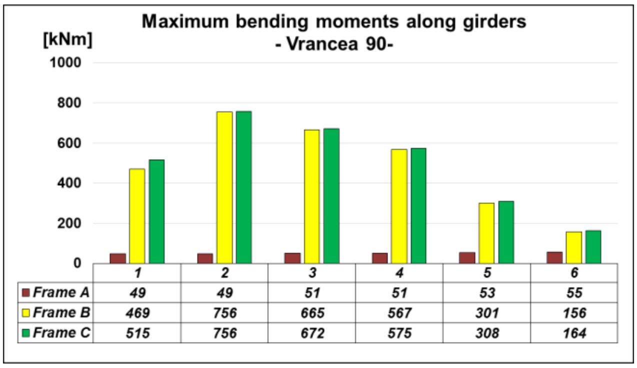


Fig. 1.22 Maximum bending moments along girders
-Vrancea 90-

Along the frame girders, the highest values of axial forces are recorded in case of Frame A, and the lowest values of axial forces in the girders are observed in case of Frame B (see Fig. 1.17, Fig. 1.19 and respectively Fig. 1.21). For the frames with six storeys, differences between the extreme values were on average up to 19%. On average, the values of the maximum axial forces in the girders of frame C, were 11% lower than those of frame A.

In most situations, in case of the six storeys frames, the largest values of bending moments in the girders were observed for frame C. On average, the values of the bending moments in the girders were, about 3.4% lower for Frame B and smaller with up to 89% for Frame A, compared to the values recorded for Frame C (see the values from Fig. 1.18, Fig. 1.20 and Fig. 1.22).

1.1.3.2 Maximum forces in the central columns

During all the dynamic nonlinear analyses with the three considered acceleration records, the largest values of bending moments as well as the smallest values of axial forces, resulted usually for the central columns of the Frame B.

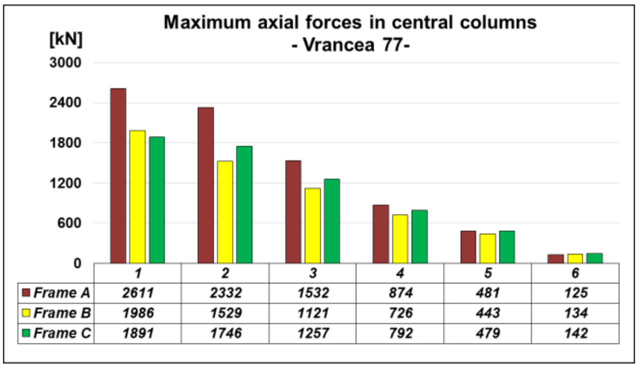


Fig. 1.23 Maximum axial forces in central columns -Vrancea 77-

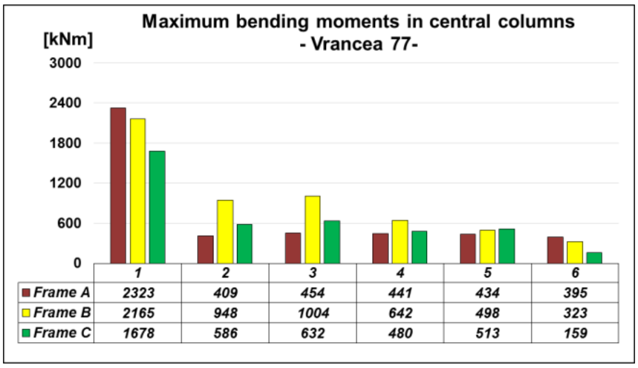


Fig. 1.24 Maximum bending moments in central columns –Vrancea 77-

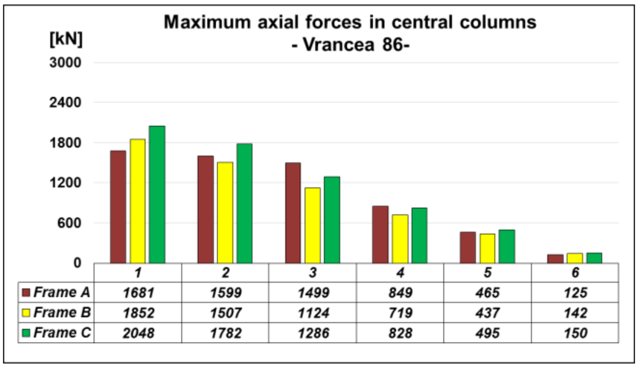


Fig. 1.25 Maximum axial forces in central columns -Vrancea 86-

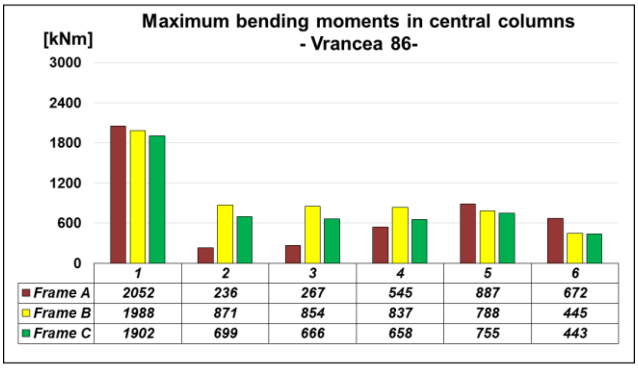
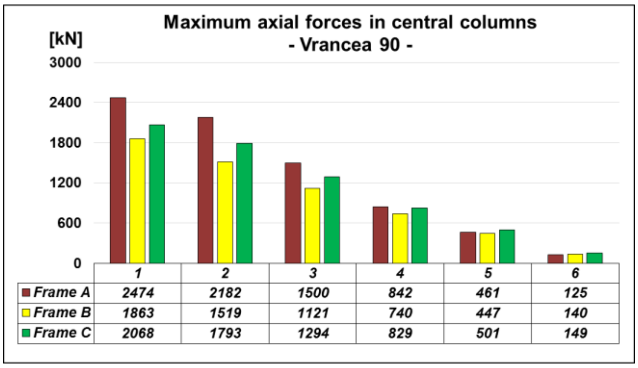


Fig. 1.26 Maximum bending moments in central columns -Vrancea 86-

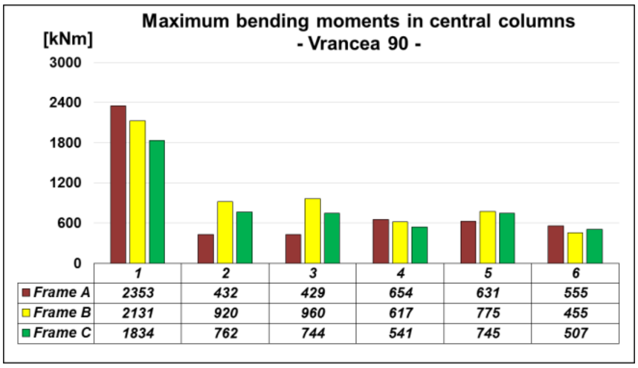
For the six storeys frames, the highest values of axial forces in the central columns are usually recorded in case of Frame C. Compared to the axial force values obtained for Frame C, in the analysis with the Vrancea 90 acceleration record, in case of Frames A and B the values are lower on average with about 5.6% and respectively 11.4% (see Fig. 1.27).

The highest values of bending moments in the central columns are recorded in most situations in case of Frame B (see Fig. 1.24, Fig. 1.26 and Fig. 1.28). For the six storeys frames, the maximum bending moment values recorded in the central columns were on average with about 19.4% lower for Frame A and respectively with up to 11.4% smaller for Frame C, compared to the ones obtained in case of Frame B.



	1	2	3	4	5	6
Frame A	2474	2182	1500	842	461	125
Frame B	1863	1519	1121	740	447	140
Frame C	2068	1793	1294	829	501	149

Fig. 1.27 Maximum axial forces in central columns -Vrancea 90-

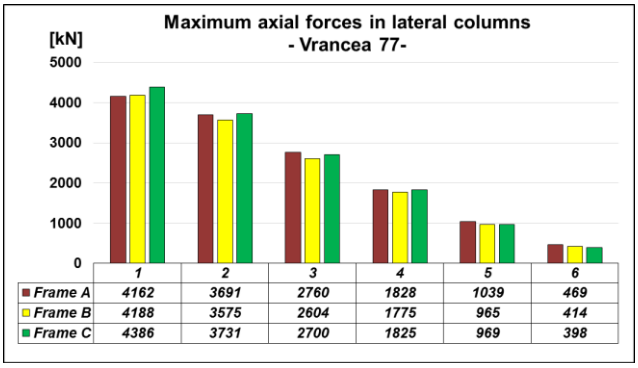


	1	2	3	4	5	6
Frame A	2353	432	429	654	631	555
Frame B	2131	920	960	617	775	455
Frame C	1834	762	744	541	745	507

Fig. 1.28 Maximum bending moments in central columns -Vrancea 90-

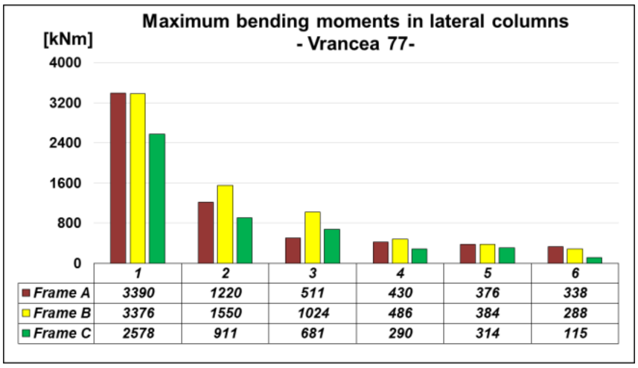
1.1.3.3 Maximum forces in the lateral columns

During dynamic nonlinear analyses, the highest values of axial forces in the lateral columns could be observed for frame C and the lowest values of axial forces were recorded for frame B. During the performed dynamic nonlinear analyses, the differences between the axial force values obtained for the two frames, were on average about 3.5% (Vrancea 77), up to 14% (Vrancea 86) and respectively about 4.3% (Vrancea 90) higher for Frame C.



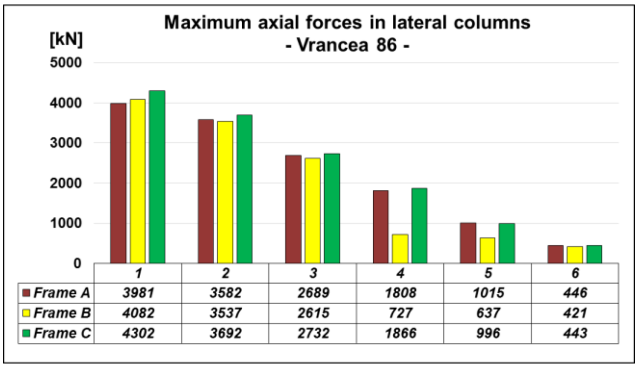
	1	2	3	4	5	6
Frame A	4162	3691	2760	1828	1039	469
Frame B	4188	3575	2604	1775	965	414
Frame C	4386	3731	2700	1825	969	398

Fig. 1.29 Maximum axial forces in lateral columns -Vrancea 77-



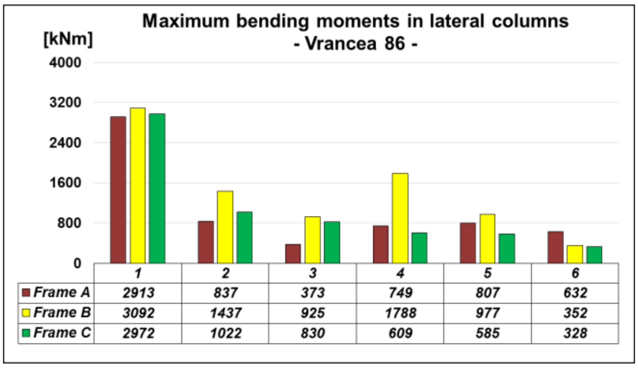
	1	2	3	4	5	6
Frame A	3390	1220	511	430	376	338
Frame B	3376	1550	1024	486	384	288
Frame C	2578	911	681	290	314	115

Fig. 1.30 Maximum bending moments in central columns -Vrancea 77-



	1	2	3	4	5	6
Frame A	3981	3582	2689	1808	1015	446
Frame B	4082	3537	2615	727	637	421
Frame C	4302	3692	2732	1866	996	443

Fig. 1.31 Maximum axial forces in lateral columns -Vrancea 86-



	1	2	3	4	5	6
Frame A	2913	837	373	749	807	632
Frame B	3092	1437	925	1788	977	352
Frame C	2972	1022	830	609	585	328

Fig. 1.32 Maximum bending moments in central columns -Vrancea 86-

In most cases during dynamic nonlinear analyses, the smallest bending moment values recorded in the lateral columns were observed for Frame C, and the highest values were obtained for Frame B. On average, the differences between the values of the bending moments in the lateral columns were about 31% (for the analyses performed with the Vrancea 77 acceleration record), up to 25% (for the dynamic nonlinear analyses in which the Vrancea 86 acceleration record was used) and about 14% (for the analyses performed with the Vrancea 90 acceleration record), higher in the case of Frame B compared to the values obtained for Frame C.

