Seismic response of ½ scaled two storey reinforced concrete moment resisting frame system using nonlinear static analysis

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Abstract. Reinforced concrete (RC) frame systems represent one of the structural solutions used in seismic zones by engineers. For this reason, the importance of knowing the real seismic response for these types of structures is essential and presents the research problem studied in this article. Thus, the seismic response for two storey axial RC frame (one bay-one span) system was studied using nonlinear static analysis in ATENA software. The structural degradation of the two storey RC frame system was investigated for several steel reinforcement possibilities and three distinct RC beams cross sections. Particular attention was paid to RC beam-column joints degradation areas and to seismic energy dissipation mechanism in the marginal regions of the RC columns. Thus, it was observed a nonlinear inelastic response in the potential degradation zones with contrary effects with respect to the specified conclusions in the current seismic design norms. Also, it was studied the RC slab bending stiffness influence to horizontal structural elements (RC beams) and to vertical structural elements (RC columns) alongside the cracking mode for horizontal static actions and RC slab local degradation beside RC beam-column joint area. In these conditions, conclusions regarding the seismic response of the moment resisting (MR) RC frame system with low height regime designed according to the current seismic code were specified and an unsatisfactory seismic response was proved.

1. Introduction
The structural systems developed according to the dissipative design concept, begin to be implemented in New Zealand, USA and Japan between 1965-1970 [1-12]. Currently, this design philosophy has become a legal norm through anti-seismic regulations [13-20].

Thus, structural systems, including MR RC frame structures, have become practical solutions for seismic design by structural engineers. The phenomenological specificity regarding this dissipative concept, especially for bare-frame RC systems, consists in sufficient deformation capacity in plastic range with certain specially detailed/ reinforced critical zones which can allow the important lateral displacements of the structure without general collapse [21-25] (see figure 1).

In these conditions, the idealized global seismic response mechanism, represented in figure 2, with plastic hinges at the end of the beams (without considering the height regime of the structures) and dissipative areas developed at the extremities of the columns (in the area of restrain of the columns in the foundations), becomes a basic principle in the seismic design of the RC frame structures [23-26].
Figure 1. Phenomenological representation of the ductile and fragile behavior of the structure through the F-D relationship [23, 27].

Figure 2. The idealized global plastic mechanism considered in P100-1 code [13] for bare-frame MR RC structures required to severe seismic actions [27-28].

Thus, in the current literature [23-26] some particularities regarding the seismic energy dissipation mechanisms for pure MR RC frame systems through the lateral behaviour of the seismic-structural elements are specified.

In these conditions, it was proposed to check the theoretical specifications regarding plastic hinges development mechanisms and specific zones of local deformations in lateral RC elements for ½ scaled
GF+1F (ground floor + 1 floor) bare MR RC frame system, using nonlinear static analysis performed in ATENA 3D software [29].

In all nonlinear static analyses, the results from the experiments performed on a GF+9F dual reinforced concrete prototype [30-32] with preponderant RC frames, tested on a seismic platform in Japan [33] were taken into account.

2. Particularities regarding the procedure considered for seismic energy dissipation in case of a pure MR RC frame systems using dissipative design concept

2.1. Theoretical perception of the RC columns deformability

Reinforced concrete columns required to severe earthquake action, are considered non-dissipative vertical elements in theoretical perception of structural engineering [13-26].

These lateral elements (RC columns) do not present significant degradations/important concrete cracks/major steel reinforcements elongation in nonlinear inelastic domain for any zone, except the bottom of the ground floor and upper end for the top floor [13-26].

Another important aspect regarding RC columns deformability are the capable efforts considered exceeded in the moment of seismic event. Thus, according to P100-1 [13], it is considered a global seismic response of the RC frame structure through local plasticization mechanisms in critical (potential plastic) areas of the RC columns from bending moment effects with structural RC element stiffness/strength reduction impact.

In these conditions, pure MR RC frame structure present the idealized global plastic mechanism according to figure 2.

2.2. Theoretical perception of the RC beams deformability

Reinforced concrete beams are considered the main dissipative structural elements of the bare MR RC frame system, according to ductile design concept [13-20], [22-27], [34] (see figure 1 and figure 2).

