Seismic behaviour of ten storeyed concentrically braced frames

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Abstract. The present paper is intended to illustrate the main advantages and disadvantages of four different ten storeyed concentrically braced frames designed under severe seismic actions. All structural members (braces, beams and columns) had built up I-shaped cross-sections, sized according to the provisions of P100-1/2013 and SR EN 1993-1-1. Each of the four considered braced frames were subjected to nonlinear dynamic analyses, using three base excitations (from the 1977-, 1986- and 1990-Vrancea earthquakes), recorded at the INCERC Institute in Bucharest, calibrated all to a peak ground acceleration value of about 0.3 times the acceleration of gravity. Rayleigh damping was taken into consideration. The maximum values of inelastic deformations, bending moments and axial forces in various structural elements, the amount of energy dissipated through plastic deformations and the estimated steel consumption were compared. The extreme values of base shear forces and horizontal displacements were observed. The successive formation of plastic hinges in the different braced frames was analysed.

1. Introduction

A ten storeyed structure located in Bucharest, Romania was considered, having two spans and four bays of 6.0m. The storey height was 3.5m. Two pairs of the concentrically braced were provided on each main direction of the structure, as indicated in Figure 1.

Figure 1. Plan view of the structure with the location of the braced frames.

Four distinct bracing configurations were taken into consideration for the concentrically braced frames. Each frame equipped with a distinct bracing system (see Figure 2), was sized for the same seismic action, evaluated according to the provisions of the in charge Romanian seismic design code P100 - 1/2013 [1].

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 [2]. The webs of the braces cross-sections were placed normally to the plane of the frames (in order to ensure the in-plane buckling of the diagonals), while the cross-sections of the frames girders and columns are orientated with the webs in the bracing plane.
The following steps were considered in the design:
- At first the diagonals were sized as primary dissipative elements to the forces generated by the non-amplified seismic design load $S_{code}$ [1, 3]. Then an amplification factor ($\Omega^N$) was evaluated for the designed cross-sections of the diagonals.
- Secondary dissipative elements (potentially plastic zones with reduced cross-sections, located along the frame girders at about 1.0m from the column axes [4]) were sized for the forces produced by an amplified seismic load ($1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot S_{code}$) [5, 6]. For the cross-sections of these potentially plastic zones an additional amplification factor ($\Omega^M$) was evaluated.
- 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 ($1.1 \cdot \gamma_{ov} \cdot \Omega^N \cdot 1.1 \cdot \gamma_{ov} \cdot \Omega^M \cdot S_{code}$) [5, 6].

Where:
- $\Omega^N$ is the minimum value of $\Omega^N_i$; $\Omega^N = \min\{\Omega^N_i\}$;
- $\Omega^N_i = N_{pl,Rd,i}/N_{Ed,i}$, $N_{pl,Rd,i}$ is the plastic tensile design resistance of diagonal “i” and $N_{Ed,i}$ is the design value of the axial force in the same diagonal “i” in the seismic design situation [1, 3];
- $\Omega^M$ is the minimum value of $\Omega^M_i$; $\Omega^M = \min\{\Omega^M_i\}$;
- $\Omega^M_i = M_{pl,N,Rd,i}/M_{Ed,i}$, $M_{pl,N,Rd,i}$ is the plastic flexural design resistance of the potentially plastic zone “i” taking into account the presence of the axial force $N_{Ed,i}$;
- $M_{Ed,i}$ and $N_{Ed,i}$ are the design values of the bending moment and axial force in the same potentially plastic zone “i” in the seismic design situation [1, 3];
- $\gamma_{ov}$ is the over-strength factor of the material (the ratio between the expected yield strength value and the nominal yield strength value); according to P100-1/2013 [1] for S235 steel $\gamma_{ov} = 1.40$.

The first three modal periods of the designed frames are indicated in Figure 3.

**Figure 2.** Considered concentrically bracing configurations.

**Figure 3.** Modal periods of the designed frames.
All four concentrically braced frames resulted after the design, were subjected to dynamic nonlinear analyses [7] using the N-S components of Vrancea acceleration records from 04.03.1977, 31.08.1986 and 30.05.1990, 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 [7].

2. Extreme values for base shear forces and horizontal displacements
The smallest base shear values during dynamic nonlinear analyses could be noticed for frame DC, while the largest values could be noticed for frame X. The differences were up to 10% for one sense of motion, respectively about 6.2% for the opposite sense of motion (see the values in Table 1).

