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STATIC NON-LINEAR ANALYSIS OF AN RC MOMENT RESISTING FRAME BY CONSIDERING DIFFERENT VALUES FOR THE LONGITUDINAL REINFORCEMENT RATIO IN THE COLUMNS

BY

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Abstract. Analytical studies regarding influences of the concrete strength class on the ductile seismic energy dissipation mechanism for RC frame systems with rigid beams, register a favorable lateral response for superior concrete class. These important results are coupled with an active cracking/ yielding of the concrete/ rebars in the compressed and tensioned areas for RC columns. In these conditions, it is studied the effectiveness of the longitudinal steel reinforcement ratio for these RC structural elements. Thus, it was performed three RC frame models with ATENA software (FEM static nonlinear analysis). These type of RC frame structures (representative model with rigid beams) studied in the previous analytical research were chosen for FEM pushover analysis because they meet the most unfavorable conditions for the nonlinear strain of RC columns. The obtained results demonstrate the structural efficacy of the superior longitudinal steel reinforcement ratio of RC columns on the ductile seismic response of the RC moment resisting frame systems.

Keywords: FEM static nonlinear analysis; RC frame system with rigid beams; longitudinal rebars; concrete strain; RC columns strain.

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1. Introduction

Reinforced concrete (RC) frame structures present particular interest in terms of severe seismic behavior, because they are widely and reliably used in current seismic design orientation by structural engineers (P100-1, 2013; ACI 318, 2011; EC 2, 2006; MCBC, 2004; BRI, 2001; NZS 3101, 2006) etc.

Thus, it was proposed to study the nonlinear behavior of these types of structures through of some representative structural RC models. These models are especially composed with boundary geometric conditions to obtain accurate analytical results (Fig. 1). After establishing all the parameters necessary for the practical construction (concrete strength class, steel reinforcement (rebar) diameters, cross sections for structural elements etc.), it is desired to evaluate the seismic performance (with observation of the real seismic energy dissipation mechanisms) of the optimal RC frame model through experimental test on the seismic platform.

In the first stage of analytical study, it was investigated the influence of the concrete strength class on the inelastic hinges formation (location) mechanism of the lateral resistance elements, considering a RC frame model with longitudinal rigid beams (Sococol *et al.*, 2020).

Following the establishment of the beneficial influence of the superior concrete strength class (C20/25) on the plastic hinges location for a RC moment resisting frame structure (with special interest on the deformability/ principal specific strains location of RC columns) (Sococol *et al.*, 2020), it was proposed to use the identical representative structural model (Fig. 1*a* with longitudinal rigid RC beams and the same inter-axis distances) to study the influence of the longitudinal steel reinforcement ratio of the RC columns in the most unfavorable limit.

In these conditions, it is used ATENA software (ATENA software, 2015) with subsequent FEM (**F**inite **E**lement **M**ethod) corrections specified in Mihai *et al*. (2010) for numerical modeling (Fig. 1*d*). Thus, it is used pushover analysis as a form of nonlinear static analysis of structural models (Fig. 1*b*) because „pushover analysis is a simplified, static, nonlinear procedure in which a predefined pattern of earthquake loads is applied incrementally to framework structures until a plastic collapse mechanism is reached. This analysis method generally adopts a lumped-plasticity approach that tracks the spread of inelasticity through the formation of nonlinear plastic hinges at the frame element's ends during the incremental loading process" (Zou and Chan, 2005; Jalilkhani *et al.*, 2020).

This representative RC frame structure with longitudinal rigid beams is a continuation of the study conducted by Sococol *et al.* (2020) and presents the same input data regarding structural analysis (Fig. 1*a*):

i) the dimensions of the ½ scaled RC frame model are: L=2.4 m, B=1.8 m;

ii) Height regime: P+1E (small scale buildings);

iii) Storey height: h_{st}=1.4 m; H_{tot}=2.8 m;

iv) Importance building class: III, according to P100-1 (P100-1, 2013);

v) Type of structure: pure RC frame (without non-structural components to avoid their negative effects (Sococol *et al.*, 2019a));

vi) Location: Iasi;

vii) Structural ductility class: DCH, according to P100-1 (P100-1, 2013).

