INTERNATIONAL SCIENTIFIC CONFERENCE CIBV 2014
7-8 November 2014, Braşov

TOWARDS THE INFLUENCE OF THE LOCAL COLLAPSE OF STRUCTURAL ELEMENTS TO GENERATE PROGRESSIVE COLLAPSE

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Abstract: *After the total or partial collapse of several important buildings the specialists in civil engineering began to treat more seriously and accuracy the problem of completely avoiding progressive or general collapse or just in the first instance in order to ensure complete evacuation of people and / or important goods. Considering these aspects, in this paper I'll present two parallel study cases for buildings with 5 and 10 levels, which is supposed to have a local collapse of one first floor column (corner, marginal or central) realizing simple or complex analysis in order to identify problems that ascend on the whole building.*

Key words: *collapse; local; progressive; ductility; hinges*

1. Introduction

The main objective of these studies was the assessment of influence of local/partial collapse to generate progressive collapse. In this consideration all the evaluations were performed according to the following parameters:

- ***The number of levels of structure***: two identical structures were selected with two different height levels: a low-rise structure (with 5 levels) and a medium high-rise structure (with 10 levels).
- ***The structural damage case*s**: according to emergency scenarios from GSA (General Service Administration – October 24, 2013): were removed separately, one corner column, one marginal column closer to the midpoint of the structure and one of the central columns located as close to the center of the structure.
- ***Adopted analysis method*s**: usual static linear calculations were performed, followed by nonlinear static analysis (pushover) for a better interpretation of phenomena.

The secondary objective was to determine the worst damage scenario. The following steps have been completed in order to accomplish analysis:

- Evaluation of structural composition, materials and loads to be taken into account;
- A pre-design of all the structural elements;
- Determining the status of sectional efforts and deformations using ETABS program;

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- Designing the stiffness through the lateral forces by checking the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) according to Eurocode 8 (EC8);
- Designing all the reinforcement types in beams and columns;
- Choosing the scenarios generating local collapse under GSA recommendations in the field;
- Checking the drifts for the damaged structures;
- Beams behavior analysis after the columns collapse in agreement with the chosen scenarios;
- Performing pushover nonlinear static analysis that followed the steps of: defining the potential plastic hinges for beams and columns; defining the load cases for nonlinear analysis; calculation of target movement according EC8.

Due to a better understanding of the structural behavior of materials and with increasing the computational power, the modern structures are better designed than in the past. This optimization resulted in the reduction of inherent safety margins, but still due to this the capacity to resist for unexpected events decreased. This increased vulnerability may be associated with modern construction methods targeting at reducing the costs and also because of the modern architectural design directions with lightweight construction and large spans. Lastly, the increased fear for terrorist threats highlighted the need to consider the design of unforeseen events such as: blasts, external impact, detonations, etc.

2. Computation Strategies

The buildings studied have RC frame structure, occupying an area plan with dimensions 25x25 m^2, with five spans and five bays of 5 m. The height of 3m is set for all the levels. The building functionality were set as offices. Exterior curtain walls and interior drywall partitions were used. The concrete slabs have a thickness of 13 cm, ensuring the required strength and acoustic comfort. The buildings location were set in a region with a horizontal design acceleration (a_g) of 0.30g, according to EC8. The importance and exposure class is II ($\gamma_{e,I}$ = 1.0). The periods T_B=0.16 sec, T_c=1.60 sec and the ductility class was set at high class (HD). The snow zone: $s_{o,k}$ = 2,0 kN/m^2. Execution technology: monolithic RC (including floors).

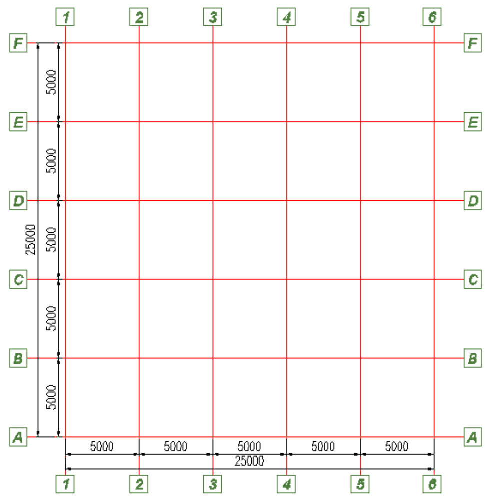


Fig.1. *Axes sketch*

Used materials:

Concrete characteristics Table 1

Concrete	f_{ck} N/mm^2	f_{cm} N/mm^2	f_{ctm} N/mm^2	$f_{ctk,0.05}$ N/mm^2	E_{cm} GPa
C25/30	25	33	2.6	1.8	31
C35/45	35	43	3.2	2.2	34