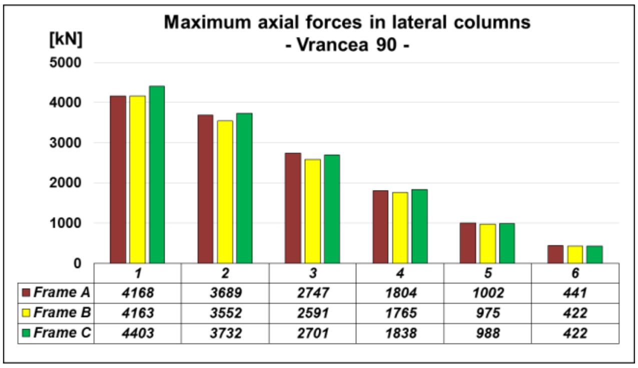


Fig. 1.33 Maximum axial forces in lateral columns
-Vrancea 90-

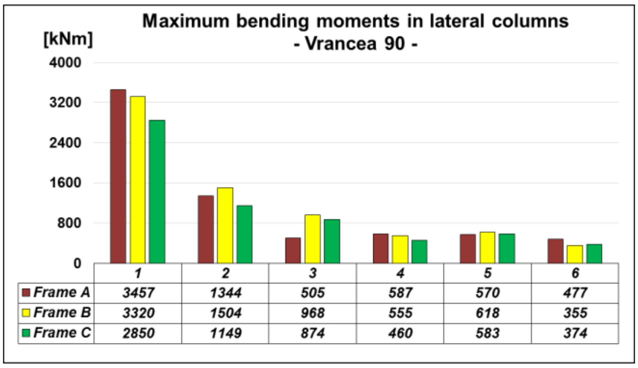


Fig. 1.34 Maximum bending moments in central columns
-Vrancea 90-

1.1.4 Estimated steel consumptions

For diagonals, the smallest value of the estimated steel consumption was obtained in case of Frame B and the largest value for Frame A. Compared to Frame B, the value of the estimated steel consumption for the diagonals of Frame A was about 18.6% larger. For Frame C the estimated consumption value was about 10.8% higher than the one for Frame A (see Fig. 1.35).

For girders, the largest estimated steel consumption value was obtained for Frame B and the lowest value was observed for Frame A. Compared to the estimated steel consumption value obtained for the beams of Frame A, greater values could be noticed with about 27% in case of Frame C, and respectively with over 23% in case of Frame B (see the values and graphs shown indicated in Fig. 1.36).

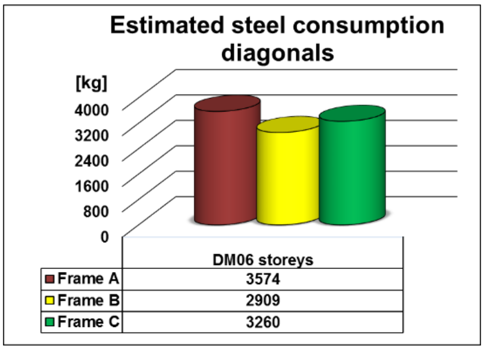


Fig. 1.35 Estimated steel consumption for diagonals

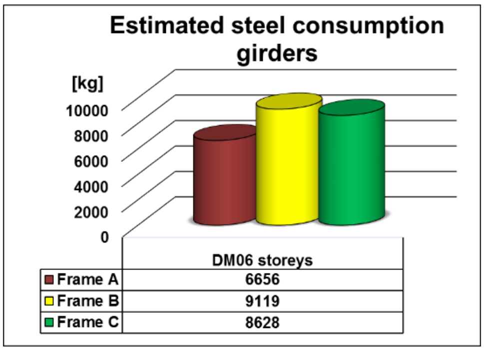


Fig. 1.36 Estimated steel consumption for girders

The highest values of the estimated material consumption for the central and respectively lateral columns, were recorded in the case of Frame A and the lowest values could be noticed for Frame C (see Fig. 1.37 and Fig. 1.38). The differences between the estimated consumption values were about 14% in case of the central columns and about 2% in case of the lateral columns.

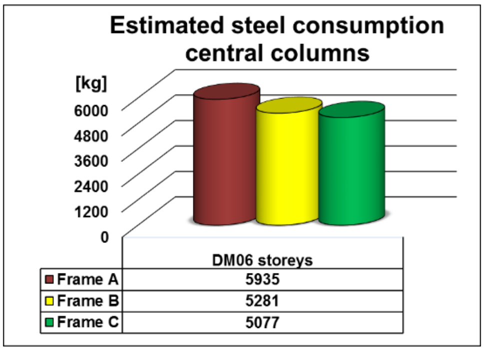


Fig. 1.37 Estimated steel consumption for central columns

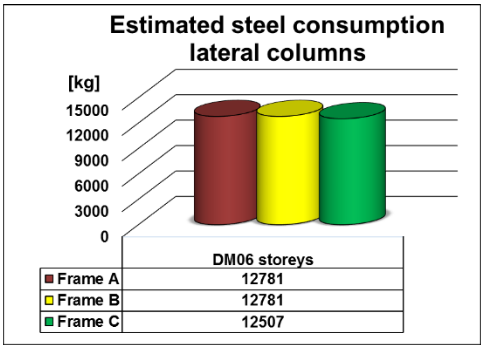


Fig. 1.38 Estimated steel consumption for lateral columns

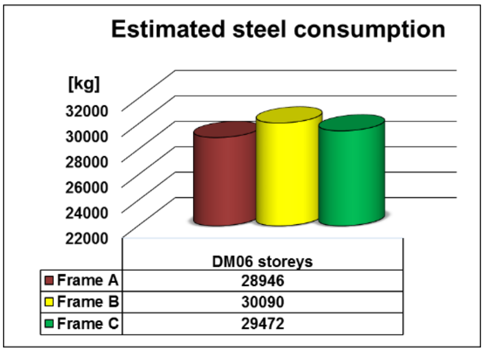


Fig. 1.39 Estimated steel consumption

The smallest value of for the total estimated steel consumption was obtained for Frame A, while the highest value was observed for Frame B. Compared to the value of the total steel consumption estimated for Frame A, the consumption for Frame B was approximately 4% higher and in the case of Frame C up to 1.7% higher (see Fig. 1.39).

The largest steel consumption obtained for Frame B is mainly explained by the more developed sections resulting from girders and lateral columns. Although, in the case of Frame A the highest estimated steel consumption is obtained in the case of diagonals and central columns, the much lower bending moments found in the case of frame girders lead to much less developed sections for them and to a lower total steel consumption for Frame A.

1.2 Seismic behaviour of the concentrically braced frames with ten storeys

In Fig. 1.40 are presented the first three modal periods for the frames with ten storeys, which were analyzed:

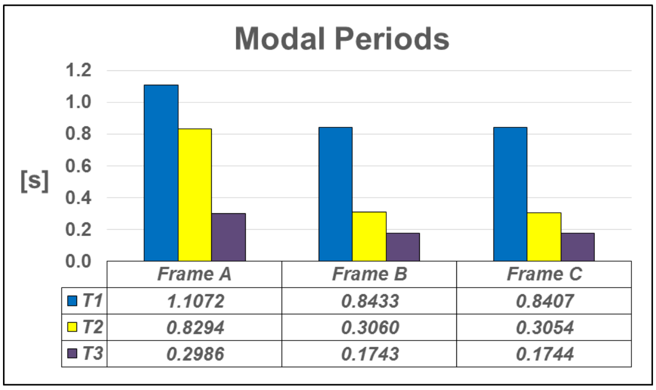


Fig. 1.40 The modal periods for the frames with ten storeyed

The smallest modal periods values were obtained for the frame with rigid connections at the diagonals and beams ends. This frame resulted with the highest stiffness when subjected at horizontal loads. For Frame A, the one with hinged connections at the diagonals and girders ends, was the most flexible under the action of horizontal loads. The highest modal periods values were recorded for Frame A (see Fig. 1.40).

The following cross-sections were obtained after the design, for each considered constructive variant of the ten storeyed frames:

	DIAGONALS		GIRDERS		CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	220 x 7	220 x 14	360 x 12	250 x 20	700 x 25	600 x 40	850 x 30	800 x 65
2	260 x 8	270 x 18	400 x 12	300 x 25	700 x 25	600 x 40	850 x 30	800 x 65
3	260 x 8	270 x 18	400 x 12	300 x 25	700 x 25	600 x 40	850 x 30	800 x 65
4	260 x 8	270 x 18	400 x 12	300 x 25	500 x 14	400 x 25	700 x 22	600 x 40
5	260 x 8	270 x 15	400 x 12	260 x 25	500 x 14	400 x 25	700 x 22	600 x 40
6	260 x 8	270 x 15	400 x 12	260 x 25	500 x 14	400 x 25	700 x 22	600 x 40
7	220 x 7	220 x 14	360 x 12	250 x 22	400 x 12	350 x 20	500 x 14	400 x 25
8	220 x 7	220 x 14	360 x 12	250 x 22	400 x 12	350 x 20	500 x 14	400 x 25
9	180 x 6	180 x 10	280 x 9	220 x 18	400 x 12	350 x 20	400 x 12	350 x 20
10	180 x 6	180 x 10	270 x 8	200 x 18	400 x 12	350 x 20	400 x 12	350 x 20

Tab. 1.4 Sections for Frame A

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	180 x 6	180 x 12	440 x 14	350 x 30	130 x 30	750 x 25	700 x 40	850 x 30	750 x 60
2	230 x 7	220 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	850 x 30	750 x 60
3	230 x 7	220 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	850 x 30	750 x 60
4	230 x 7	220 x 14	420 x 18	360 x 40	190 x 40	600 x 16	400 x 35	700 x 22	600 x 40
5	220 x 7	210 x 12	440 x 14	350 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
6	220 x 7	210 x 12	440 x 14	350 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
7	180 x 6	180 x 12	400 x 10	330 x 22	180 x 22	450 x 14	400 x 30	550 x 15	400 x 30
8	180 x 6	180 x 12	400 x 10	330 x 22	150 x 22	450 x 14	400 x 30	550 x 15	400 x 30
9	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20
10	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20

Tab. 1.5 Sections for Frame B

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	170 x 6	190 x 12	440 x 14	340 x 30	130 x 30	750 x 25	700 x 40	800 x 25	800 x 60
2	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	800 x 25	800 x 60
3	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	800 x 25	800 x 60
4	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	600 x 16	400 x 35	700 x 22	600 x 40
5	210 x 7	220 x 12	440 x 14	340 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
6	210 x 7	220 x 12	440 x 14	340 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
7	170 x 6	190 x 12	400 x 10	330 x 22	170 x 22	450 x 14	400 x 30	550 x 15	400 x 30
8	170 x 6	190 x 12	400 x 10	330 x 22	170 x 22	450 x 14	400 x 30	550 x 15	400 x 30
9	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20
10	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20

Tab. 1.6 Sections for Frame C

1.2.1 Extreme values for base shear forces and horizontal displacements

For the ten storeyed frames, the largest horizontal displacements values could be noticed in case of dynamic nonlinear analyses with the Vrancea 77 acceleration record. The differences among the maximum values of the horizontal displacements, were about 5.9% for one sense of the seismic action, (the one with negative values), respectively up to 33.0% for the other sense of the seismic motion (see Fig. 1.42).

From the ten storeys frames, the highest base shear force value was recorded during the dynamic nonlinear analysis with the Vrancea 77 acceleration record, in case of frame C. The lowest values of the base shear force resulted for Frame A. For the negative sense of the seismic action, the maximum difference obtained among the extreme base shear force values was about 1.9% and for the positive sense of the seismic action, the maximum difference was up to 2.6% (see Fig. 1.41).