Thus, RC beam end margins represent portions of the beam with plastic deformation/cracking and plastic rotation according to figure 3 [34], that allow through nonlinear inelastic deformations the lateral displacement of the structure and seismic energy dissipation.

2.3. Theoretical perception of the RC beam-column joints deformability

Reinforced concrete beam-column joints of the pure RC frame systems are considered in the current Romanian seismic standard [13] (standard elaborate according to foreign codes [14-20]), structural rigid components with linear-elastic behaviour/response in seismic situations.

Lateral stiffness particularity and lateral superior characteristic strength developed in accordance with the current ductile design concept [13-26] represent a consequence of the considered seismic design efforts/reinforcement method.

Thus, superior stiffness and strength to lateral loading cycles of the RC beam-column joints is similar with the lateral stiffness and strength of the RC columns.

Figure 3. Plastic hinge in fixed beam with consideration of shear force: (a) first loading cycle in one direction; (b) first loading cycle in opposite direction; (c) second loading cycle in one direction [34].
In these conditions, the RC beam-column joints are considered component part of the RC columns [13-26]. The principal explanation of this structural consideration comes from the necessity to plastic hinges development in the marginal areas of the RC beams (practically, in adjacent regions to the RC beam-column joint).

2.4. Theoretical perception of the RC slabs deformability

Reinforced concrete slabs are considered in usual seismic design conditions [13] infinitely rigid structural elements with linear-elastic response to seismic events.

Particular aspect regarding theoretical perception of the RC slabs seismic response is the slab independence in relation to the RC beam-column joint. Partial influence of the RC slab on the lateral stiffness and lateral strength of the RC beams (see figure 4) exists with a minor role on the overall behaviour of the structure (to their nonlinear inelastic deformations).

These theoretical aspects have analytical application in the seismic design phase. Thus, RC beam is calculated with effective width (with T shape – which takes into account only a portion of the real width of the slab) [13], [23-26]. In these conditions, the RC slab idealization considered in the seismic design phase can take another form in the practical seismic response.

![Figure 4. Cracking pattern of the RC slabs with the formation of the plasticizing mechanism at the limitrophe zones of the RC beams [26].](image-url)

3. Particularities regarding seismic response of a ½ scaled GF+1F bare MR RC frame system designed according to dissipative regulations

3.1. General data

Theoretical perceptions regarding seismic response of the pure MR RC frame systems were proposed to be verified with the numerical simulations for ½ scaled GF+1F pure axial frame MR RC structure represented in figure 5 [35-36]. It was considered necessary to perform numerical simulations on ½ scaled RC frame models because the structural dimensions of the RC frame prototypes are bigger than the dimensions of the seismic platform. Thus, these reductions of the RC frame models are required for a subsequent experimental research study and the obtained results will be compared with the analytical results.

In these conditions, it is desired to recognize the analytical seismic response and seismic energy dissipation mechanisms for this type of structures (pure seismic-resistant RC frame systems with low and medium height regime*) designed in accordance to the dissipative concept [13], [21-27] and described on short in section 2 [37-42].

*Note: In Ishiyama [2] the following classification according to the height regime is presented:
• small scale buildings (H≤12 m, where H=building height);
• medium scale buildings (12 m<H≤20 m, where H=building height);
• large scale buildings (20 m<H≤31 m, where H=building height);
• large scale buildings (31 m<H≤60 m, where H=building height);
• high-rise buildings (H>60 m, where H=building height).

The details regarding the general geometric dimensions of the RC frame are given in figure 5 (a). Similitude relations [30-32], [46] recognized in the engineering literature, were used in the structural scaling stage of the RC frame prototypes.

Seismic design of the RC frame structure was conducted in accordance with current Romanian standards [13], [47-50]. Structural modelling [51] and numerical simulation were performed using ATENA 3D software [29]. Mean values for the material characteristics were considered in the current research, which are presented in table 1 and table 2.