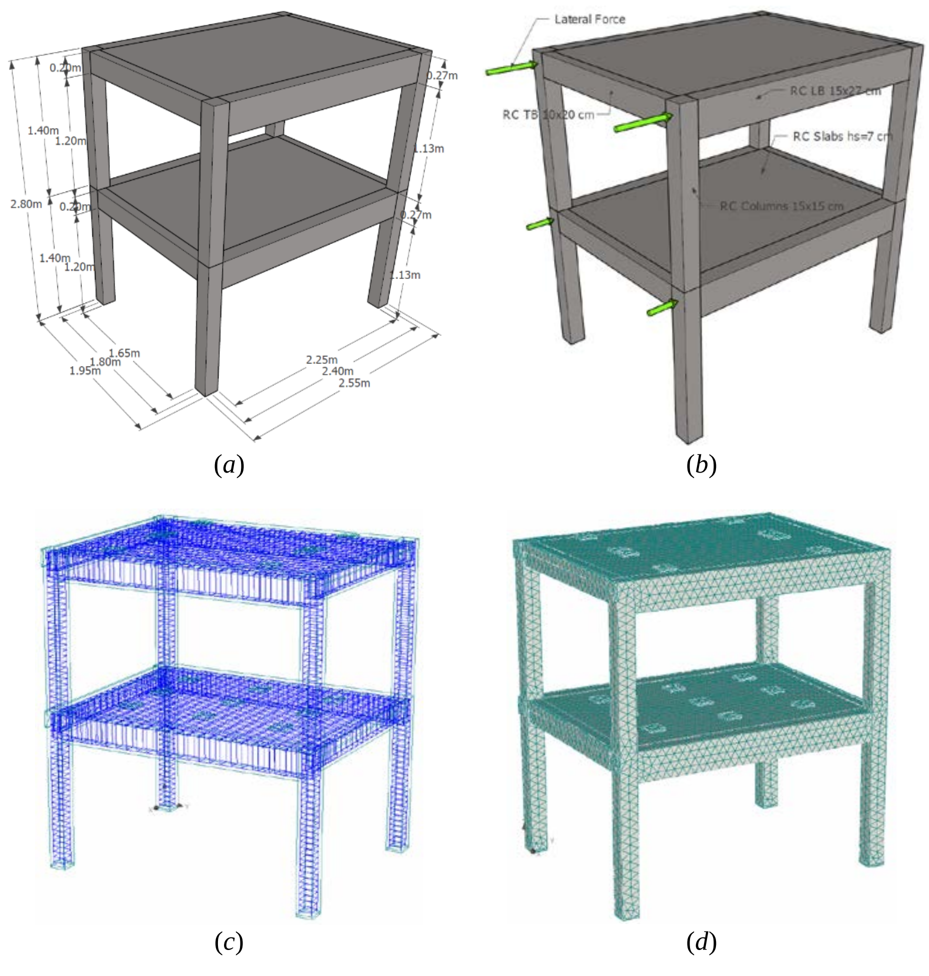


Fig. 1 − (*a*) General dimensions of the RC moment resisting frame models with longitudinal rigid beams; (*b*) Lateral static loading consideration mode for pushover performing of the RC frame models (Sococol *et al.*, 2020); (*c*) Steel reinforcement positioning in RC frame models (or representative RC frame model) (Sococol *et al.*, 2020); (*d*) Total mesh discretization of structural elements (ATENA software, 2015; Mihai *et al.*, 2007).

As in the case of the study conducted by Sococol *et al*. (2020), it were considered representative ½ reduced RC moment resisting frame model according to the similarity relations (rules), having as variable the longitudinal steel reinforcement percentage of RC columns.

Thus, it was considered in analytical simulations three different longitudinal steel reinforcement ratio of the structural vertical elements (RC columns) (see Table 1).

The cross sections of the lateral elements were considered (Fig. 1*b*):

i. RC columns: (bxh):15x15 cm;
ii. RC beams: LB (bxh): 15x27 (cm) and TB (bxh): 10x20 (cm);
iii. RC slabs: h_s: 7 cm;

where: RC – **R**einforced **C**oncrete; b – cross section width; h – cross section height; h_s – thickness of the RC slab; LB – **L**ongitudinal **B**eams; TB – **T**ransverse **B**eams.

Representation of the cross sections for the RC moment resisting frame models, can be studied in the Sococol *et al*. source (Sococol *et al.*, 2020).

As specified in Table 1, RC columns were considered for the next longitudinal steel reinforcement ratio:

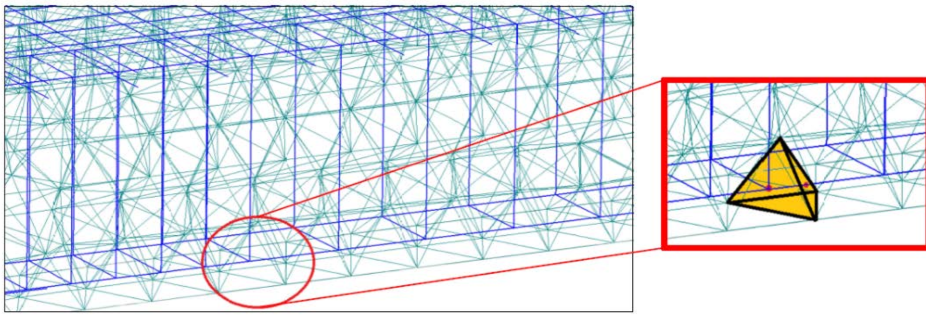
i. 4ϕ10 Bst 500S (M_3 model);
ii. 4ϕ12 Bst 500S (M_4 model);
iii. 4ϕ14 Bst 500S (M_5 model).

All structural RC frame models were considered with C20/25 concrete strength class, according to conclusions and results obtained by Sococol *et al*. (2020) (see Table 1).

Reinforced concrete beams (RC LB and RC TB) were reinforced with 4ϕ10 Bst 500S and RC slabs with standard welded wire 116GQ283 type (6x100/6x100 – welded wire with 6 mm diameter and square mesh). The steel reinforcement carcase of the entire (total, complete) structure is shown in Fig. 1*c*.