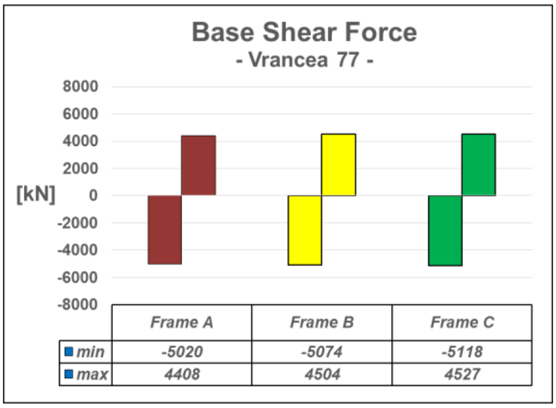


Fig. 1.41 Maximum values for the base shear force - Vrancea 77 -

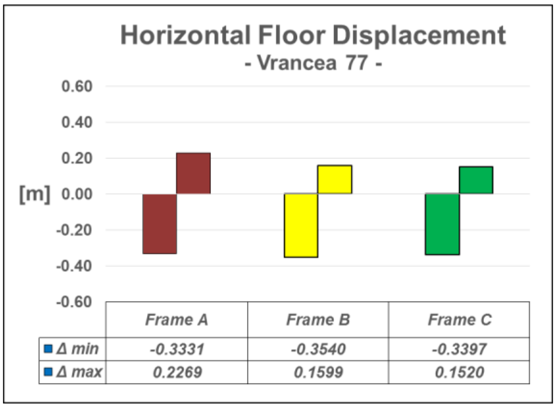


Fig. 1.42 Maximum values of horizontal floor displacements - Vrancea 77 -

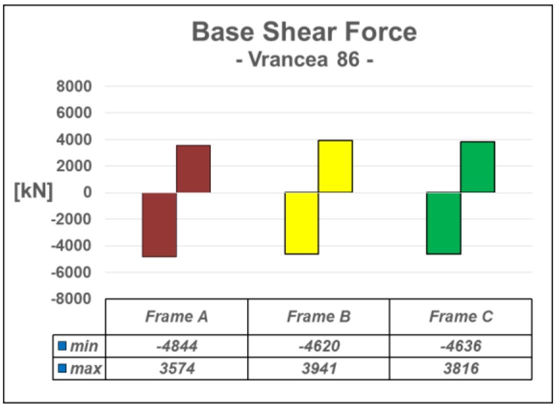


Fig. 1.43 Maximum values for the base shear force - Vrancea 86 -

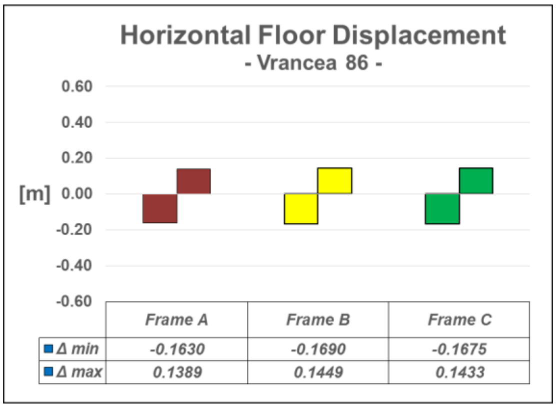


Fig. 1.44 Maximum values of horizontal floor displacements - Vrancea 86 -

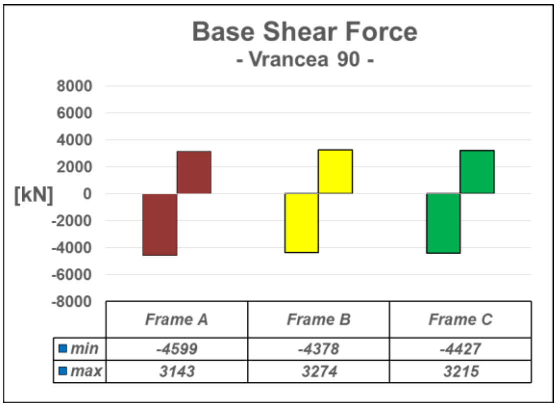


Fig. 1.45 Maximum values for the base shear force - Vrancea 90 -

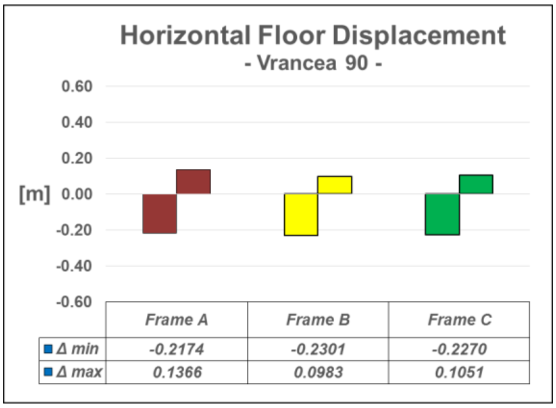


Fig. 1.46 Maximum values of horizontal floor displacements - Vrancea 90 -

1.2.2 Maximum inelastic deformations along diagonals and girders

All frames had a favourable behaviour during the dynamic nonlinear analyses, having all inelastic deformations concentrated in the diagonals and in the potentially plastic zones placed along the frame girders. Plastic hinge rotations did not appear along the girders of Frame A, because the connections of the beams to the frame columns were hinged (see Fig.1.48, 1.50 and 1.52).

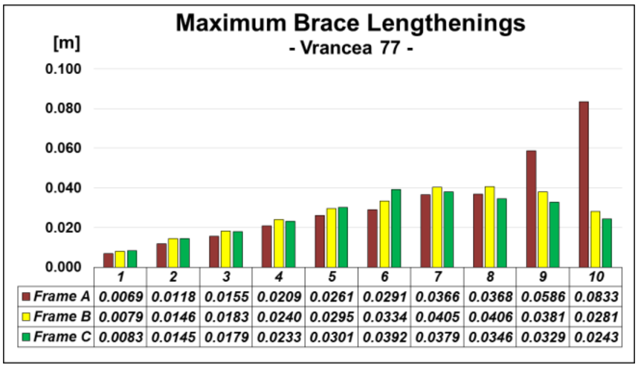


Fig. 1.47 Maximum Brace Lengthenings – Vrancea 77

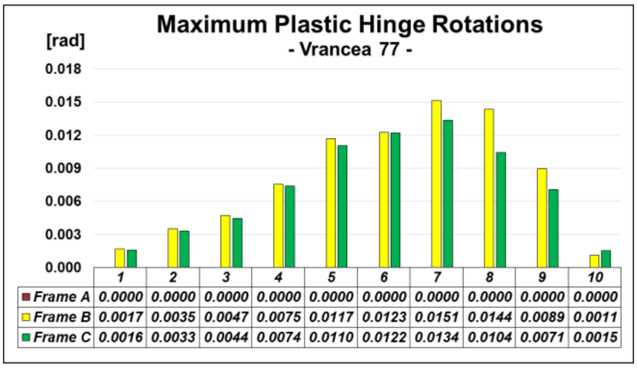


Fig. 1.48 Maximum Plastic Hinge Rotations – Vrancea 77

The largest values of the rotations in the potentially plastic zones and of the brace lengthenings were noticed during the dynamic nonlinear analyses with the Vrancea 77 acceleration record.

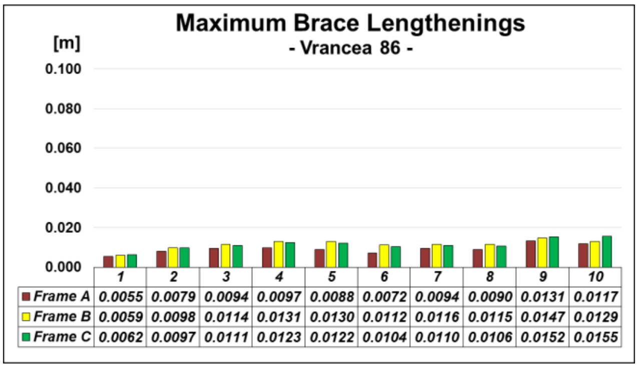


Fig. 1.49 Maximum Brace Lengthenings – Vrancea 86

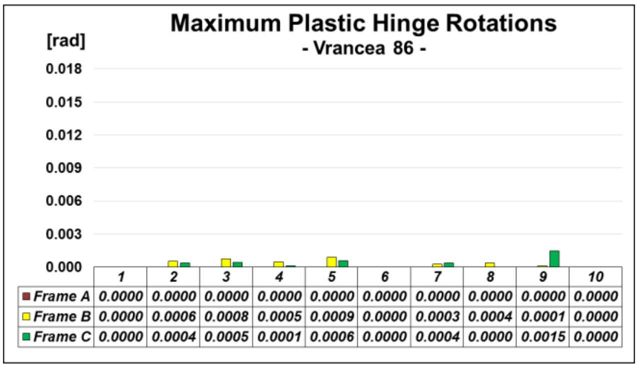


Fig. 1.50 Maximum Plastic Hinge Rotations – Vrancea 86

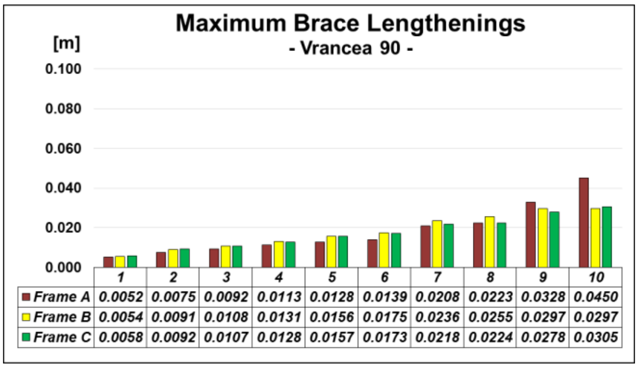


Fig. 1.51 Maximum Brace Lengthenings – Vrancea 90

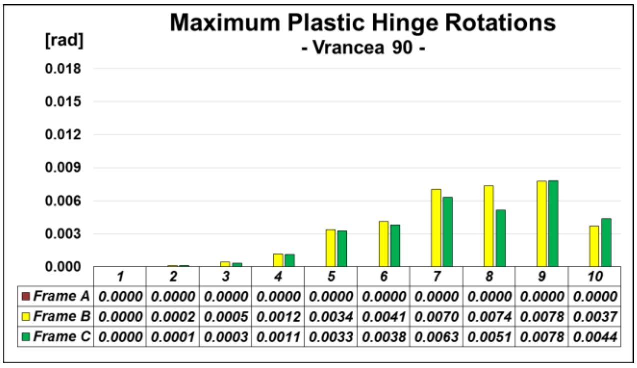


Fig. 1.52 Maximum Plastic Hinge Rotations – Vrancea 90

With the exception of the dynamic nonlinear analyses with the Vrancea 90 acceleration record, the smallest plastic hinge rotations values were registered in case of Frame C, the one with fixed girders/columns and diagonals/columns connections. On average, the differences between the values of the plastic hinge rotations placed along the frame girders was about 10.6% in case of Frame B and Frame C, for the dynamic nonlinear analyses with the Vrancea 77 acceleration record.

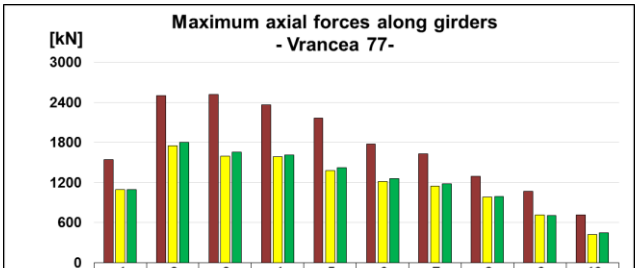
In case of dynamic nonlinear analyses with the Vrancea 77 and Vrancea 90 acceleration records of the ten storeys frames, the highest plastic deformations values were noticed along the diagonals of Frame A, and the lowest ones in case of Frame C. On average, the differences among the maximum deformations along the diagonals were about 19.3% in the case of the Vrancea 77 acceleration record and about 4.0% in the case of the Vrancea 90 acceleration record (see Fig. 1.47 and Fig. 1.51). In case of dynamic nonlinear analyses with the Vrancea 86 acceleration record, the values of the brace lengthenings were much smaller (see Fig. 1.49).

1.2.3 Maximum member forces

In most cases, for the structures with ten storeys, the largest values of the different sectional stress were registered during the dynamic nonlinear analyses with the Vrancea 77 acceleration record.

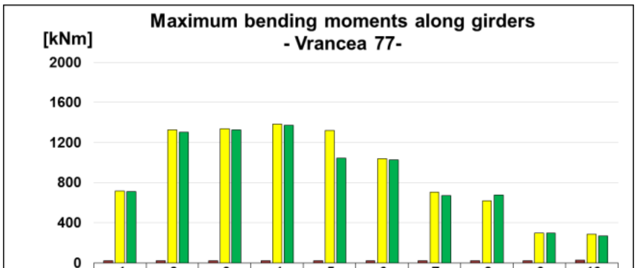
1.2.3.1 Maximum forces along girders

The largest values of axial forces along the frame girders are recorded in the case of Frame A, and the smallest values of the axial forces in the girders are recorded in the case of Frame B (see Fig. 1.53). The differences between the extreme values were on average 32.3%. On average, the values of the maximum axial forces in the girders of Frame C were 31% lower than those of Frame A.