### Table 1. Steel reinforcement strength values considered in nonlinear static analyses performed with ATENA 3D software [29].

| Material name | Type                        | Elastic modulus E [MPa] | σ_y [MPa] | σ_t [MPa] | ε_{lim} |
|---------------|-----------------------------|-------------------------|-----------|-----------|---------|
| Bst 500 S     | Bilinear with Hardening     | 2.000E+05               | 575.000   | 632.500   | 0.060   |

### Table 2. Concrete strength values considered in nonlinear static analyses performed with ATENA 3D software [29].

| Material name                        | Elastic modulus E [MPa] | Poisson’s ratio µ | Tensile strength f_t [MPa] | Compressive strength f_c [MPa] |
|--------------------------------------|-------------------------|-------------------|---------------------------|--------------------------------|
| C12/15 concrete strength class       | 2.700E+04               | 0.200             | 1.570E+00                 | -2.000E+01                     |
| C16/20 concrete strength class       | 2.900E+04               | 0.200             | 1.900E+00                 | -2.400E+01                     |
| C20/25 concrete strength class       | 3.000E+04               | 0.200             | 2.200E+00                 | -2.800E+01                     |

A non-linear static analysis (push-over analyses) [24], [52-54] (figure 5 (b), figure 6) was performed with output data in crack panels configuration for all RC frame models at each lateral loading step. The “Force - Displacement” capacity curves associated to ultimate lateral capable displacements were plotted. General representation of the steel reinforcement and general structure mesh discretization scheme for the RC frame models are attached in figure 5 (c) and figure 5 (d).
Figure 5. (a) General geometric dimensions of the ½ scaled two storey RC frame models [35-36]; (b) "Pushover loading consideration for RC frame models" [36]; (c) Representation scheme of the steel reinforcement carcase for RC frame models [29], [35-36]; (d) Structural representation of the lateral elements mesh discretization for RC frame models [29], [35-36].
Several RC frames models (½ scaled GF+1F bare MR RC frame structures) were considered with the following variables*:

- RC beams cross section [35] (see figure 7);
- RC slabs thickness [36, 43] (see figure 7);
- Concrete strength class [44] (see figure 7);
- RC columns steel reinforcement ratio [45] (see figure 7);
- RC beams steel reinforcement ratio [36] (see figure 7);
- RC slabs steel reinforcement ratio [36] (see figure 7).

*Note: The very large volume of research data led to the specification of general remarks regarding the seismic energy dissipation mechanisms recorded for the analysed RC frame models which were compared with the theoretical mechanisms specified in current seismic design standards.

In several research studies [35], [36], [43], [44], [45] it was implicitly investigated the obtained values through the comparative method.

For this article, the seismic response for three RC frame models was studied. The main variable of this systematization is the cross-section height \(h_L\) of the RC beams. This variable \(h_L\) was chosen on the principle that the main dissipative elements of MR RC frame structures are the beams.

Case 1 of RC frame systems has the largest cross section of the beams in the predimensioning condition \((h_L=1/8L)\). Type 2 of RC frame systems was considered with mean dimensions of the RC
beams cross sections in the predimensioning condition \((h_L=1/12L)\). Type 3 of RC frame systems has ductile RC beams that have been predimensioned from the \(h_L=1/16L\) condition (seismic design condition specified in the new provisions for completing and amending the P100-1/2013 technical regulation).

The detailed dimensions of the RC beams, RC columns and RC slabs cross sections and afferent steel reinforcement ratio with particular concrete strength class consideration are specified in figure 7.

**Table 1.** Principal characteristics of the \(\frac{1}{2}\) scaled two storey RC frame models \((h_L\) – height of longitudinal RC beams, \(L\) – opening, \(GL\) – longitudinal RC beam, \(GT\) – transversal RC beam, \(h_s\) – slab thickness) \([35-36],[44-45],[56]\). (Note: in numerical simulation code column, \(V\) notation comes from the „Version“ word).

| Model Characteristics | Concrete | Numerical Simulation Code |
|-----------------------|----------|---------------------------|
| RC Frame Systems Type 1 | V1, V2, V3 | 4014, 4010, 4018 |
| RC Frame Systems Type 2 | V4, V5, V6 | 4019, 4010, 4018 |
| RC Frame Systems Type 3 | V7, V8, V9 | 4019, 4010, 4018 |

**Figure 7.** Principal characteristics of the \(\frac{1}{2}\) scaled two storey RC frame models (\(h_L\) – height of longitudinal RC beams, \(L\) – opening, \(GL\) – longitudinal RC beam, \(GT\) – transversal RC beam, \(h_s\) – slab thickness) \([35-36],[44-45],[56]\). (Note: in numerical simulation code column, \(V\) notation comes from the „Version“ word).
3.2. Results