„Cross-sectional steel reinforcement of the RC columns and RC beams it was performed with ϕ4 Bst500M stirrups positioned at 5 cm in critical zones and 10 cm in other areas. Also, it was considered that the RC columns present a critical region on the whole height of the element” (Sococol *et al.*, 2020).

(*a*)



(*b*)

Fig. 2 – Graphic representation of coupling finite elements with demonstration of interaction between steel reinforcements and concrete for M_5 RC frame model: (*a*) 3D total mesh discretization; (*b*) Local representation of rebars – concrete interaction (ATENA software, 2015; Mihai *et al.*, 2007; Bitencourt Jr. *et al.*, 2018).

Table 1
Principal Characteristics Used in the Numerical Analysis for the RC Frame Models Represented in Fig. 1 and Sococol et al. (2020)

CSC	NSC	RC C (15x15 cm)	RC LB (15x27 cm)	RC TB (10x20 cm)	RC S (h_s=7 cm)
RC longitudinal rigid beams predimensioning from h_B=1/8L condition					
C20/25	*M_3*	*4ϕ10*	*4ϕ10*	*4ϕ10*	*ϕ6*
C20/25	*M_4*	*4ϕ12*	*4ϕ10*	*4ϕ10*	*ϕ6*
C20/25	*M_5*	*4ϕ14*	*4ϕ10*	*4ϕ10*	*ϕ6*
*Note: CSC – **C**oncrete **S**trength **C**lass; NSC – **N**umerical **S**imulation **C**ode; RC – **R**einforced **C**oncrete; C – **C**olumns; LB – **L**ongitudinal **B**eams; TB – **T**ransverse **B**eams; S –**S**labs; h_s – RC slabs thickness; h_B – RC beams thickness.*					

Regarding the analytical study, it can be specified that for „accurate and efficient modeling of the nonlinear behavior of RC frame models by the **F**inite **E**lement **M**ethod (FEM), it were appropriately represented three principal components: concrete, steel reinforcement and the bond-slip between steel and concrete" (Bitencourt Jr. *et al.*, 2018). Thus, it were taken into consideration these three aspects (Bitencourt Jr. *et al.*, 2018):

i. „concrete mesh discretization based on the geometry of the structural member" (Fig. 1*d*);
ii. „definition of the rebars and corresponding mesh discretization" (Fig. 1*c*);
iii. „definition of **C**oupling **F**inite **E**lements (CFEs) to describe the interaction between concrete and rebars" (Fig. 2*a*, *b*).

Thus, it were considered the same set of output data (results), present in Sococol *et al*. (2020) for all structural RC frame models:

i. **U**ltimate **L**ateral **D**isplacements (ULD) (Fig. 3);
ii. **U**ltimate **L**ateral **F**orces (ULF) (Fig. 4);
iii. **T**otal **S**trains **E**ps zz (TSE) (Fig. 5 – Fig. 6);
iv. **P**rincipal **F**racture **S**trains **M**ax (PFSM) (Fig. 7 – Fig. 8);
v. Crack panel for ultimate lateral displacement step (Fig. 6 and Fig. 8).

2. FEM Pushover Analysis Results

The seismic performance of the RC moment resisting frame models (see Table 1) was studied using the results obtained from the global seismic analysis (see Table 2) (Budescu and Ciongradi, 2014). The representative RC frame structure (for three RC frame models) was laterally loaded in the longitudinal direction with equivalent static forces as in Fig. 1*b*, registering horizontal displacements (Fig. 3), lateral forces at the top storey (Fig. 4) and significant principal specific strains in intensely cracked areas (Figs. 5 – Fig. 8).

So, it were accentuated the effects of the longitudinal steel reinforcement ratio in the RC columns for all structural RC frame models, observing the next aspects:

Compared to the other two structural models (M_4 and M_5), the M_3 RC frame model presents the lowest values of the lateral displacements (D_{M_3} = 0.0191 m) (Fig. 3) and ultimate lateral forces (F_{M_3} = 33.6 kN) (Fig. 4). Thus, the minimum longitudinal steel reinforcement ratio (4ϕ10 Bst 500S) (Table 1) in RC columns for RC frame system with longitudinal rigid beams, leads to inferior global deformation capacity of the structure with elements of nonlinear inelastic location and principal specific strains concentration (Fig. 6*a*; Fig. 8*a*) exactly in the end areas of RC columns. These effects are inappropriate character in current design regulations (P100-1, 2013; EC 8, 2004).

The ultimate lateral displacements values of the M_4 RC frame model (D_{M_4} = 0.0237 m) (Fig. 3) are close to the values of the M_5 model, but registered inferior lateral forces (F_{M_4} = 42 kN) (Fig. 4) compared to the same structural system (M_5). The global cracking panel of the analytical model presents distribution deficiencies of nonlinear principal strains and demonstrates a tendency of strains concentration at both end zones of RC columns (Fig. 6*b*, Fig. 8*b*). As in the case of the M_3 model, the longitudinal steel reinforcement ratio of the RC columns (4ϕ12 Bst 500S) (Table 1) is insufficient.