	1	2	3	4	5	6	7	8	9	10
Frame A	1543	2498	2517	2363	2163	1774	1633	1297	1069	721
Frame B	1100	1749	1597	1589	1381	1213	1152	981	712	427
Frame C	1095	1805	1655	1613	1424	1262	1183	997	705	451

Fig. 1.53 Maximum axial forces along girders
-Vrancea 77-



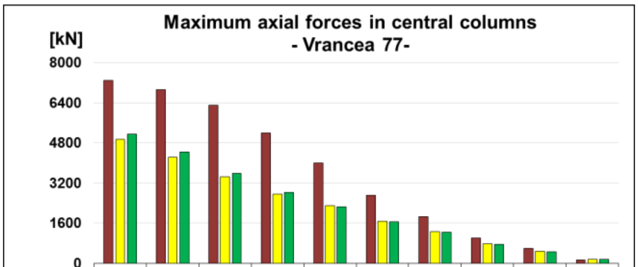
	1	2	3	4	5	6	7	8	9	10
Frame A	21	21	21	21	21	21	21	21	21	27
Frame B	719	1327	1340	1383	1321	1040	708	622	297	289
Frame C	711	1305	1324	1374	1044	1029	668	675	298	268

Fig. 1.54 Maximum bending moments along girders
– Vrancea 77 -

In most cases, the lowest bending moment values in the girders were observed for Frame A and the highest values for Frame B. On average, the values of the bending moments in the girders of Frame B were approximately 98% higher than those found in the case of Frame A (see Fig. 1.54).

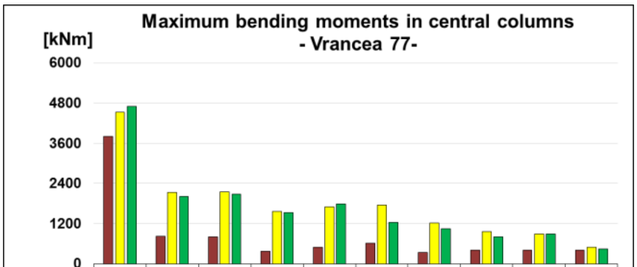
1.2.3.2 Maximum forces in central columns

The largest values for the axial forces in the central columns were observed for Frame A. On average for Frames B and C, the maximum values of the axial forces were about 38.9% and respectively 37.4% smaller (see Fig. 1.55).



	1	2	3	4	5	6	7	8	9	10
Frame A	7291	6918	6293	5194	3998	2714	1873	1021	591	135
Frame B	4940	4221	3439	2754	2304	1689	1253	782	476	158
Frame C	5151	4438	3587	2820	2257	1662	1243	764	467	158

Fig. 1.55 Maximum axial forces in central columns
-Vrancea 77-



	1	2	3	4	5	6	7	8	9	10
Frame A	3810	823	802	368	490	607	337	409	413	401
Frame B	4525	2123	2147	1569	1707	1753	1209	954	889	489
Frame C	4694	2016	2076	1535	1793	1230	1050	800	883	435

Fig. 1.56 Maximum bending moments in central columns
– Vrancea 77 -

Regarding the maximum values of the bending moments in the central columns, they record the highest values in the case of Frame B (see Fig. 1.56). The maximum bending moments in the central columns of Frames A and C were about 51.3% and respectively 4.9% smaller compared to the values obtained for Frame B.

1.2.3.3 Maximum forces in lateral columns

During dynamic nonlinear analyses, the biggest values of the axial forces in the lateral columns were obtained for Frame A. Compared to the maximum values of the axial forces along the lateral columns of Frame A, values for Frame B were about 9% smaller and values for Frame C were by about 7.5% lower (see Fig. 1.57).

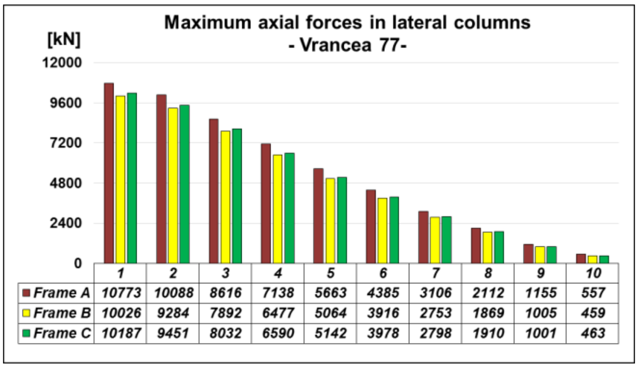


Fig. 1.57 Maximum axial forces in lateral columns -Vrancea 77-

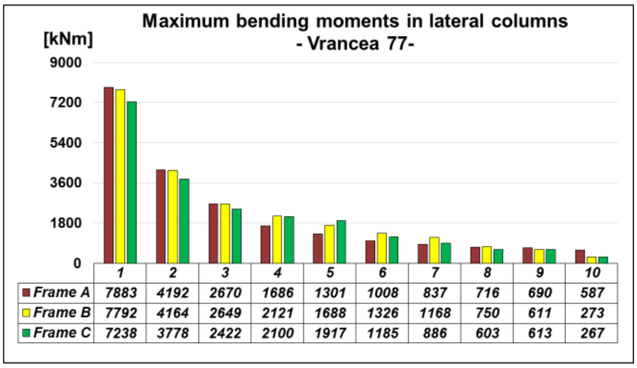


Fig. 1.58 Maximum bending moments in lateral columns – Vrancea 77 -

The highest values of the bending moments in the lateral columns, during the dynamic nonlinear analyses were obtained in the case of Frame B. On average, the maximum values of bending moments along the lateral columns were about 4.3% lower for Frame A and respectively about 6.8% for Frame C compared to the maximum values obtained for Frame B (see values and graph from Fig. 1.58).

1.2.4 Estimated steel consumptions

The smallest estimated steel consumption for diagonals was observed for Frame B. Compared to this value, for the diagonals of Frame A the estimated steel consumption was about 32% higher, and for Frame C it was about 2.8% larger (see Fig. 1.59).

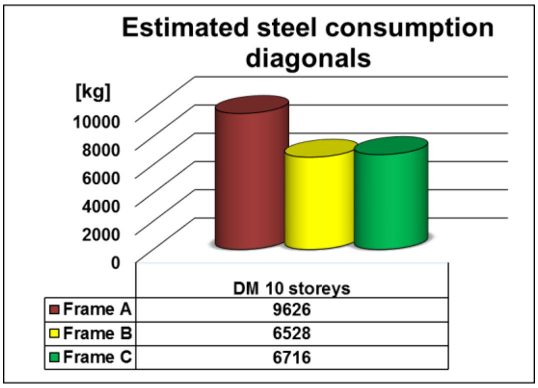


Fig. 1.59 Estimated steel consumption for diagonals

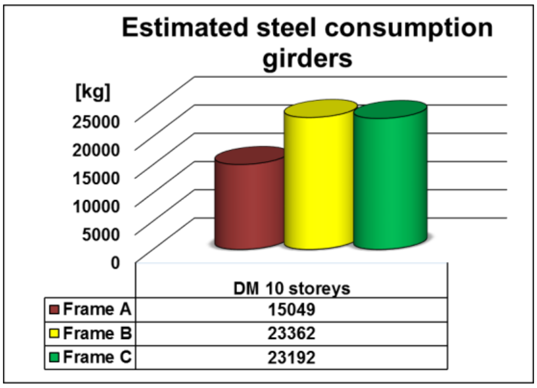


Fig. 1.60 Estimated steel consumption for girders

In case of Frame A, the hinged connections between the girders and the columns and between the diagonals and the columns, lead to the appearance of greater axial forces in the diagonals and to larger cross-sections for the braces. In case of Frames C, the fixed connections at the ends of the diagonals lead to the occurrence of reduced bending moments in the diagonals, which, however, lead to slightly larger cross-sections for the diagonals of these frames, compared to those in frame B, where the hinged joints at the ends of the diagonals lead only to the development of axial forces in the diagonals (without bending moments).

The hinged connections at the ends of the girders of Frame A, led to the development of much lower bending moments along the girders, to smaller cross-sections and therefore to the lowest values of the estimated steel consumption for the girders.

Compared to Frame A, the estimated steel consumption for the girders of Frame C was up to 35% higher, and for Frame B it was about 35.6% larger (see Fig. 1.60).

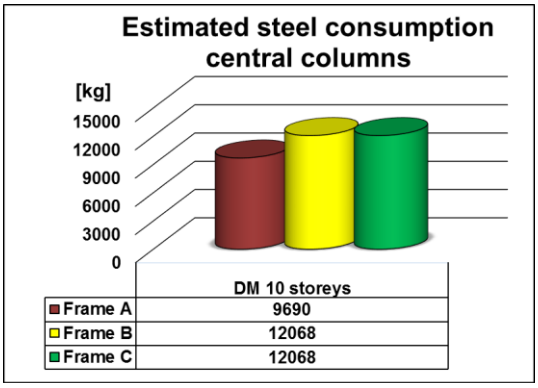


Fig. 1.61 Estimated steel consumption for central columns

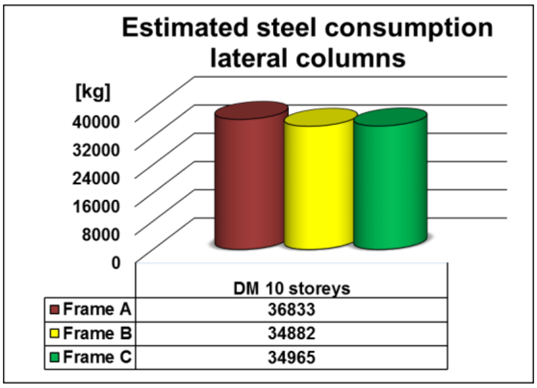


Fig. 1.62 Estimated steel consumption for lateral columns

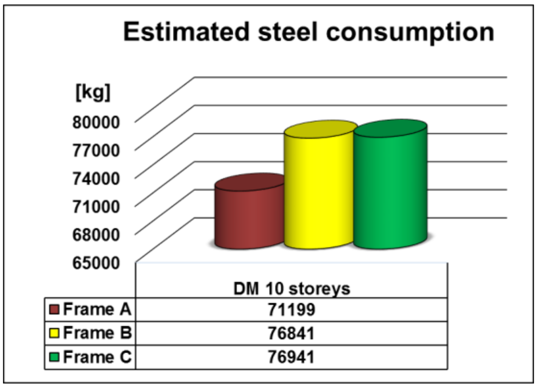


Fig. 1.63 Estimated steel consumption

The lowest estimated steel consumption for the central columns, was obtained for Frame A. Compared to value, for Frame B and Frame C the estimated steel consumption obtained it was by approximately 19.7% higher (see Fig. 1.61).

The smallest values of the estimated steel consumption for lateral columns were obtained for Frame B. Compared to this, the estimated steel consumption of lateral columns for Frames C and A was about 0.2% and respectively about 5.3% higher (see Fig. 1.62).

The lowest value for the total estimated material consumption resulted in case of frame A. The biggest value for the estimated steel consumption was obtained in case of Frame C. Compared to the lowest value of the total steel consumption obtained for Frame A, in case of Frame B the estimated material consumption was about 7.3% higher, and in case of Frame C it was about 7.5% larger (see the values in Fig. 1.63).

1.3 Conclusions

The highest values of the lateral stiffness resulted for Frame C for both categories of frames (with six and ten storeys), and the lowest values for Frame A. Therefore, the highest base shear force values, were obtained for Frame C, during the dynamic nonlinear analysis with the Vrancea 86 acceleration record were used (for the six storeys frames) and respectively Vrancea 77 record (for the ten storeys frames). In case of the frames with six storeys, for the positive sense of the seismic action, the difference between the extreme values was about 16.9%, and for the negative sense of the seismic action the difference was about 7.5%. In case of the ten storeys frames, for the negative sense of the seismic action, the difference between the extreme values was around 1.9% and for the positive sense of the seismic action, the difference was about 2.6%.

Regarding the biggest values of horizontal floor displacements, in the case of frames with six storeys, the highest values were obtained for Frame A for both directions of action of seismic loading. For the frames with ten storeys, the extreme values of the horizontal displacements were recorded in the case of Frame A for the positive direction of the seismic action and in the case of Frame B for the other direction.

In most cases, the largest plastic deformations could be noticed during the dynamic nonlinear analyses performed with the Vrancea 86 acceleration record for the structures with six storeys and respectively with the Vrancea 77 acceleration record for the structures with ten storeys. The largest plastic deformations along the diagonal were usually observed in case of Frames B (for both categories of frames with six and respectively ten storeys). Exceptions are the last two storeys where the largest values resulted for Frame A, due to some local dynamic amplifications at the last storeys of the whip effect type.