3.2.1. General results
Type 1 of the RC frame models (figure 7, figure 8) laterally loaded with static forces [52-54], present the following conclusions:

- Superior longitudinal steel reinforcement ratio in RC columns, leads to superior lateral strength/stiffness for the structure [45].
- RC columns present a ductile behaviour with incursions in the nonlinear inelastic domain [45].
- RC frame models are loaded with a higher lateral force for superior concrete strength classes [44].
- Superior longitudinal steel reinforcement ratio in longitudinal RC beams leads to superior lateral strength for the structure [36].
- Large cross sections of the longitudinal RC beams determine the appearance of the principal stress/strain concentration effects at the top/inferior end margins of the RC columns with the nonlinear inelastic deformations of the RC beam-column joints [35].
- RC beams are partially deformed/cracked and they are not the principal dissipative structural elements [35].
- Steel reinforcement ratio in RC slabs has insignificant influence on the global seismic response of the structures [36], [55].

Figure 8. Representation of the fracture specific strain (in the global direction z) concentration [29] in limitrophe zones of the RC columns for V16_2 RC frame model (type 1 RC frame system – see figure 7) with concrete cracks panel in ultimate lateral loading step. (Note: V16_2 is the numerical simulation code – see figure 7).

Type 2 of the RC frame models (figure 7, figure 9) longitudinally loaded with equivalent static forces [52-54], present the following conclusions:

- Superior concrete strength classes in combination with higher steel reinforcement ratios in RC slabs lead to superior ultimate lateral displacements [44].
- Superior concrete strength classes in combination with higher longitudinal steel reinforcement ratios in RC columns and minimum longitudinal steel reinforcement ratios in RC beams lead to maximum global (horizontal) displacements of the RC frame structures. In these cases, maximum principal deformations in tensioned regions of the RC beams with ample stress/strain concentrations in the marginal areas of the RC columns is registered [44].
Superior concrete strength classes in combination with maximum longitudinal steel reinforcement ratios in RC columns, lead to higher lateral load forces of the RC frame structures (RC frame models) [44].

RC columns present significant nonlinear inelastic degradations in the marginal areas [45].

RC beam-column joints are influenced by stress-strain panel at the end regions of the RC columns and RC beams [35-36], [44-45].

RC beam-column joints present important nonlinear inelastic degradations [35-36], [44-45].

Figure 9. Representation of the fracture specific strain (in the global direction z) concentration [29] in marginal areas of the RC columns with the possibility of plastic hinges formation and general collapse of the V30 structural system (type 2 RC frame model – see figure 7). (Note: V30 is the numerical simulation code – see figure 7).

Type 3 of the RC frame models (figure 7, figure 10) horizontally loaded with equivalent static forces [52-54], present the following conclusions:

- Superior concrete strength class (C20/25) [44] in combination with superior longitudinal steel reinforcement ratio in RC columns (2.90%) [45] present the peak point of the seismic response in terms of lateral forces (V12_2 RC frame model– see figure 7).

- The ultimate specific strain in the global direction z of the RC columns registering the maximum values for C20/25 concrete strength class in combination with minimum longitudinal reinforcement ratio in RC columns (1.89%). Continuous deformation effect of the structural vertical elements (RC columns) occurs due to the:
  - transverse steel reinforcement mode;
  - longitudinal steel reinforcement yielding (elongation);
  - superior concrete strength class.

- Steel reinforcement ratio in RC slabs has insignificant influence on the global seismic response of the RC frame structure [36].

- RC beams present nonlinear inelastic deformations and do not represent the essential dissipative elements [35-36], [43-45].

- RC columns suffer significant degradations/ rotations/ cracks throughout their height [45].

- RC beam-column joints describe important cracks and do not remain in the linear-elastic domain [35-36], [43-45].
Figure 10. Representation of the fracture specific strain (in the global direction z) concentration \([29]\) on the total RC columns height/ on the entire RC beams length for ultimate lateral loading step of the V12 structural system (type 3 RC frame model – see figure 7). (Note: V12 is the numerical simulation code – see figure 7).