The M_5 RC frame model is loaded with a maximum lateral force (F_{max} = 48.3 kN) (Fig. 4), developing the largest horizontal displacements (D_{max} = 0.0246 m) (Fig. 3). In these conditions, the superior longitudinal steel reinforcement ratio in RC columns (4ϕ14 Bst 500S) (Table 1) leads to superior seismic energy dissipation capacity mechanism, taking into consideration the results of the „F-d” capacity curve, according to the general study model present in structural engineering literature (Ghayoumian and Emami, 2020; Varga and Chiorean, 2016). Also, it is developed the mechanism of plastic specific strains distribution with potential plastic degradation in several areas (RC columns end zones and RC beam-column joints) (Fig. 8*c*, *d*).

Table 2

Principal Analysis Results for The Moment Resisting RC Frame Models after Pushover Simulations (Graphic Representation of the Representative Model - Fig. 1 (Table 1))

CSC	NSC	ULD [m]	ULF [kN]	TSE	PFSM
C20/25	*M_3*	*0.0191*	*33.6*	*0.002254*	*0.03102*
C20/25	*M_4*	*0.0237*	*42*	*0.002773*	*0.2038*
C20/25	*M_5*	*0.0246*	*48.3*	*0.002637*	*0.02524*

*Note: CSC – **C**oncrete **S**trength **C**lass; NSC – **N**umerical **S**imulation **C**ode; ULD – **U**ltimate **L**ateral **D**isplacements; ULF – **U**ltimate **L**ateral **F**orces; TSE – **T**otal **S**train **E**ps zz; PFSM – **P**rincipal **F**racture **S**train **M**ax.*

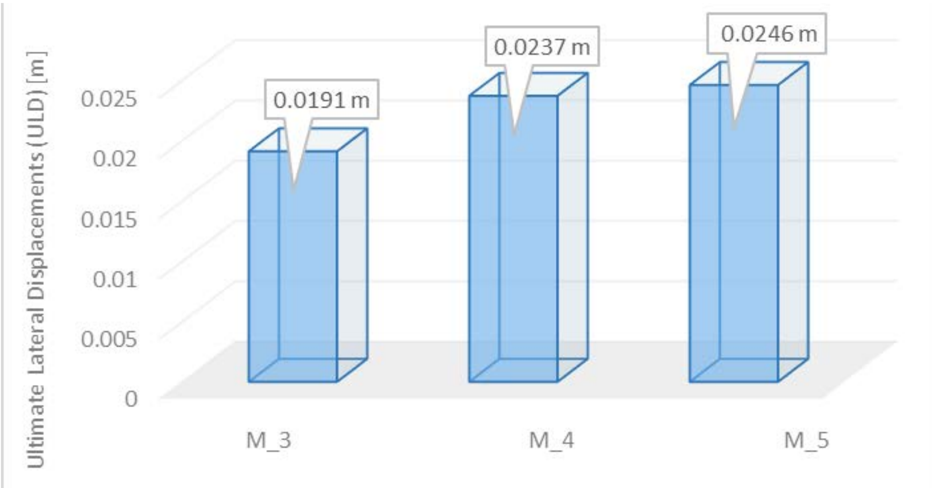


Fig. 3 – Influence of longitudinal steel reinforcement ratio in the RC columns on the **U**ltimate **L**ateral **D**isplacements (ULD) response of the M_3, M_4 and M_5 moment resisting RC frame models (see Table 1, Table 2).

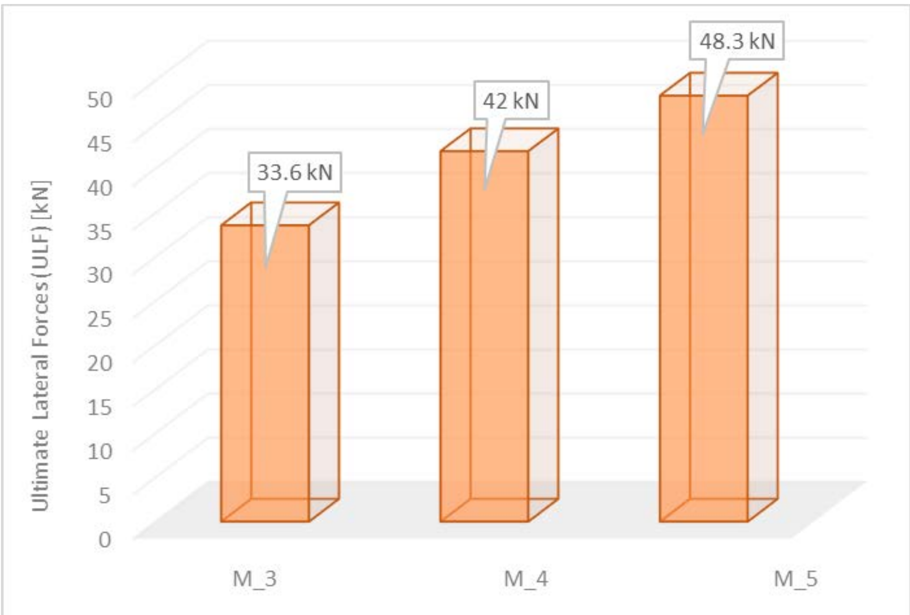


Fig. 4 – Influence of longitudinal steel reinforcement ratio in the RC columns on the **U**ltimate **L**ateral **F**orces (ULF) response of the M_3, M_4 and M_5 RC moment resisting frame systems (see Table 1 and Table 2).