![Figure 4. Extreme horizontal floor displacements.](image)

In most situations, the largest horizontal floor displacements during dynamic nonlinear analyses were recorded for frame DC, while the smallest values were observed for frame 2X and frame X (see the values in Table 2 and Figure 4). The maximum differences were up to 30%.

**Table 1.** Extreme base shear force values [kN].

| Accel. record | Fb | DC   | DM   | X    | 2X   |
|---------------|----|------|------|------|------|
| **VN 77**     |    |      |      |      |      |
| min           | -4896 | -5118 | -5200 | -5202 |
| max           | 4392  | 4527  | 4848  | 4609  |
| **VN 86**     |    |      |      |      |      |
| min           | -4471 | -4636 | -4880 | -4625 |
| max           | 3937  | 3816  | 4084  | 3548  |
| **VN 90**     |    |      |      |      |      |
| min           | -4136 | -4427 | -4652 | -4442 |
| max           | 3229  | 3215  | 3275  | 2986  |

**Table 2.** Extreme horizontal floor displacement values [m].

| Accel. record | Fb   | DC       | DM       | X        | 2X        |
|---------------|------|----------|----------|----------|----------|
| **VN 77**     |      |          |          |          |          |
| min           | -0.3918 | -0.3396  | -0.3005  | -0.3074  |
| max           | 0.1645  | 0.1527   | 0.1903   | 0.1658   |
| **VN 86**     |      |          |          |          |          |
| min           | -0.1814 | -0.1675  | -0.1383  | -0.1513  |
| max           | 0.1532  | 0.1441   | 0.1297   | 0.1431   |
| **VN 90**     |      |          |          |          |          |
| min           | -0.2389 | -0.2267  | -0.2028  | -0.2143  |
| max           | 0.1020  | 0.1058   | 0.0889   | 0.1283   |
In case of all four frames, the largest values for horizontal floor displacements and for base shear forces were obtained for the dynamic nonlinear analyses using the Vrancea-77 acceleration record. The smallest values were recorded in most situations in case of the dynamic nonlinear analyses with the Vrancea-86 acceleration record.

3. Maximum inelastic deformations along diagonals and girders
All considered concentrically braced frames had a favourable behaviour during the dynamic nonlinear analyses, having all inelastic deformations concentrated along the diagonals and in the potentially plastic zones placed along the frame girders and near the bottom of all first storey columns (see Figure 5).

![Figure 5](image1.png)

**Figure 5.** Plastic deformations distributions at 7.02 seconds from the start of the dynamic nonlinear analyses (Vrancea-77).

Generally the largest inelastic deformations along the diagonals could be noticed in the upper storeys of frame DC and 2X and in the lower storeys of frame X, for all considered acceleration records (see Figures 6 and 7). On the contrary, the smallest plastic deformations in the diagonals were recorded in the first five storeys of frame DC and DM, respectively in the last four storeys of frame X.

The maximum deformations along the diagonals were on average up to 12% smaller for frame X, compared to frame DC for the dynamic nonlinear analyses with the Vrancea-90 acceleration record. In case of the analyses using the Vrancea-77 acceleration record the maximum brace lengthenings were on average about 21% larger for frame DC compared to frame DM.

![Figure 6](image2.png)  
**Figure 6.** Maximum inelastic deformations in the braces (VN 90).

![Figure 7](image3.png)  
**Figure 7.** Maximum inelastic deformations in the braces (VN 77).
In most cases during the dynamic nonlinear analyses using the Vrancea-77 and Vrancea-90 acceleration records, the largest plastic hinge rotations were recorded along the girders of frame DC and the smallest values were observed for frame DM and frame X (as indicated in Figure 8). The maximum differences were about 32% for the analyses with the Vrancea-77 acceleration record and over 83% in case of the analyses using the Vrancea-90 acceleration record.

![Figure 8. Maximum plastic deformations in the girders (VN 77).](image)

![Figure 9. Maximum plastic deformations in the girders (VN 86).](image)

Inelastic deformations did not appear along many girders during the dynamic nonlinear analyses with the Vrancea-86 acceleration record (see Figure 9).