In addition to the general remarks of the current analytical study regarding seismic response of the RC frame models, the “F-D” capacity curves for each RC frame model type was plotted (figure 11, figure 12 and figure 13), taking into consideration: lateral deformation mode for each lateral loading step, structural degradation mode and other deformation indicators etc.

Figure 11. “F-D” capacity curves for some type 1 RC frame models (V5, V10 and V15 RC frame models), (Note: V5, V10 and V15 are the numerical simulation codes – see figure 7).
Figure 12. “F-D” capacity curves for some type 2 RC frame models (V22, V26, V28 and V30 RC frame models), (Note: V22, V26, V28 and V30 are the numerical simulation codes – see figure 7).

Figure 13. “F-D” capacity curves for some type 3 RC frame models (V2_2, V7_2 and V12_2 RC frame models), (Note: V2_2, V7_2 and V12_2 are the numerical simulation codes – see figure 7).

It is observed that type 3 RC frame models present superior seismic response with appropriate “F-D” curve shapes represented in figure 13. However, the global seismic energy dissipation mechanism for this RC frame structures type, does not correspond to the dissipative concept considered in structural engineering design [13], [22-26], [42].
3.2.2. Analytical seismic response of the RC columns
Numerical analyses of the three types scaled bare MR RC frame models, present RC columns as important dissipative structural elements.

In terms of specific strain, RC columns reach 35% of the total specific deformations of the structure (see figure 14 and figure 15) for type 1 and type 2 models. In case of type 3 models, RC columns reach 20% of the total specific deformations.

In these conditions, RC columns develop nonlinear inelastic seismic response [39, 41], [57-58] for all three types of the RC frame models (see figure 8, figure 9 and figure 10) with complex structural degradation mechanism.

**Figure 14.** Value representation of the all RC columns specific strain in the global direction z and fracture specific strain for V15 RC frame model (type 1 RC frame model), (Note: V15 is the numerical simulation code – see figure 7).

**Figure 15.** Percentage (ratio) representation of the all RC columns specific strain in the global direction z and fracture specific strain for V15 RC frame model (type 1 RC frame model), (Note: V15 is the numerical simulation code – see figure 7).
Concrete cracking panel representation of the RC columns for V30 RC frame model (where V30 is explained in figure 7) in each lateral loading step, can be studied in figure 16. Thus, it can be observed the destructive process by which the RC columns are the first required structural elements with a multitude of concrete cracks in large areas (especially for ultimate lateral loading steps).

In each horizontal loading step of the V30 RC frame structure, the plastic zones formation in marginal areas of the RC columns is emphasized. These areas are the limitrophe tensioned/compressive regions from the RC columns with contrary seismic dissipative mechanism declared in P100-1 standard [13].

In conclusion, a different seismic response (nonlinear inelastic response) of the RC columns is observed compared to the linear elastic seismic response declared in the actual seismic design standard [13] for all RC frame model types.

RC columns present important concrete cracks, significant steel reinforcement buckling and steel reinforcement elongation in the tensioned marginal areas with large inter-storey displacements and high global displacements (figure 16).

The major risk of the structural system is collapse through potential hinges, located in the column’s ends [35-36], [39-41], [43-45], [57-58].
Figure 16. Concrete cracking representation and structural deformation mode (fracture specific strain (in the global direction z) concentration at the marginal regions of the RC columns) of the V30 type 2 RC frame model – for each lateral loading step [29], (Note: V30 is the numerical simulation code – see figure 7).
3.2.3. Analytical seismic response of the RC beams

RC beams designed in accordance with the ductile concept [13-26] represent structural dissipative elements for all three models. These horizontal dissipative elements provide a concrete cracking panel (figure 16) that develop in limited potential plastic tensioned areas [38-39]. However, RC beams are sufficiently stiff and they can rotate only together with the RC slab and RC beam-column joints.

In other words, the RC beam develop plastic deformations in terms of cracked concrete/ buckled steel reinforcements in combination with other structural material (see figure 16).

In these conditions, the potential plastic hinge length of the RC beams is determined by the nonlinear degradation length of the RC slab.