Regarding the influence of the longitudinal steel reinforcement ratio in RC columns on the local degradation mechanism through TSE (**T**otal **S**trains **E**ps zz effects) (Table 2, Fig. 5, Fig. 6) and PFSM (**P**rincipal **F**racture **S**trains **M**ax effects), it can be mentioned the following aspects:

All structural RC frame models (M_3, M_4 and M_5) present important nonlinear inelastic specific strains in the marginal zones of the columns (see Fig. 6*a*, *b*, *c*). In terms of values, TSE for M_3 (ε_{cu} = 0.002254), TSE for M_4 (ε_{cu} = 0.002773) and TSE for M_5 (ε_{cu} = 0.002637) (Fig. 5) do not exceed the ultimate specific concrete strain (to compression) value $\varepsilon_{cu,c}$ = 0.0035 for C20/25 concrete strength class (see Table 3). However, concrete has double specific strains in tensioned areas of the vertical structural elements. This double increase in terms of the specific strains is due to the concentration mechanism of the ultimate specific deformations in a reduced number of RC columns (Fig. 6*a*, *b*), with local material ductility influence, based on the horizontal rebars yielding from the structural element for ultimate loading (lateral loading) step (Sococol *et al.*, 2019b).

In these conditions, the yielding process of longitudinal steel reinforcement in the RC columns is actively growing and rebar specific strain exceeds locally (in a single vertical structural element) (see Fig. 7, Fig. 8*b*) ($\varepsilon_{u,steel}$ = 0.2038) up to 2.7 ≈ 3.0 times the characteristic deformation limit ε_{uk} = 0.075 (see Table 3) for M_4 RC frame model. These deformation/ degradation/ cracking mechanisms of RC columns represent „unwanted" mechanisms in current engineering practice (P100-1, 2013; EC 8, 2004).

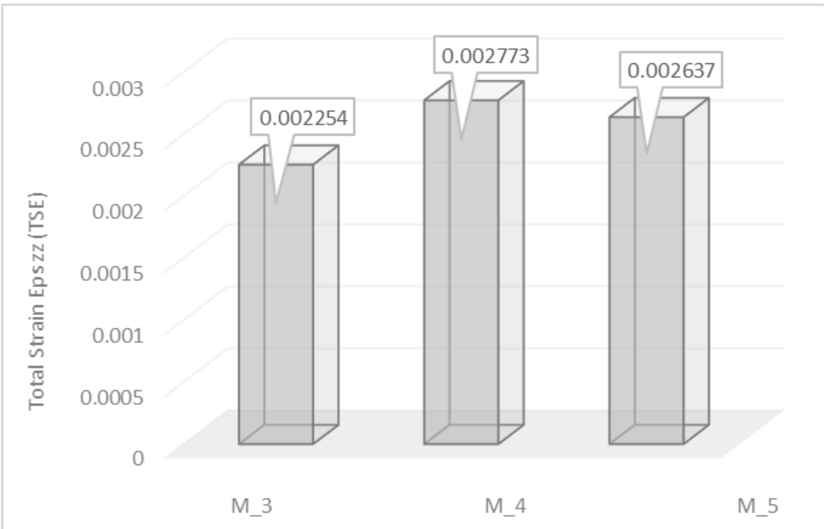


Fig. 5 – Influence of longitudinal steel reinforcement ratio in the RC columns on the lateral (seismic) response in **T**otal **S**trains **E**ps zz (TSE) of the M_3, M_4 and M_5 moment resisting RC frame systems (general informations: Table 1 and Table 2).