The largest plastic hinge rotations in the potentially plastic zones along the girders could be observed in most cases for Frame B (for both categories of frames with six and respectively ten storeys). Compared to the values recorded in Frames C, the differences were on average about 14% for the girders of the six storeys frames and respectively about 12% for the girders of the ten storeys frames.

For both six and ten storeys structures, the lowest axial force values were recorded for Frame B (in the case of girders, central columns and lateral columns). For the three frames with six storeys, the highest values of axial forces were observed in Frame A (for girders), respectively in Frame C (for central and lateral columns). In case of the frames with ten storeys, the largest axial forces resulted for Frame A (for girders, central columns and respectively lateral columns).

For the structures with six storeys, the lowest bending moment values were registered in case of Frame A (for girders, central columns and lateral columns). For the ten storeys structures, the smallest bending moment values were obtained in case of Frame A (for girders and central columns) and in case of Frame C (for lateral columns).

The highest estimated total steel consumption value was obtained for Frame B for the structures with six storeys and respectively for Frame C for ten storeys frames and the lowest value for Frame A (for both categories of frames with six and respectively ten storeys). The maximum difference recorded for the six storeys frames was about 3.8% (between Frames B and A), and for the ten storeys frames the difference was about 7.5% (between Frames C and A).

The smallest estimated steel consumption for the six storey frames was obtained for the central and lateral columns of Frame C, for the girders of Frame A and for the diagonals of Frame B. For the frames with ten storeys, the lowest estimated steel consumption resulted for the diagonals and lateral columns of Frame B and for the girders and central columns of Frame A.

Frame A, with hinged connections at the ends of diagonals and girders, was the most advantageous .regarding the estimated steel consumption. The smallest plastic deformations during dynamic nonlinear analyses could be observed in case of Frame C, with fixed connections for diagonals and girders.

2 Positioning of the potentially plastic zones along the girders

The analysed frames are part of a structure with two spans and four bays of 6.0 m, with storey height of 3.5 m, located in Bucharest. A concentrically braced frame that is part of a structural system with six and ten storeys was subjected to analysis. As shown in Fig. 2.1, on each main direction of the construction are provided two concentrically braced frames placed perimeter.

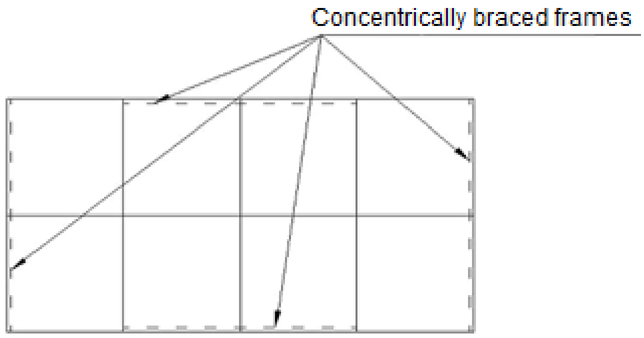


Fig. 2. 1 Plan view of the structure with the location of the braced frames

The diagonals were positioned in structure descending from the lateral columns to the central column (DM type bracing system), as shown in Fig. 2.2:

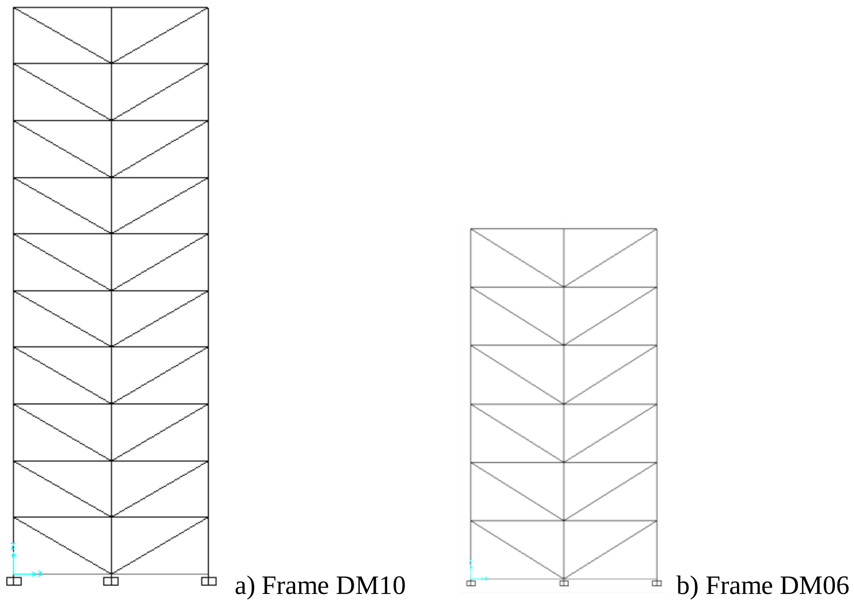


Fig. 2. 2 Analysed frames

All structural members (diagonals, girders and columns) had built up I-shaped cross-sections sized according to the prescriptions of SR EN 1993-1-1[3] and the connections between all kind of structural elements were fixed.

For the analysis the potentially plastic zones with reduced cross-sections along the girders were provided at 1m and 2m of the columns axis.

For each distinct configuration of the placement of potentially plastic zones along the girders the following cross-sections resulted from the sizing:

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	170 x 6	190 x 12	440 x 14	340 x 30	130 x 30	750 x 25	700 x 40	800 x 25	800 x 60
2	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	800 x 25	800 x 60
3	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	750 x 25	700 x 40	800 x 25	800 x 60
4	230 x 7	230 x 14	420 x 18	360 x 40	190 x 40	600 x 16	400 x 35	700 x 22	600 x 40
5	210 x 7	220 x 12	440 x 14	340 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
6	210 x 7	220 x 12	440 x 14	340 x 30	180 x 30	600 x 16	400 x 35	700 x 22	600 x 40
7	170 x 6	190 x 12	400 x 10	330 x 22	170 x 22	450 x 14	400 x 30	550 x 15	400 x 30
8	170 x 6	190 x 12	400 x 10	330 x 22	170 x 22	450 x 14	400 x 30	550 x 15	400 x 30
9	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20
10	140 x 5	160 x 9	300 x 9	250 x 15	130 x 15	400 x 12	400 x 20	400 x 12	300 x 20

Tab. 2.1 Sections for Frame DM10 – 1m

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	170 x 6	190 x 12	400 x 12	340 x 22	140 x 22	750 x 25	700 x 40	800 x 25	800 x 60
2	230 x 7	230 x 14	450 x 14	360 x 25	180 x 25	750 x 25	700 x 40	800 x 25	800 x 60
3	230 x 7	230 x 14	450 x 14	360 x 25	180 x 25	750 x 25	700 x 40	800 x 25	800 x 60
4	230 x 7	230 x 14	450 x 14	360 x 25	180 x 25	600 x 16	400 x 35	700 x 22	600 x 40
5	210 x 7	220 x 12	400 x 12	340 x 22	170 x 22	600 x 16	400 x 35	700 x 22	600 x 40
6	210 x 7	220 x 12	400 x 12	340 x 22	170 x 22	600 x 16	400 x 35	700 x 22	600 x 40
7	170 x 6	190 x 12	340 x 10	280 x 18	150 x 18	450 x 14	400 x 30	550 x 16	400 x 30
8	170 x 6	190 x 12	340 x 10	280 x 18	140 x 18	450 x 14	400 x 30	550 x 16	400 x 30
9	140 x 5	160 x 9	230 x 7	250 x 12	140 x 12	400 x 12	400 x 20	400 x 12	300 x 18
10	140 x 5	160 x 9	230 x 7	250 x 12	140 x 12	400 x 12	400 x 20	400 x 12	300 x 18

Tab. 2 2 Sections for Frame DM10 – 2m

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	180 x 6	180 x 12	400 x 10	330 x 20	180 x 20	600 x 20	450 x 40	750 x 25	550 x 40
2	190 x 6	220 x 12	400 x 12	350 x 25	180 x 25	600 x 20	450 x 40	750 x 25	550 x 40
3	180 x 6	180 x 12	400 x 12	350 x 20	180 x 20	400 x 14	400 x 25	550 x 15	400 x 30
4	180 x 6	180 x 12	360 x 10	330 x 20	180 x 20	400 x 14	400 x 25	550 x 15	400 x 30
5	150 x 5	160 x 9	310 x 9	240 x 16	120 x 16	400 x 12	350 x 20	400 x 12	350 x 20
6	150 x 5	160 x 9	220 x 7	160 x 14	100 x 14	400 x 12	350 x 20	400 x 12	350 x 20

Tab. 2 3 Sections for Frame DM6 – 1m

	DIAGONALS		GIRDERS		DOG BONES	CENTRAL COLUMNS		LATERAL COLUMNS	
Storey	hw x tw	b x tf	hw x tw	b x tf	b x tf	hw x tw	b x tf	hw x tw	b x tf
1	180 x 6	180 x 12	330 x 10	270 x 18	140 x 18	600 x 20	450 x 40	750 x 25	550 x 40
2	190 x 6	220 x 12	400 x 12	280 x 20	140 x 20	600 x 20	450 x 40	750 x 25	550 x 40
3	180 x 6	180 x 12	330 x 10	280 x 20	140 x 20	400 x 14	400 x 25	500 x 15	400 x 30
4	180 x 6	180 x 12	330 x 10	260 x 18	230 x 18	400 x 14	400 x 25	500 x 15	400 x 30
5	150 x 5	160 x 9	240 x 8	240 x 15	120 x 15	400 x 12	350 x 20	400 x 12	350 x 20
6	150 x 5	160 x 9	220 x 6	180 x 12	100 x 12	400 x 12	350 x 20	400 x 12	350 x 20

Tab. 2 4 Sections for Frame DM6 – 2m

All concentrically braced frames resulted after the design were subjected to dynamic nonlinear analyses [4], using the N-S components of Vrancea acceleration records from 04.03.1977, 31.08.1986 and 30.05.1990, all recorded at INCERC Bucharest and calibrated to a peak ground acceleration value of about 0.3 times the acceleration of gravity. Rayleigh damping was taken into consideration. Mass and stiffness proportional damping factors were considered for the first and third modal periods [5].

The first three modal periods of the designed frames are indicated in Fig. 2.3 and Fig. 2.4.

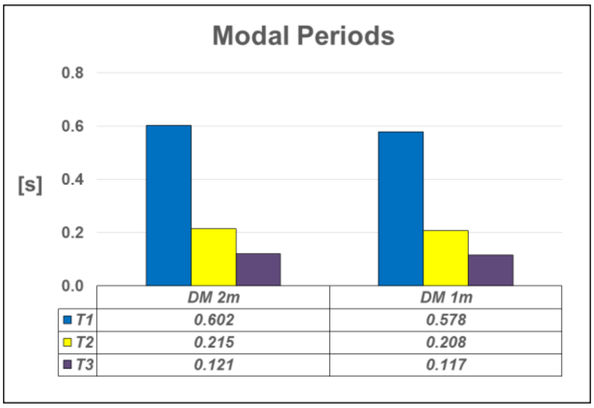


Fig. 2. 3 Modal periods of the designed frames with six storeys

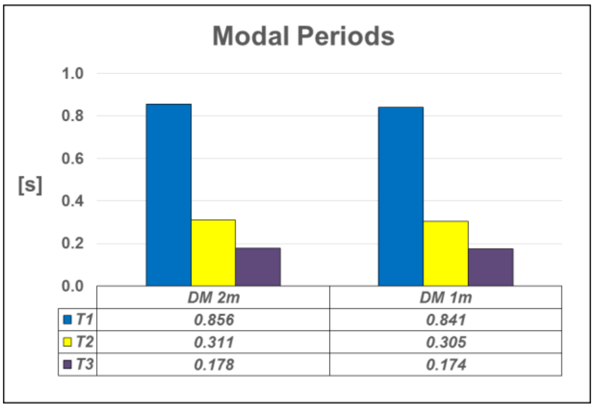


Fig. 2. 4 Modal periods of the designed frames with ten storeys

It can be observed that the larger modal periods were obtained for frame DM06-2m and respectively frame DM10-2m. These frames were more flexible than those with the potentially plastic zones placed along the girders at about 1.0m from the columns axes (see Fig. 2.3 and Fig. 2.4).

2.1 Seismic behaviour of six storeyed concentrically braced frames

2.1.1 Extreme values for base shear forces and horizontal displacements

The largest base shear values for the structures with six storeys were observed in case of the DM-1m frame during dynamic nonlinear analysis using the Vrancea 86 acceleration record. In case of the DM-2m frame, the highest value of the base shear force was recorded during the dynamic nonlinear analysis with the Vrancea 77 acceleration record. The difference between the two values was up to 6% (see Fig. 2.5).