Steel Characteristics Table 2

Steel	f_y N/mm^2	f_u N/mm^2	E_a N/mm^2
S500	500	550	2.1E+8

Seismic load it was considered defining the design spectrum:

$$0 \le T \le T_B: \quad S_d(T) = a_g \cdot \left[1 + \frac{\frac{\beta_0}{q} - 1}{T_B} \cdot T\right] \tag{1}$$

and if
$$T > T_B: \quad S_d(T) = a_g \cdot \frac{\beta(T)}{q} \tag{2}$$

As can be seen the design spectrum is obtained from the elastic spectrum by reducing the range of it with the behavior factor q for values of the period T> TB.

For periods T ≤ TB design spectrum is determined by a behavior factor q, q = 1 it reaching T = 0.

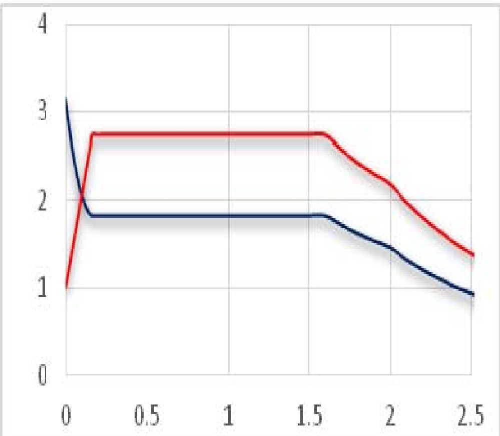


Fig.2. *Comparison between elastic spectrum (red) and design spectrum (dark blue) q= 4.73 and T= 1.6s*

To determine the structural elements efforts of the building, the structural analysis program ETABS [15] were used. Dimensions obtained from the pre-design stage defined the structural elements in the program: beams and columns as linear FRAME finite elements and the slabs as planar SLAB finite elements. It was considered that concrete were cracked: for beams $0.5E_cI_c$ and for columns $0.8E_cI_c$.

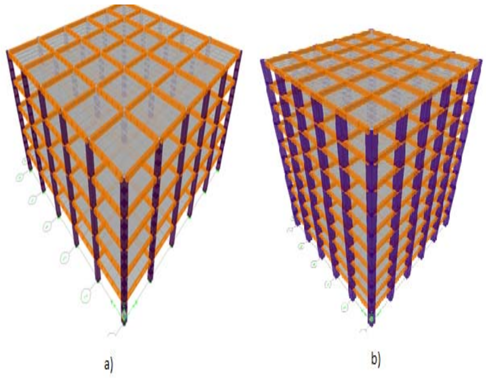


Fig. 3. *Structural model in ETABS: a) 5 levels, b) ten levels*

3. Scenarios That Generate Local Collapse

The scenarios presented in this paper on the removal of the columns from the ground floor are confirmed with the recommendations of the GSA [5].

This design guide has the following structural failures: removal of a corner column; removal of a marginal column located at midpoint; removal of a central column.