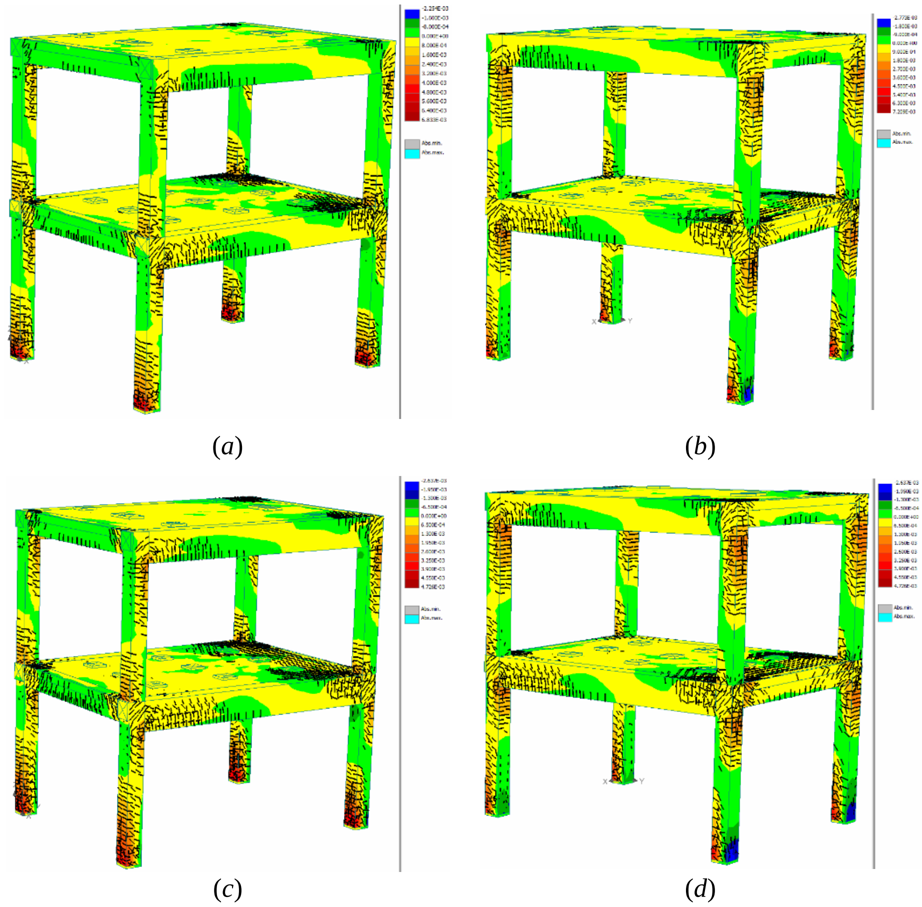


Fig. 6 – **T**otal **S**trains **E**ps zz (TSE) for: (a) M_3; (b) M_4; (c), (d) M_5 moment resisting RC frame systems (models) in the case of the ultimate lateral loading step (see Table 1, Table 2 and Fig. 5).

Regarding the longitudinal steel reinforcement ratio in the RC columns influence on the global mode of structural RC frame models cracking through PFSM (**P**rincipal **F**racture **S**trains **M**ax values and effects) (Table 2, Fig. 7, Fig. 8), it can be mentioned next aspects:

M_3 structural model records PFSM (**P**rincipal **F**racture **S**trains **M**ax) at the marginal end zones of the RC columns (Fig. 8*a*), exceeding the concrete ultimate specific strain value at compression (ε_{PFSM} = 0.03102 > $\varepsilon_{cu,c}$ = 0.0035) (Fig. 7, Table 3). Thus, the tensioned longitudinal steel reinforcement from the RC columns enters in the yielding process with double reserve to the ultimate specific strains (ε_{PFSM} = 0.03102 < ε_{uk} = 0.075) (Fig. 7, Table 3). However, the crack panel presents inactive participation of the other lateral elements (RC beams and RC slabs) in the seismic energy dissipation mechanism. Moreover, it is observed the formation of „slab-node-beams" rigid block, which limits the creation of potentially plastic areas in the adjacent zones of the RC column-beam joint (Sococol *et al.*, 2019c; Sococol *et al.*, 2020). In these conditions, M_3 RC frame model presents important deficiencies in terms of structural redundancy (P100-1, 2013; EC 8, 2004).

M_4 structural RC frame model records a three times PFSM value ($\varepsilon_{PFSM} = 0.2038 > \varepsilon_{uk} = 0.075$) higher than steel reinforcement characteristic strain at maximum force of the longitudinal tensioned rebars from the RC columns (Table 2, Table 3, Fig. 7). Though, the location of the recorded deformations is unique (at the bottom region of a single RC column) (see Fig. 8*b*). The effects of this structural degradation process on severe seismic actions are extremely disastrous and not recommended in current seismic design regulations (P100-1, 2013; EC 8, 2004). Regarding the crack panel, it can be observed a more intense RC rigid beams and RC slabs participation in seismic energy dissipation mechanism, compared to the M_3 RC moment resisting frame model. Also, the generation of the RC „beams-node-slab" rigid block conduct to the plastic hinges formation at the end zones of the RC columns (Sococol *et al.*, 2019c; Sococol *et al.*, 2020). Thus, the superior longitudinal steel reinforcement ratio in the RC columns produces positive effects on the global seismic response of the RC frame structural model, but has important deficiencies in local deformation areas.

M_5 RC moment resisting frame model develops the most areas of inelastic specific strains (deformations) (see Fig. 8*c*, *d*), compared to the other (M_3 and M_4 RC frame models) structural systems. Thus, the RC beam-column joint regions are strongly degraded, highlighting the intense cracking tendency of RC beams and RC slabs (Fig. 8*c*, *d*). The higher longitudinal steel reinforcement ratio in RC columns (see Table 1) leads to the development of a more redundant structural system with a higher seismic energy dissipation capacity. **P**rincipal **F**racture **S**trains **M**ax (PFSM) exceed the ultimate specific strains limit of the concrete ($\varepsilon_{PFSM} = 0.2524 > \varepsilon_{cu,c} = 0.0035$) (Table 2, Fig. 7), based on the rebar ductility ($\varepsilon_{PFSM} = 0.2524 > \varepsilon_{uk} = 0.075$) (Sococol *et al.*, 2019b). The ideal crushing mechanism for compressed concrete, presented in structural engineering literature (Budescu and Ciongradi, 2014; Paulay and Priestley, 1992; Park and Paulay, 1975; Postelnicu, 2012; Stratan, 2014), does not occur simultaneously with the yielding of tensioned rebars in RC columns. Also, the M_5 RC frame model develops the same RC „beams-node-slabs" common block (Sococol *et al.*, 2019c), but presents the most effective structural system in terms of the higher longitudinal steel reinforcement ratio in RC columns.