The smallest values of the base shear force resulted both for the DM-1m frame and for the DM-2m frame, from the dynamic nonlinear analysis with the Vrancea 90 acceleration record, the differences between the values being about 5%.

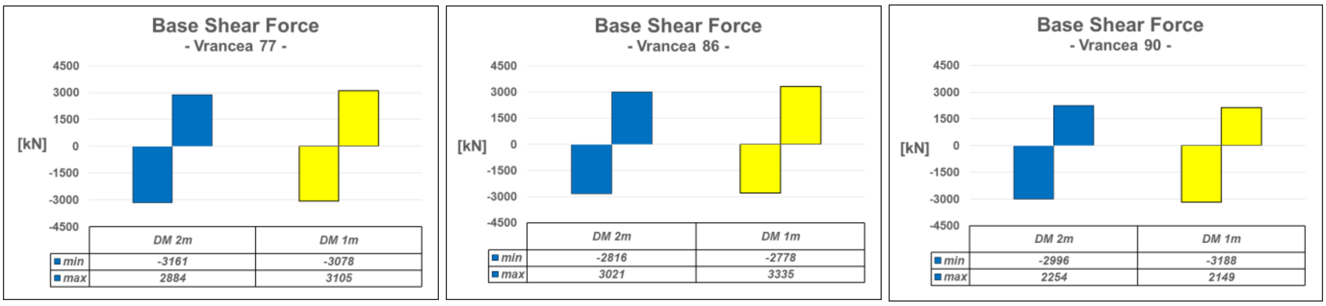


Fig. 2. 5 Extreme base shear force values (Vrancea 77, Vrancea 86, Vrancea 90) - frames with six storeys

For both six storey frames, the largest horizontal floor displacements values were recorded during dynamic nonlinear analyses using the Vrancea 86 acceleration record. The highest values of horizontal displacements were obtained for frame DM-2m. The difference between the maximum values of the horizontal displacements of the two frames with six storeys was up to 14%.

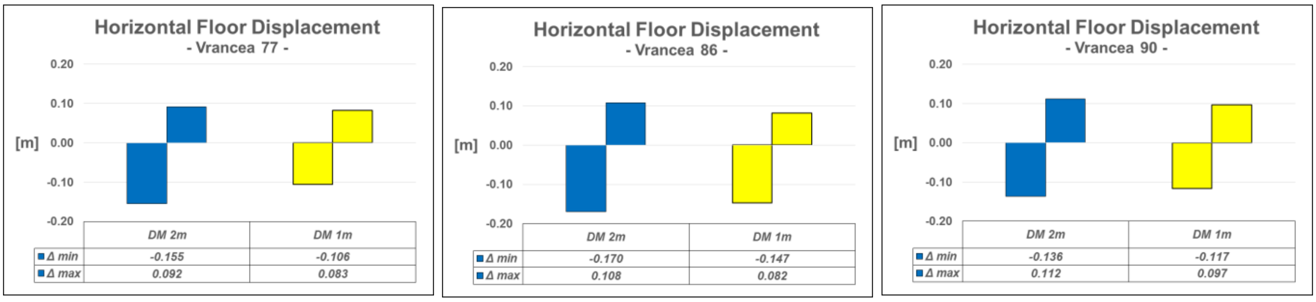


Fig. 2. 6 Extreme horizontal floor displacements values (Vrancea 77, Vrancea 86, Vrancea 90) - frames with six storeys

2.1.2 Maximum inelastic deformations along diagonals and girders

All frames had a favourable behaviour during the dynamic nonlinear analyses, having all inelastic deformations concentrated in the diagonals and in the potentially plastic zones placed along the frame girders. The largest inelastic deformations along the diagonals could be noticed in frame DM-2m during the dynamic nonlinear analyses using the Vrancea 86 acceleration record. On average, the difference between the values of the inelastic deformations along the diagonals obtained for the frames with six storeys was about 16%.

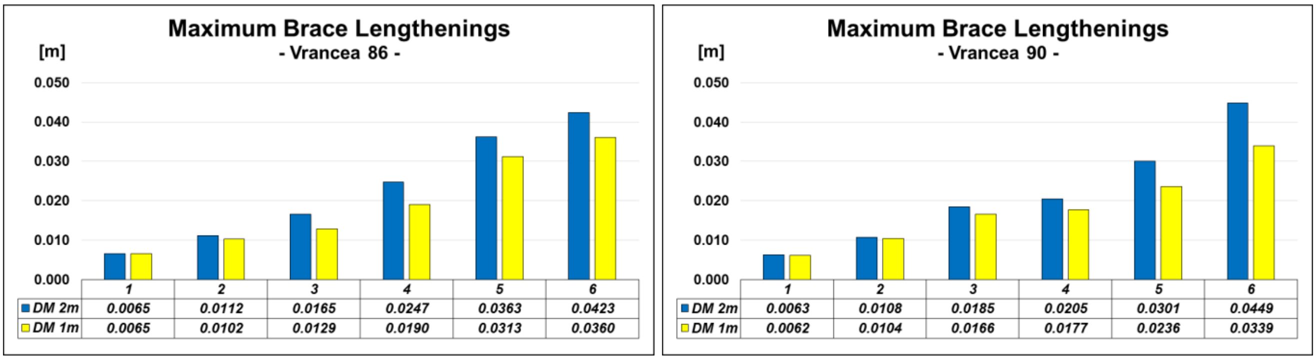
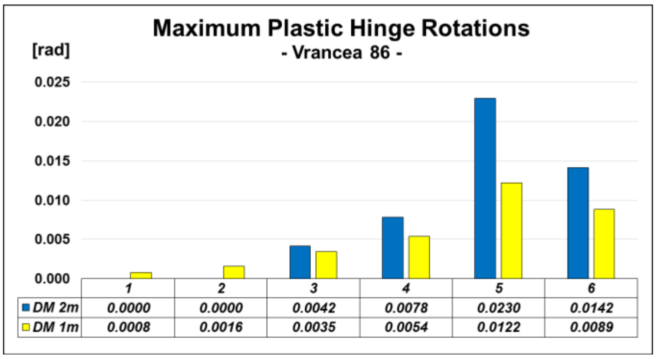


Fig. 2. 7 Maximum brace lengthenings (Vrancea 86, Vrancea 90) - frames with six storey

Regarding the rotations in the potentially plastic zones located along the frame girders, it can be observed that the highest values were obtained for the DM-2m frame. During the dynamic nonlinear analyses with the Vrancea 86 and Vrancea 90 acceleration records, for the DM-2m frame no inelastic rotations could be noticed in the potentially plastic zones at the first two storeys of the structure (see

Fig. 2.8). On average, the values noticed for the DM-1m frame were about 34% lower than those obtained for the DM-2m frame (Vrancea 86).



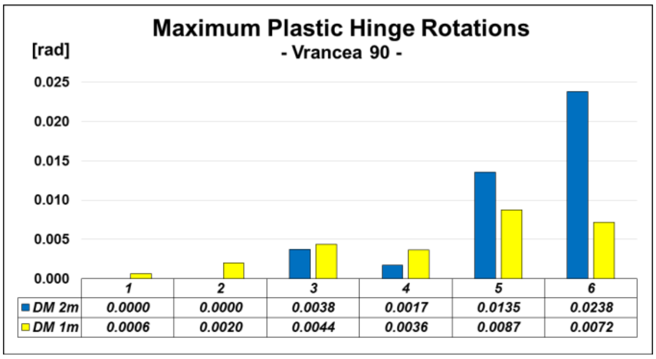


Fig. 2. 8 Maximum plastic hinge rotations (Vrancea 86, Vrancea 90)

2.1.3 Maximum member forces

During dynamic nonlinear analyses, smaller values of axial forces and bending moments were usually recorded in the beams of the DM-2m frame, compared to the DM-1m frame. In case of axial forces, the values were quite close. The values of axial forces in the beams of the DM-1m frame were about 0.6% higher, compared to those recorded for the frame with potentially plastic zones located at about 2m from the columns axes (see Fig. 2.9).

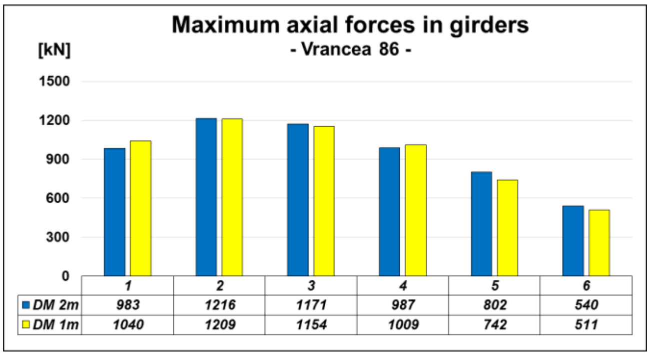


Fig. 2. 9 Maximum axial forces along girders

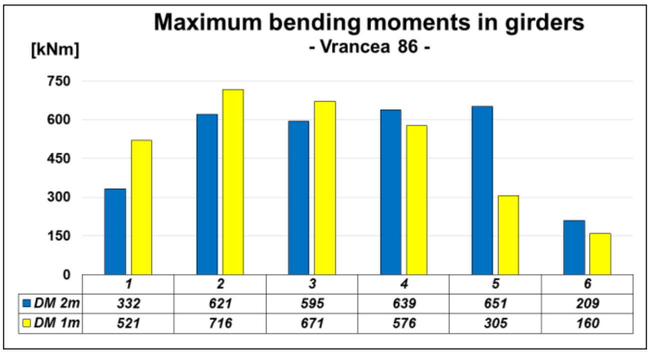


Fig. 2. 10 Maximum bending moments in the frame girders

On average, the values of the bending moments observed in the beams of frame DM-2m were approximately 5% lower than those recorded in the case of frame DM-1m (see Fig. 2.10).

Higher axial force values could be observed during dynamic nonlinear analyses in the central columns of frame DM-2m, compared to the ones noticed for frame DM-1m.

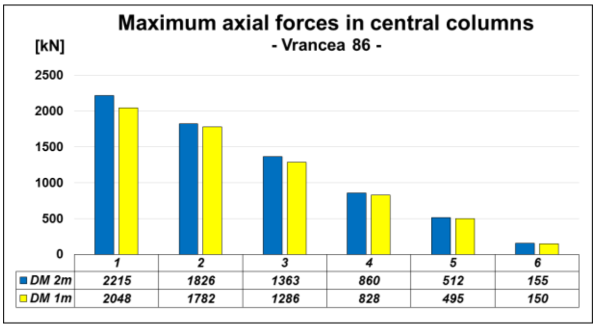


Fig. 2. 11 Maximum axial forces in central columns

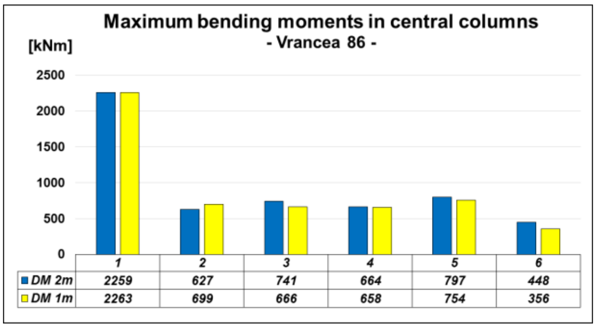


Fig. 2. 12 Maximum bending moments in central columns

In case of frame DM-1m the values of axial forces were on average about 5% lower than in case of frame DM-2m (see Fig. 2.11).

On average, the maximum bending moment values in the central columns of frame DM-1m were about 3% lower than in case of frame DM-2m (see Fig. 2.12).

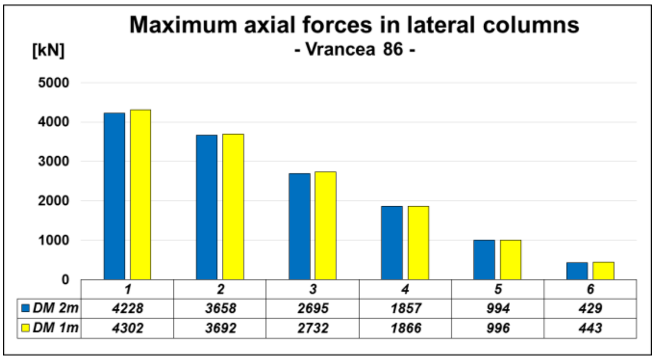


Fig. 2. 13 Maximum axial forces in lateral columns

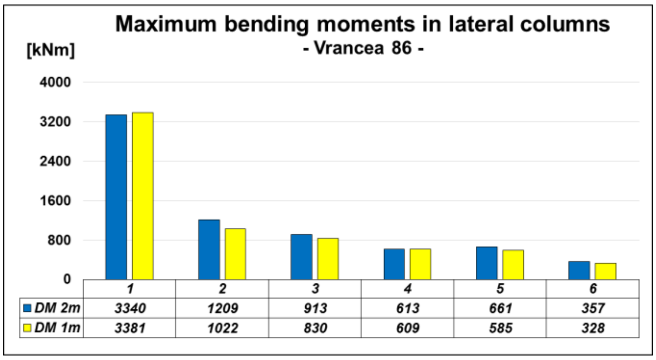


Fig. 2. 14 Maximum bending moments in lateral columns

On average, the maximum values of the axial forces in the lateral columns were about 1% higher in case of frame DM-1m, compared to those in frame DM-2m (see Fig. 2.13). The maximum values of the bending moments observed during the dynamic nonlinear analyses in the lateral columns were about 5% lower for frame DM-1m compared to frame DM-2m (see Fig. 2.14).