The components of the dissipated energy during dynamic nonlinear analyses with different acceleration records are indicated in the Figures 10-13. In all these figures zone 1 (the yellow zone) represents the amount of energy consumed through damping, zone 2 (the black zone) represents the kinetic energy, zone 3 (the green zone) represents the amount of energy consumed through plastic deformations in the diagonals, zone 4 (the red zone) represents the amount of energy dissipated through inelastic deformations in the potentially plastic zones placed in the girders, zone 5 (the blue zone) represents the amount of energy consumed through plastic deformations in unwanted zones (outside the diagonals and the potentially plastic zones located along the frame girders and near the bottom of all first storey columns).

![Figure 10. Dissipated energy. Frame X-VN77.](image)

![Figure 11. Dissipated energy. Frame DC-VN77.](image)

By analysing the graphics in the Figures 10 and 11, it can be observed on one hand, that the area of the red zone (the amount of energy dissipated through inelastic deformations in the girders) is smaller in case of frame X (see Figure 10), compared to frame DC (see Figure 11). This fact can be explained by the larger plastic hinge rotations noticed in the potentially plastic zones located in the girders of frame DC compared to the ones in frame X (see the graphics and values in Figure 8).

On the other hand, it can be noticed that the area of the green zone (the amount of energy dissipated through plastic deformations in the diagonals) is larger in case of frame X (see Figure 10), compared to frame DC (see Figure 11). This fact can be explained by the greater number of diagonals in frame X compared to frame DC and by the fact that the values of the plastic lengthening of the diagonals are in most cases in the same range for frame X and frame DC (as shown in Figure 7).
The dissipated energy during the dynamic nonlinear analyses with the Vrancea-77 acceleration record is indicated in Figure 10 for frame X and frame DC.

**Figure 12.** Dissipated energy. Frame DC-VN86.

**Figure 13.** Dissipated energy. Frame DC-VN90.

By analysing the graphics in the Figures 11, 12 and 13, it can be observed, that the largest amount of energy dissipated through plastic deformations (respectively the largest inelastic deformations along the diagonals and girders) were obtained for the dynamic nonlinear analysis with the Vrancea-77 acceleration record, while the smallest values could be noticed for the Vrancea-86 acceleration record. The areas for the green and red zones are the largest for the dynamic nonlinear analysis with the Vrancea-77 acceleration record (see Figure 11), are respectively smaller for the Vrancea-90 acceleration record (as indicated in Figure 12), and respectively are the smallest in case of the Vrancea-86 acceleration record (as shown in Figure 13).

4. Maximum member forces

In most cases, the largest axial force values recorded along the girders during dynamic nonlinear analyses, were observed in case of frame DM and the smallest ones in case of frame 2X. These differences were on average up to 44% (see Figure 14).

The smallest bending moments along the frame girders were noticed for frame X and the largest for frame DM (see Figure 15). On average the values of the bending moments in the girders of frame DM were about 40% larger than the ones in frame X, up to 24% greater than the values in frame 2X and about 7% larger than the values in frame DC.

**Figure 14.** Maximum axial forces along girders.

**Figure 15.** Maximum bending moments in the frame girders.

In most situations during dynamic nonlinear analyses the largest values for bending moments and axial forces could be noticed along the central columns of frame DC, respectively in the lateral columns of frame DM.

The maximum axial forces along the central column of frame DC were up to 12% larger, compared to frame DM, over 60% bigger than for frame X and about 63% greater than in case of frame 2X (see Figure 16).
The values of the maximum bending moments recorded along the central column of frame DC were about 6% greater compared to frame DM, up to 27% bigger than for frame 2X and about 40% greater than for frame X (see Figure 17).

![Figure 16. Maximum axial forces along central columns.](image1)

![Figure 17. Maximum bending moments along central columns.](image2)

For the lateral columns, the maximum axial forces noticed in case of frame DM were about 19% larger than the ones in frame 2X, up to 20% greater than the values in frame X and about 32% larger compared to frame DC (see Figure 18).

The values of the maximum bending moments recorded along the lateral columns of frame DM were about 8% greater compared to frame DC, up to 11% larger than for frame 2X and about 18% greater than for frame X (see Figure 19).

![Figure 18. Maximum axial forces along lateral columns.](image3)

![Figure 19. Maximum bending moments along lateral columns.](image4)

In case of frame DM and frame DC the horizontal component of the axial forces in the diagonals is balanced by axial forces along the girders, while the vertical component of the axial forces in the diagonals is balanced by axial forces along the columns.