Table 3
Specific Strain Values of C20/25 Concrete Strength Class and S500 Steel Reinforcement Mark for Reinforced Concrete (Kiss and Onet, 2008; EC 2, 2006)

The concrete ultimate specific strain value at compression $\varepsilon_{cu,c}$ (‰) of C20/25 concrete strength class	
Concrete strength class	*Concrete ultimate specific strain at compression $\varepsilon_{cu,c}$ (‰)*
C20/25	*3.5*

Characteristic strain value ε_{uk} (%) at maximum force of S500 steel reinforcement mark for reinforced concrete			
Rebar (steel) mark	*Trade name*	*Ductility class*	*Characteristic strain value ε_{uk} (%) at maximum force*
S500	*Bst 500S*	*C*	*≥ 7.5*

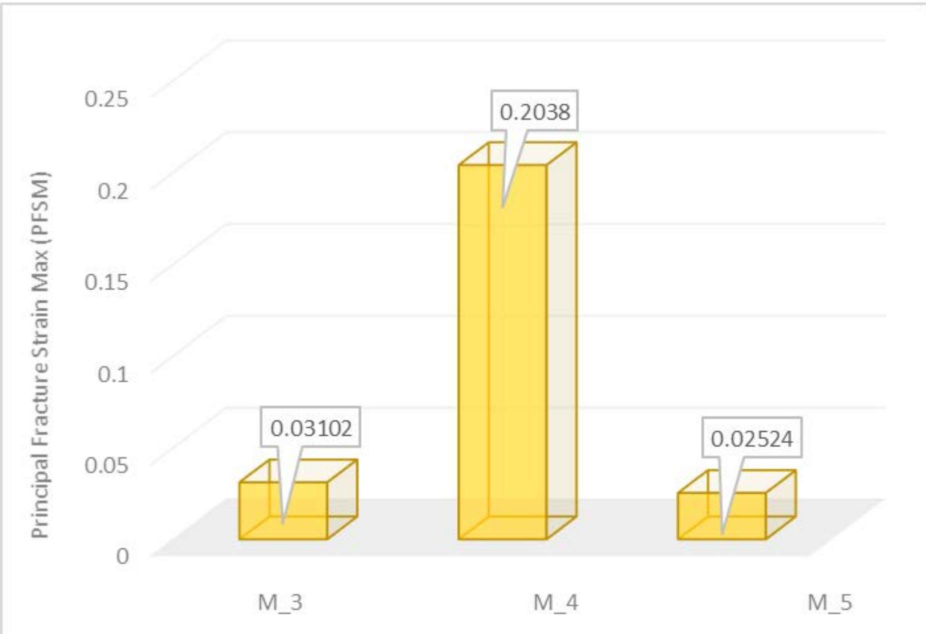
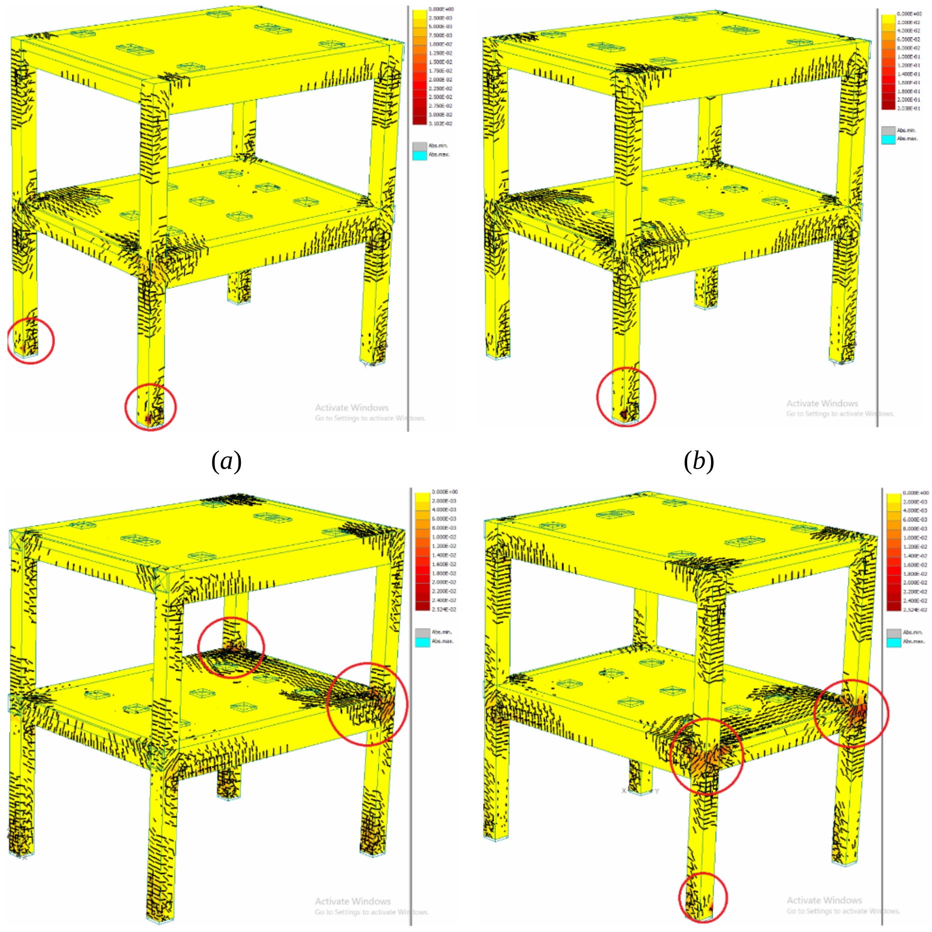