2.1.4 Dissipated energy during dynamic nonlinear analyses

The components of the dissipated energy during dynamic nonlinear analyses of six storeyed frames with Vrancea 86 acceleration records are indicated in the Fig. 2.15 and Fig. 2.16.

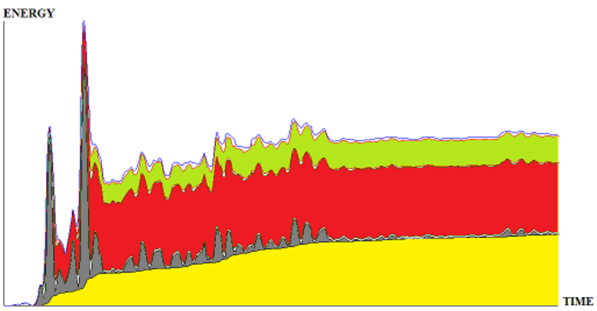


Fig. 2. 15 Dissipated energy. Frame DM 1m (Vrancea 86)

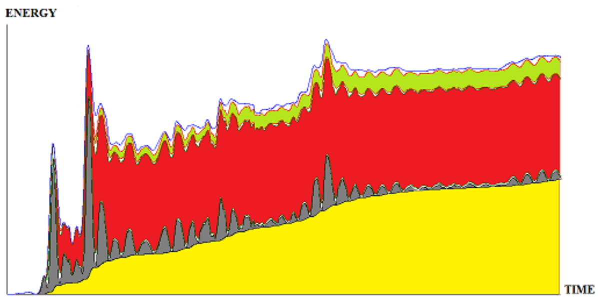


Fig. 2. 16 Dissipated energy. Frame DM 2m (Vrancea 86)

In all these figures, the yellow zone represents the amount of energy consumed through damping, the gray zone represents the kinetic energy, and the white zone represents the amount of energy consumed through plastic deformations in unwanted zones, the red zone represents the amount of energy consumed through plastic deformations in the diagonals and the green zone represents the amount of energy dissipated through inelastic deformations in the potentially plastic zones from girders.

By analysing the graphic in the Fig. 2.16, it can be noticed that in case of frame DM-2m, the amount of energy dissipated through inelastic deformations in the diagonals has a higher share than the energy dissipated through inelastic deformations in the potentially plastic zones of the girders (the red surface has a larger area than the green one). By comparison with Fig. 2.15 it can be noticed that the mechanical work consumed through inelastic deformations in the potentially plastic zones along the girders has a higher value for frame DM-1m compared to frame DM-2m, and the amount of energy dissipated through plastic deformations in the diagonals has a higher value for frame DM-2m, compared to frame DM-1m.

2.2 Seismic behaviour of ten storeyed concentrically braced frames

2.2.1 Extreme values for base shear forces and horizontal displacements

For the ten storeys structures, the highest values of base shear force were observed during the dynamic nonlinear analysis with the Vrancea 77 acceleration record for both frames (DM-1m and respectively DM-2m) for the same sense of the seismic action. The difference was about 14%.

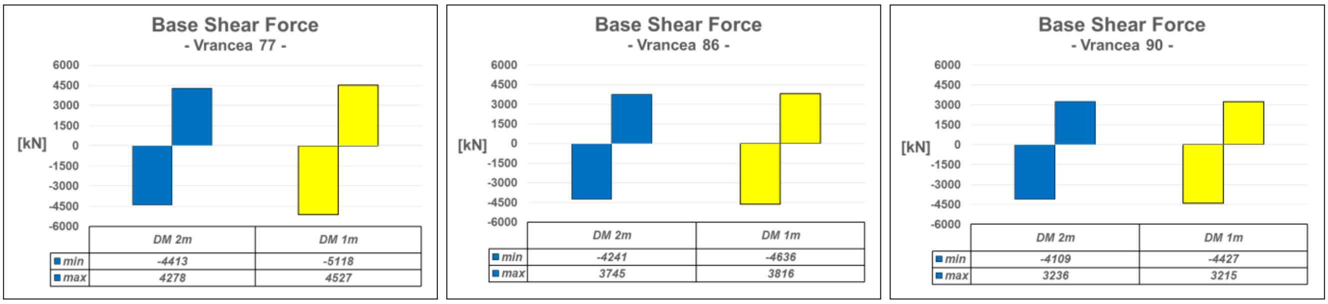


Fig. 2. 17 Extreme base shear force values (Vrancea 77, Vrancea 86, Vrancea 90) - frames with ten storeys

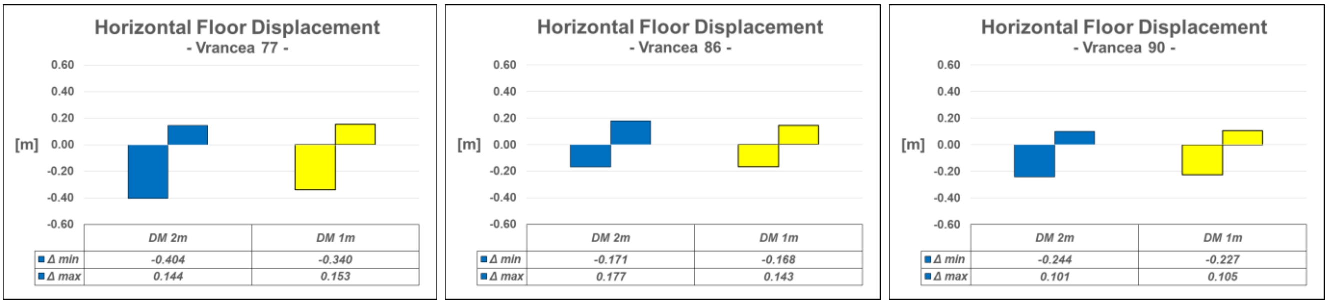


Fig. 2. 18 Extreme horizontal floor displacements (Vrancea 77, Vrancea 86, Vrancea 90) - frames with ten storeys

The highest values of the horizontal displacements were observed for the frames with ten storeys from the dynamic nonlinear analysis in which the Vrancea 77 acceleration record was used. The highest values of the horizontal displacements were obtained for the frame DM-2m. For the two frames with ten storeys, the difference between the maximum values of lateral displacements was about 16% (see Fig. 2.18).

Analysing the values from Fig. 2.17 and Fig. 2.18 it can be noticed that the extreme values for the base shear forces and the horizontal displacements for the ten storeys frames were recorded with small exceptions, during the dynamic nonlinear analyses with the Vrancea 77 acceleration record.

2.2.2 Maximum inelastic deformations along diagonals and girders

The largest values of plastic deformations recorded in the diagonals of the ten storeyed frames were obtained for frame DM-2m from the analysis performed with the Vrancea 77 acceleration record. On average, the difference between the values of brace lengthenings obtained for the structures with ten storeys was about 22% (see Fig. 2. 19).

Regarding the rotations in the potentially plastic zones located along the frame girders, it can be observed that the highest values were obtained for frame DM-2m. The values for frame DM-1m were on average, about 40% lower compared to the ones obtained for frame DM-2m (see Fig. 2. 20).

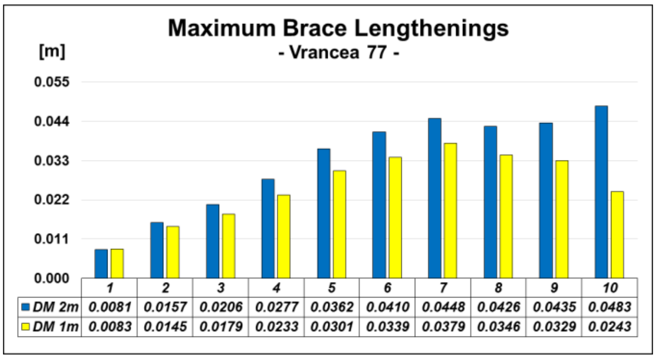


Fig. 2. 19 Maximum brace lengthenings

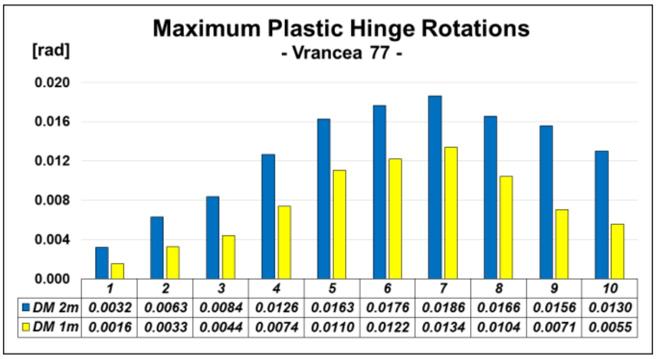


Fig. 2. 20 Maximum plastic hinge rotations

2.2.3 Maximum member forces

In case of the girders of frame DM-2m, during dynamic nonlinear analyses, lower values of axial forces and bending moments were usually recorded, compared to frame DM-1m. In case of axial forces the values were quite close. The values of axial forces in the girders of frame DM-1m are about 0.3% higher, compared to those recorded in the frames where the potentially plastic zones were positioned at about 2m from the frame columns axes (see Fig. 2.21).

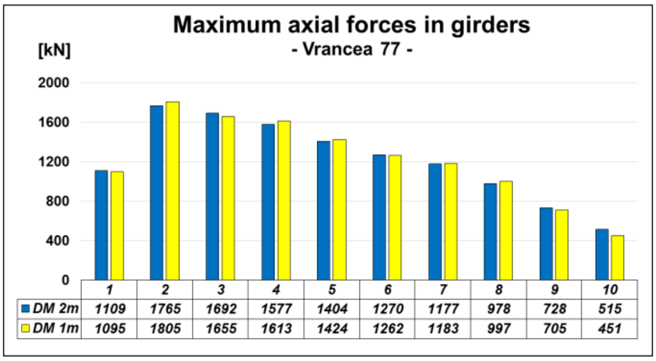


Fig. 2. 21 Maximum axial forces along girders

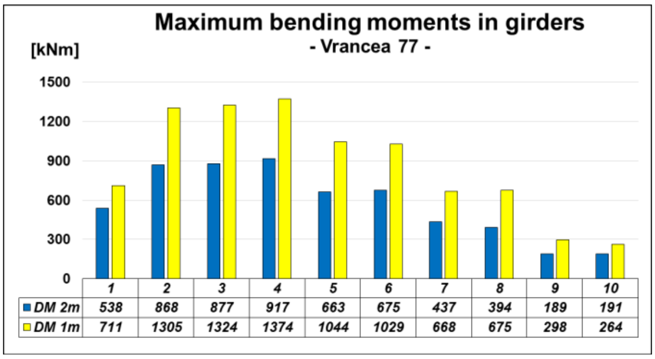


Fig. 2. 22 Maximum bending moments in the frame girders

On average, the values of the maximum bending moments observed in the girders, in case of frame DM-2m were about 34% lower, compared to those recorded in case of frame DM-1m (see the values in Fig. 2.22).

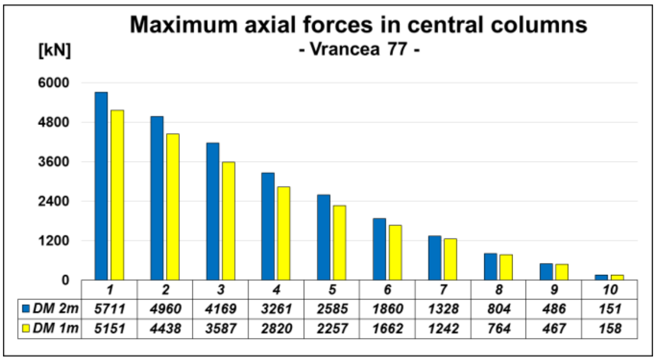


Fig. 2. 23 Maximum axial forces in central columns

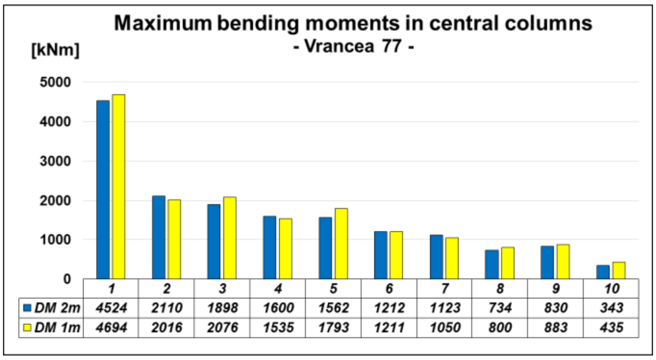


Fig. 2. 24 Maximum bending moments in central columns

During dynamic nonlinear analyses, higher values of axial forces can be observed in the central columns of frame DM-2m, compared to those found in frame DM-1m. On average, in case of frame DM-1m, the values of the axial forces in the central columns were approximately 11% lower compared to the ones recorded for frame DM-2m (see Fig. 2.23).