In the case of frame X, on one hand, two braces are intersecting each other at each floor on the lateral columns. On the other hand, four braces are crossing each other at every floor level on the central column. 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 braces, while the columns have to carry a smaller vertical component of the axial forces developed along the diagonals. For the 2X-braced frames this happens only at every second floor. In the case of frame DM and frame DC, the forces in the braces on two consecutive storeys are not conditioning each other directly and the axial forces in the girders and columns will be larger.

The smaller axial forces values generated by horizontal seismic actions along the girders of the 2X-braced frames, compared to the ones along girders of the DM- and DC-braced frames, could be explained by the fact, that in case of the 2X bracing system, two diagonals are intersecting each other in front of the lateral columns, except for the last storey. The horizontal projections of the axial forces in the two diagonals, which are intersecting each other in front of the lateral columns, (which are generating
axial forces in the frame girder), are partially balancing each other. A smaller axial force will appear in the frame girder in the intersection point of the two braces. The axial force in the girder will be proportional to the difference between the axial forces values developed in the two concurrent diagonals, projected horizontally along the frame girder!

5. Estimated steel consumption
The smallest total estimated steel consumption value was obtained for frame X, while the largest value was observed for frame DM. Compared to frame X, the overall steel consumption was about 22% larger for frame DM, about 12% greater for frame DC and up to 9% larger in case of frame 2X (see Figure 20). The smaller material consumption obtained for frame X can be explained by the smaller member forces and smaller cross-sections obtained for the girders and columns of the X-braced frame, compared to those equipped with a DC-, DM- or 2X-bracing system.

The smallest estimated steel consumption value for the diagonals was obtained in case of frame DC and the largest one for frame X (see Figure 21). The differences were about 28.4% and can be explained by the greater number of diagonal members used in case of frame X (compared to the other considered bracing systems).

For girders and lateral columns the largest estimated steel consumption values were obtained for frame DM. Compared to frame X, these values were about 36% greater for the girders and up to 21% larger in case of the lateral columns. The larger estimated steel consumption values noticed for frame DM in case of the girders and lateral columns can be explained by the larger axial forces and bending moments that appeared along the girders and lateral columns in case of the DM bracing configuration (see Figures 14-15 and respectively 18-19).

The largest estimated steel consumption value for central columns was recorded in case of frame DC (see Figure 22). The differences compared to the values obtained for frame X were about 32%.

Figure 20. Overall estimated steel consumption.

![Estimated steel consumption](image)

Figure 21. Diagonals. Estimated steel consumption.

![Estimated steel consumption](image)

Figure 22. Central Columns. Estimated steel consumption.
6. Conclusions
For the considered ten storeyed frames, the largest horizontal floor displacements and the greatest inelastic deformations could be noticed in most cases during the dynamic nonlinear analyses using the Vrancea-77 acceleration record.

The smallest inelastic deformations in the diagonals and girders were recorded for frame DM (Vrancea-77) and frame X (Vrancea-86 and Vrancea-90). In most cases the largest plastic deformations were observed along the diagonals and girders of frame DC.

Generally, the largest horizontal floor displacements were observed in case of frame DC, while the smallest values were noticed for frame X. For all performed dynamic nonlinear analyses the largest base shear force values were noticed for frame X, while the smallest values were recorded in case of frame DC and frame 2X.

During dynamic nonlinear analyses, the greatest axial forces could be observed along the girders and lateral columns of frame DM and along the central columns of frame DC. The smallest axial force values were recorded during the performed dynamic nonlinear analyses along the girders and central columns of frame 2X and along the lateral columns of frame DC.

The largest bending moments during dynamic nonlinear analyses could be noticed along the girders and lateral columns of frame DM and along the central column of frame DC. The smallest bending moment values were observed in case of frame X, for all kind of structural elements.

The largest total estimated steel consumption value was obtained for frame DM, while the smallest value could be observed for frame X. Compared to frame DM, the overall estimated steel consumption was smaller with about 22% for frame X, with up to 12% for frame 2X, respectively with about 9% for frame DC.

Taking into consideration the behaviour during the dynamic nonlinear analyses and the smaller estimated steel consumption, the bracing configuration of frame X seems to be the most favourable. The main disadvantage of the X-bracing system consists in the difficulty of the emplacement of door and window openings.

The bracing configuration of frame DC is more favourable than the one of frame DM, 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 and central columns of frame DC are greater than those obtained for frame DM.

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

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