Fig. 7 – Influence of longitudinal steel reinforcement ratio in the RC columns on the lateral (seismic) response in **P**rincipal **F**racture **S**trains **M**ax (PFSM) of the M_3, M_4 and M_5 moment resisting RC frame systems (models) (see Table 1 and Table 2).



(*a*) (*b*)

(*c*) (*d*)

Fig. 8 – **P**rincipal **F**racture **S**trains **M**ax (PFSM) for: (*a*) M_3; (*b*) M_4; (*c*), (*d*) M_5 moment resisting RC frame systems (models) in the case of the ultimate lateral loading step (see Table 1, Table 2 and Fig. 7) (Note: in the red circles are registered the maximum values of the PFSM).

3. Conclusions

Following the nonlinear static analytical study on the variation of the longitudinal steel reinforcement percentage in RC columns for three structural RC frame models, it were observed a series of local and global deformation mechanisms in structural elements.

Thus, M_3 and M_4 RC frame models with lower longitudinal steel reinforcement ratio in the RC columns, are laterally loaded with lower equivalent static forces than M_5 RC frame model. Also, the lateral displacements seismic response is superior for the M_5 RC frame type model.

Regarding the structural deformation mechanisms perspective in the potentially plastic zones, it is observed a TSE and PFSM concentration with high values in a reduced number of areas for the RC frame models weakly longitudinally reinforced in RC columns. These reinforced concrete (RC) frame structures (M_3 and M_4) are less redundant and crack panel shows (presents) the inactive lateral elements (RC beams, RC column-beam joints, RC slabs) participation in the seismic energy dissipation process.

On the other hand, the heigher longitudinal steel reinforcement ratio in RC columns leads to an accentuated seismic energy dissipation process (participation) of the other structural elements (RC beams, RC column-beam joints, RC slabs) (see M_5 RC frame model). Thus, the structural elements register extensive crack action in the required areas, presenting the importance of the material ductility, especially the rebar (steel reinforcement) ductility.

Another analytical founded mechanism in the RC moment resisting frame models is the generation of the RC „beams-node-slab" rigid block (that forms a common rigid body), requiring the stress-strain concentrations in the adjacent areas of the RC column-beam joints (end regions of the RC columns). This effect is primarily due to the RC longitudinal rigid beams and the horizontal stiffening effect imposed by the presence of the reinforced concrete (RC) slab.

Through the imposed boundary conditions (structural RC frame system with longitudinal rigid beams) for the lateral request of a representative RC frame structure with the variation of the longitudinal steel reinforcement percentage in RC columns (in order to observe the global and local optimally seismic response (per element – for RC columns)), it was concluded that the M_5 RC frame system is the most efficient moment resisting model.

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ANALIZĂ STATICĂ NELINIARĂ A UNEI STRUCTURI SEISMO-REZISTENTE TIP CADRU DE BETON ARMAT LUÂND ÎN CONSIDERARE VARIAȚIA PROCENTULUI DE ARMARE LONGITUDINALĂ A STÂLPILOR ÎN STADIUL PRELIMINAR DE PROIECTARE

(Rezumat)

Studiile analitice privind influența clasei de beton asupra mecanismului ductil de disipare a energiei seismice pentru sisteme structurale tip cadru de beton armat cu grinzi rigide, înregistrează un răspuns lateral favorabil pentru clase de beton superioare. Aceste concluzii importante sunt cuplate cu o fisurare activă a betonului/ curgere activă a armăturii în zonele comprimate/ întinse ale stâlpilor de beton armat. În aceste condiții, s-a studiat eficacitatea procentului de armare longitudinală pentru aceste elemente structurale (stâlpi de beton armat). Astfel, s-a efectuat un calcul analitic pentru trei modele tip cadru de beton armat cu ajutorul programului de calcul ATENA (FEM analiză static neliniară). Aceste tipuri de structuri (model reprezentativ cu grinzi rigide) studiate în cadrul cercetării analitice anterioare, au fost alese pentru analiza pushover deoarece îndeplinesc cele mai nefavorabile condiții pentru studiul deformabilității stâlpilor. Rezultatele obținute demonstrează eficacitatea structurală a procentelor superioare de armare longitudinală a stâlpilor asupra răspunsului seismic ductil pentru sisteme seismo-rezistente tip cadru de beton armat.