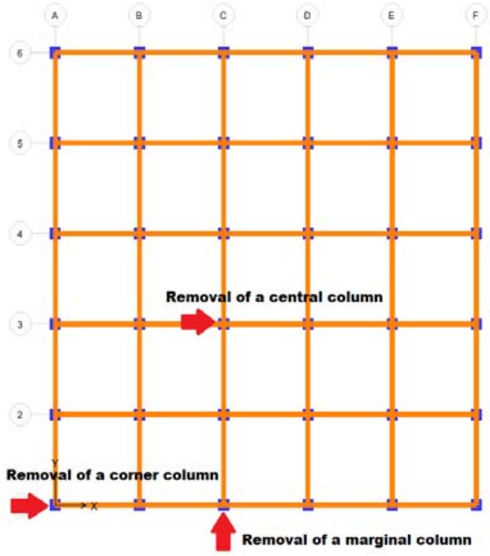


Fig. 4. *Structural damage types applied to models*

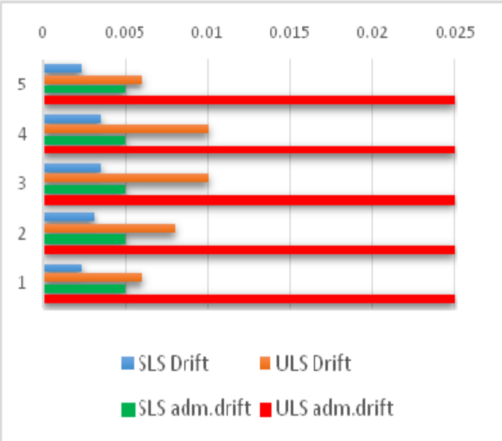


Fig. 5. *Initial 5 stories structure drifts*

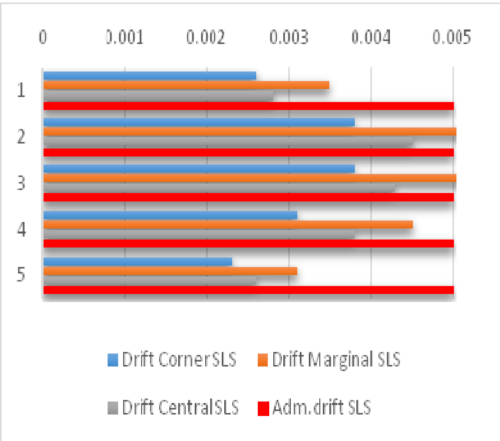


Fig.6. *5 levels scenario cases SLS drifts*

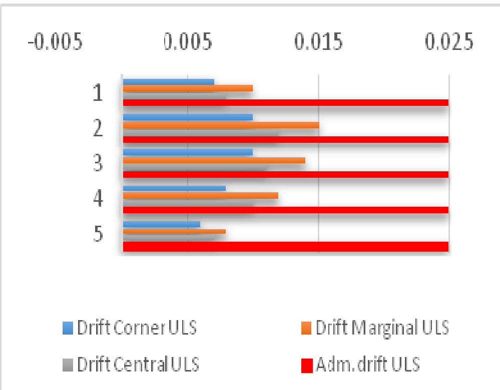
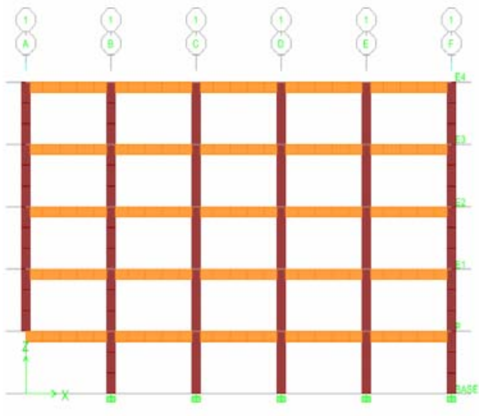
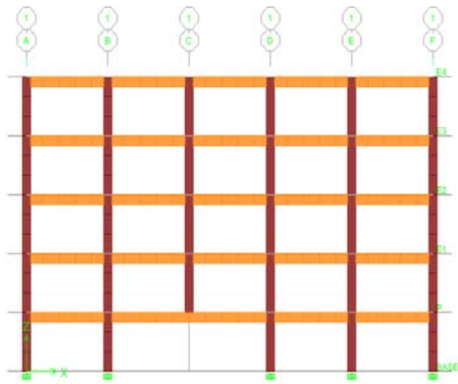


Fig.7. *5 levels scenario cases ULS drifts*

These cases are in accordance with the below scenarios:



a)



b)