On average, the maximum bending moment values noticed in case of the central columns of frame DM-1m were about 4% larger than those found in case of frame DM-2m (see Fig. 2.24).

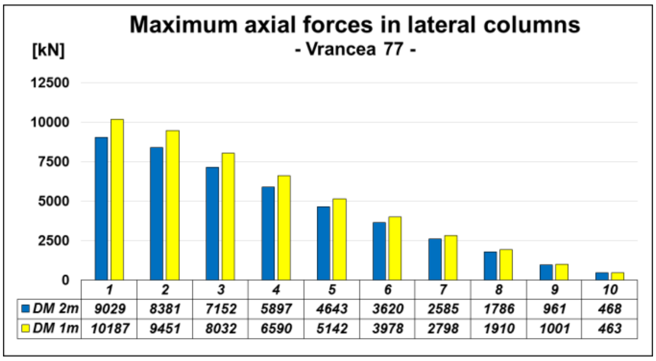


Fig. 2. 25 Maximum axial forces in lateral columns

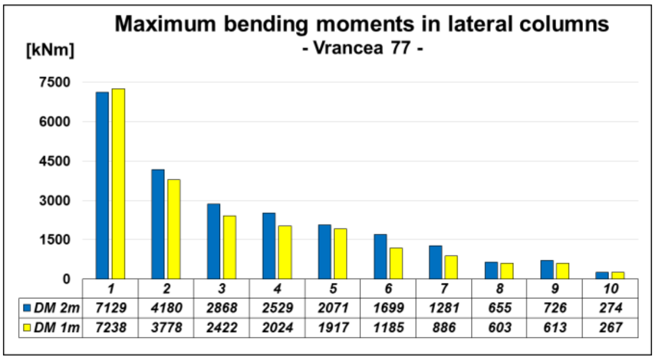


Fig. 2. 26 Maximum bending moments in lateral columns

On average, the maximum values of the axial forces in the lateral columns were about 10% higher in case of frame DM-1m, compared to frame DM-2m (see Fig. 2.25).

The maximum values of bending moments, observed during dynamic nonlinear analyses in the lateral columns were lower on average with about 11% for frame DM-1m, compared to frame DM-2m (see Fig. 2.26).

2.2.4 Dissipated energy during dynamic nonlinear analyses

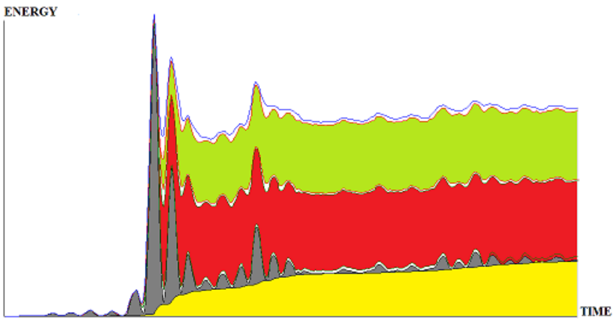


Fig. 2. 27 Dissipated energy. Frame DM1m (Vrancea 77)

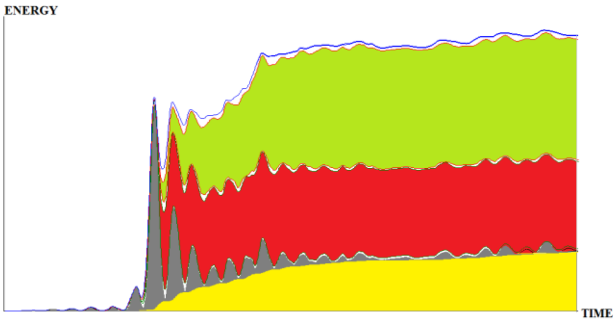


Fig. 2. 28 Dissipated energy. Frame DM2m (Vrancea 77)

In the Figures 2.27 and 2.28 the amount of energy dissipated by the analysed frames during the dynamic nonlinear analyses with the Vrancea 77 acceleration record is indicated. In these figures, the yellow zone represents the amount of energy consumed through damping, the gray zone represents the kinetic energy, and the white zone represents the amount of energy consumed through plastic deformations in unwanted zones. The red zone represents the amount of energy consumed through plastic deformations in the diagonals and the green zone represents the amount of energy dissipated through inelastic deformations in the potentially plastic zones of the girders.

Analysing Fig. 2.28, it can be seen that in the case of the frame DM-2m, the amount of energy consumed by plastic deformations in the diagonals has a lower share, than the energy consumed in the potentially plastic zones of the girders (the surface coloured in red has a smaller area than the one coloured in green). In case of frame DM-1m (see Fig. 2.27) it can be observed, that the area of the red surface is approximately equal to the one of the green surface, and the values of mechanical work consumed by plastic deformations at the diagonals and girders are comparable in case of frame DM-1m.

Comparing Fig. 2.27 and Fig. 2.28 it can be noticed, that the amount of energy consumed through post elastic deformations in the potentially plastic zones along the girders is much higher for frame DM-2m compared to frame DM-1m (in Fig. 2.28 the green surface area is significantly larger than in case of Fig. 2.27).

It can be concluded that in case of placing the potentially plastic zones of the girders at a distance of approximately 2m from the axes of the frame columns, the energy consumed by plastic deformations is significantly higher than in case of placing the potentially plastic zones of the girders at about 1m from the axes of the frame columns.

2.3 Estimated steel consumption for the analysed structures

For both considered locations of the potentially plastic zones along the girders, the same values were obtained for the estimated steel consumption for diagonals and central columns, in case of both categories of frames with six and ten storeys.

Lower values of the estimated steel consumption for the girders were obtained in case of positioning the potentially plastic zones along the girders at approximately 2m from the axes of the frame columns, (frame DM06-2m and respectively DM10-2m). Compared to these values, for frame DM06-1m the estimated steel consumption was about 34% higher and respectively for frame DM10-1m about 29% higher (see Fig. 2.29 and respectively Fig. 2.30). The location of potentially plastic zones along the girders at a greater distance from the axes of the frame columns, leads to their sizing at lower bending moments values and to smaller cross-sections for the potentially plastic zones along the girders and for the current zones of the frame girders (the beam segments outside the potentially plastic zones).

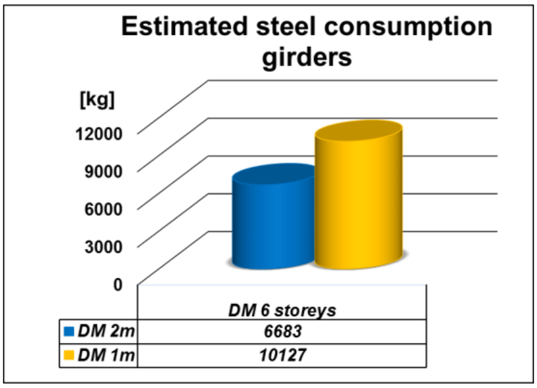


Fig. 2. 29 Estimated steel consumption for girders (DM06)

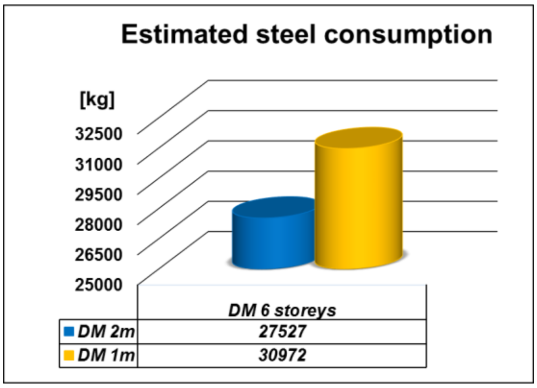


Fig. 2. 30 Estimated steel consumption (DM06)

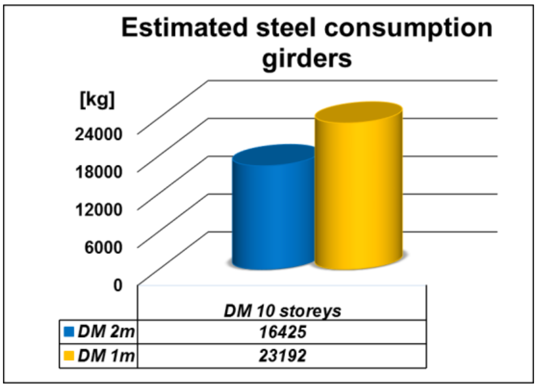


Fig. 2. 31 Estimated steel consumption for girders (DM10)

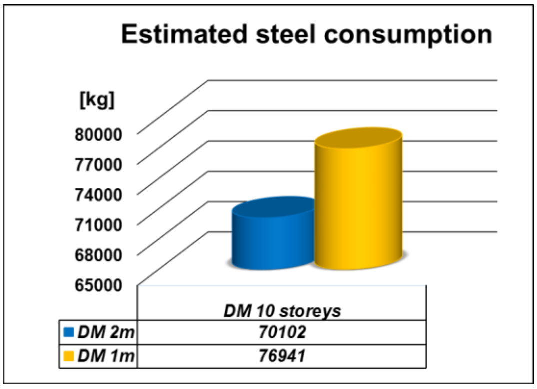


Fig. 2. 32 Estimated steel consumption (DM10)

For the two considered locations of the potentially plastic zones along the girders, the same estimated material consumption value was obtained for the lateral columns in the case of the six storeys frames. For the ten storeys frames the values of the estimated material consumption for lateral columns were very close.

In case of frame DM06-2m and respectively of frame DM10-2m smaller values of the total estimated steel consumption were obtained. When the potentially plastic zones were placed along the frame girders at about 1m from the column axes, the estimated total steel consumption was about 11% higher for frame DM06-1m compared to frame DM06-2m and respectively about 9% higher in the case of frame DM10-1m compared to frame DM10-2m (see values from Fig. 2.30 and Fig. 2.32).

2.4 Conclusions

The constructive solution with the potentially plastic zones located at about 2m from the axes of the columns leads to higher values of horizontal floor displacements with up to 16% and to lower base shear forces values with up to 14%, compared to the constructive solution in whit the potentially plastic zones positioned at about 1m from the axes of the columns.

The highest values of inelastic deformations in girders and diagonals (rotations in potentially plastic zones along the frame girders and respectively braces lengthenings) were obtained for the frames with the potentially plastic zones positioned along the girders at about 2m from the frame columns axes. The recorded braces lengthenings were about 22% larger, and the rotations in the potentially plastic zones were up to 40% greater, compared to the frames with the potentially plastic zones along the girders positioned at about 1m from the columns axes.

The constructive solution with the potentially plastic zones positioned at about 1m from the columns axes leads to higher bending moment values in the girders compared to the constructive solution in with the potentially plastic zones positioned at about 2m from the columns axes. The maximum values recorded for axial forces and bending moments during dynamic nonlinear analyses in the other categories of structural elements were comparable. Differences of up to 12.5% were found for axial forces in the lateral columns, differences of up to 10.8% for axial forces in the central columns and generally differences of less than 5% for axial forces and bending moments in the other categories of structural elements.

The constructive solution with the potentially plastic zones placed along the frame girders at about 2m from the columns axes leads to smaller estimated steel consumption values of up to 11% for the six storeys frames and about 9% for the ten storeys frames, compared to the solution with the location of the potentially plastic zones along the girders at about 1m from the column axes. These differences can be explained in particular by the larger cross-sections obtained for the girders when the potentially plastic zones in the girders are placed closer to the columns.

Both considered constructive solutions had a favourable behaviour during the dynamic nonlinear analyses with the development of plastic hinges only in the considered dissipative zones.

The constructive solution with the potentially plastic zones positioned at about 1m from the columns axes is preferred, if during severe earthquakes lower post elastic deformations and implicitly lower costs of possible repair operations are wanted. If a smaller steel consumption is wanted the constructive solution with the potentially plastic zones positioned at about 2m from the columns axes is preferred.

3 References:

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