Basically, the idealized global plastic mechanism represented in figure 2 for pure MR RC frame structures (with marginal plastic hinges of the RC beams) is not provided by the nonlinear deformations of the RC beams in extremities. Reinforced concrete beams form a common rigid block (with superior bending stiffness and slightly deformable) with RC slab and RC beam-column joints. This aspect can be observed through the graphical representation in figure 16.

Thus, it does not ensure the formation of the Strong Columns – Weak Beams (SCWB) [27] mechanism for all RC frame models types (see figure 7), presented in subsection 2.2 (figure 2).

3.2.4. Analytical seismic response of the RC beam-column joints

Numerical analyses of the RC frame models present important nonlinear inelastic deformations in the RC beam-column joints (see figure 17). It can be observed that the RC frame nodes do not develop a common body with the RC columns (see subsection 2.3).

Consequently, the RC beam-column joints of all RC frame type do not „borrow“ the RC columns strength and stiffness. Reinforced concrete frame nodes develop a common rigid body with RC beams and RC slab and extremely deform in all existing situations (see figure 16 and figure 17). It was observed the possibility of developing potentially plastic rupture regions in RC frame nodes (see figure 18).

![Figure 17](image-url). Nonlinear inelastic fracture specific strain (in the global direction z) for the ultimate horizontal loading step of the V30 RC frame model (type 2 RC frame model) [29], (where V30 is the numerical simulation code – see figure 7): (a) intermediate RC beam-column joint between the first storey and upper storey; (b) superior RC beam-column joint – upper storey; (c) intermediate RC beam-column joint between the first storey and upper storey.
Figure 18. Maximum fracture specific strain of the V30 RC frame model (type 2 RC frame model) (where V30 is the numerical simulation code – see figure 7) for step 25 lateral loading [29].

3.2.5. Analytical seismic response of the RC slabs

Reinforced concrete slabs of all RC frame model types ensure the horizontal forces transfer through the RC beams to vertical elements (RC columns) [55] in a different form compared to the effect specified in the literature [26], [13-26] (see subsection 2.4).

The RC slabs develop a common rigid body in combination with the RC beams and RC beam-column joints [35-36], [43-45], determining nonlinear deformations/ cracking of the marginal length (considered plastic joint) for the RC beam and synchronizing RC slabs and RC beams displacements with the RC frame nodes (see figure 16).

In these conditions, reinforced concrete beams achieve important bending strength and significant bending stiffness, „borrowing” these characteristics to adjacent lateral elements (such as RC beam-column joints).

Thus, the formed common rigid „RC slab-beams-frame nodes” block [35-36], [43-45], negatively influences the global seismic response of the RC frame models designed according to the ductile concept [13-26].
In conclusion, the following aspects regarding the reinforced concrete slabs consideration in design stage can be specified:

- The RC slab makes a common rigid body with the RC beams and RC frame nodes, naturally deforms and dictates the possible plastic hinges length in the RC beams. In this case, RC slab cannot present a linear-elastic behaviour.
- The RC slab makes a common rigid body with the RC beams and RC frame nodes, rotates simultaneously with the reinforced concrete beams. Practically, the efficient plastic rotation of the RC beams, entirely depends on the RC slab plastic rotation.

4. Conclusions

Nonlinear static analyses demonstrate significant structural degradation in every structural element for all RC frame models and active participation of the RC columns in the seismic energy dissipation mechanism.

The RC slab bending stiffness contributes to the increase of the RC beams bending stiffness. Thus, RC beams are not the seismic fundamental dissipative members in the pure MR RC frame studied.

Nonlinear static analyses revealed the formation of the common rigid ,,RC slab-beams-frame nodes” block for all RC frame models types, which causes the local nonlinear deformations in RC columns (in adjacent regions of the RC beam-column joints).

RC columns and RC frame nodes do not form a common rigid body specified in the engineering literature. Also, RC columns and RC frame nodes have a nonlinear inelastic seismic response with important plastic material degradations/cracks.

RC beams with large cross-section led to plastic hinges concentration mechanism at the marginal regions of the RC columns.

RC beams with minor cross-section led to minimal negative effects on the nonlinear inelastic seismic response of the RC columns.

Superior concrete strength classes have positive influences on the deformation mechanism of the pure MR RC frame models.

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