Fig. 8. *ETABS model – removed: a) corner column; b) central/marginal column*

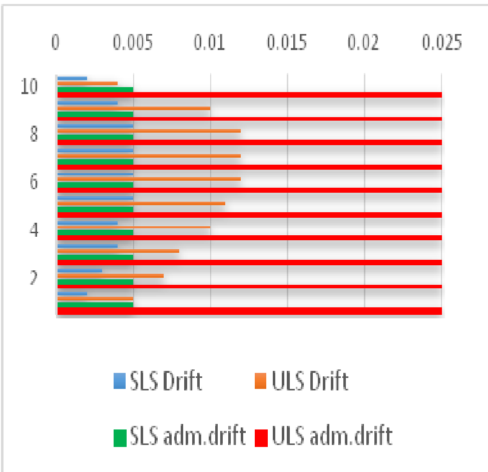


Fig. 9. *Initial 10 stories structure drifts*

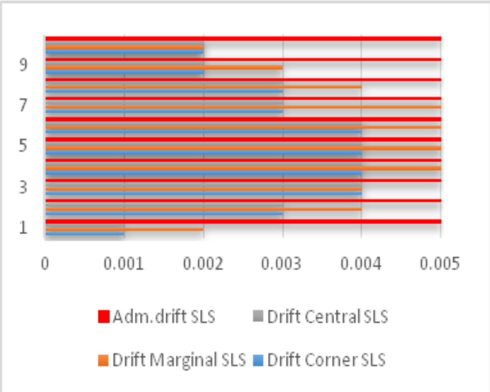


Fig.10. *10 levels scenario cases SLS drifts*

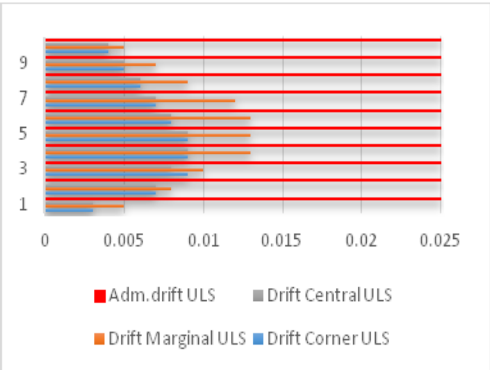


Fig.11. *10 levels scenario cases ULS drifts*

These cases are in accordance with the below scenarios:

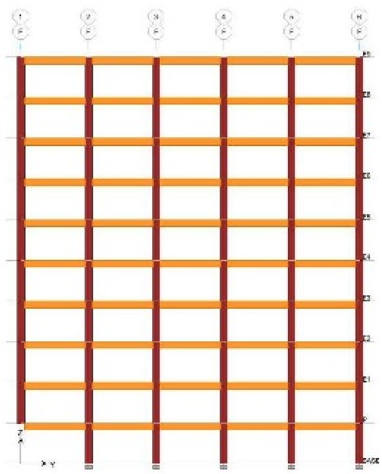


Fig. 12. *a) ETABS model – removed corner column*

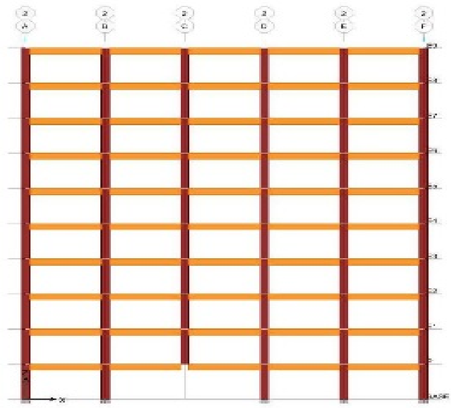


Fig. 12. *b) ETABS model – removed central/marginal column*

Joints deflection above the removed columns Table 3

Joint deflection	5 levels	10 levels
Above the removal corner column	1.25 cm	0.91 cm
Above the removal marginal column	1.13 cm	0.62 cm
Above the removal central column	0.68 cm	0.32 cm

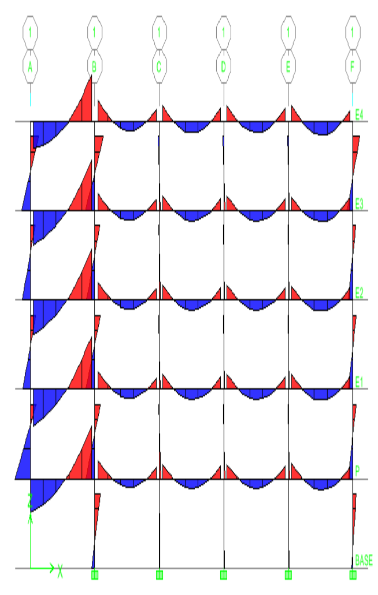
Beams deflection Table 4

Deflection	5 levels		10 levels	
	Removed corner column			
f=	12.6mm	f = f_{adm} OK	8.0mm	f < f_{adm} OK
f_{adm}=	12.5mm		12.5mm	
	Removed marginal column			
f=	12.9mm	f > f_{adm} Not OK	7.2mm	f < f_{adm} OK
f_{adm}=	12.5mm		12.5mm	
	Removed central column			
f=	10.7mm	f < f_{adm} OK	8.2mm	f < f_{adm} OK
f_{adm} =	12.5mm		12.5mm	

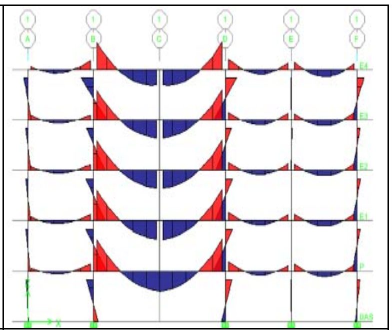
From all the analysis did, in the paper some synthetic and simple tables are presented in the followings:

The 5 levels case:

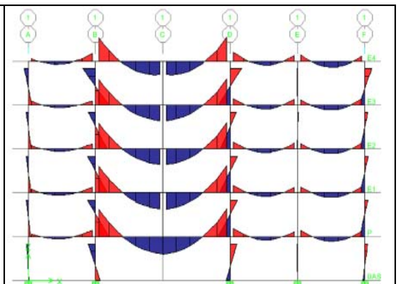
Beams bending moments check in case of corner column Table 5

M			
Levels	Envelope Case of a corner column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	OK	Not OK	Not OK
4-5	OK	Not OK	OK
Levels	Gravitational Case of a corner column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	Not OK	Not OK	OK
4-5	Not OK	Not OK	OK

Beams bending moments check in case of marginal column Table 6

M			
Levels	Envelope - Case of a marginal column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	OK	Not OK	Not OK
4-5	Not OK	Not OK	Not OK
Levels	Gravitational - Case of a marginal column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	Not OK	Not OK	Not OK
4-5	Not OK	Not OK	Not OK

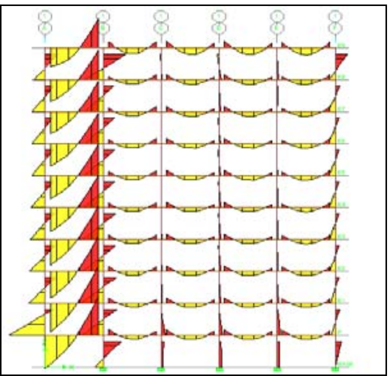
Beams bending moments check in case of marginal column Table 7

M			
Levels	Envelope - Case of a central column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	OK	OK	Not OK
4-5	OK	Not OK	OK

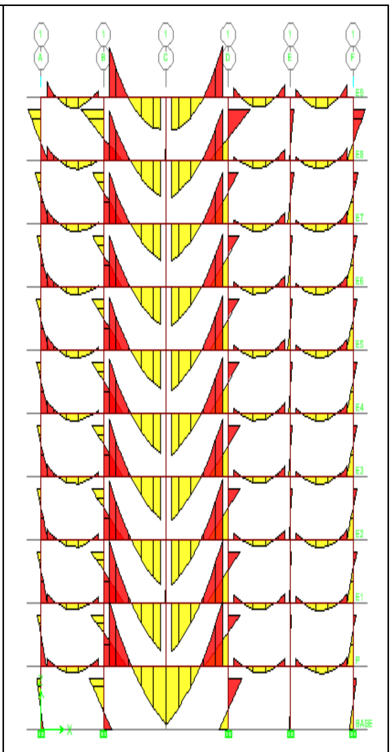
Levels	Gravitational - Case of a central column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
1-3	Not OK	Not OK	Not OK
4-5	Not OK	Not OK	OK

The 10 levels case:

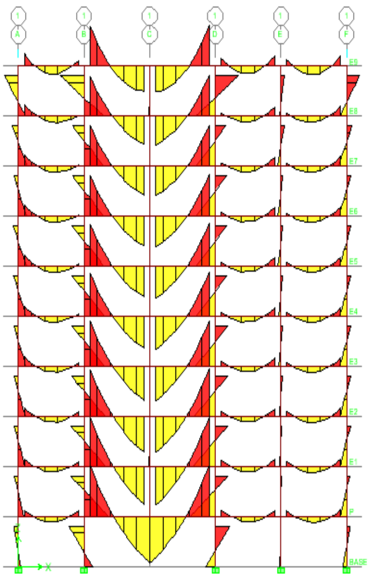
Beams bending moments check in case of corner column Table 8

M			
Levels	Envelope - Case of a corner column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Midfield
10	OK	Not OK	Not OK
8-9	OK	Not OK	Not OK
6-7	OK	OK	OK
2-5	OK	OK	OK
1	OK	Not OK	Not OK
Levels	Gravitational - Case of a corner column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Mid field
10	Not OK	Not OK	OK
8-9	OK	OK	OK
6-7	OK	OK	OK
2-5	OK	OK	OK
1	OK	OK	OK

Beams bending moments check in case of marginal column Table 9

M			
Levels	Envelope - Case of a marginal column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Midfield
10	OK	Not OK	Not OK
8-9	OK	Not OK	Not OK
6-7	OK	Not OK	Not OK
2-5	OK	Not OK	Not OK
1	OK	Not OK	OK
Levels	Gravitational - Case of a marginal column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Midfield
10	Not OK	Not OK	OK
8-9	OK	OK	OK
6-7	OK	OK	OK
2-5	OK	OK	OK
1	OK	OK	OK

Beams bending moments check in case of marginal column Table 10

M			
Levels	Envelope - Case of a central column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Midfield
10	OK	Not OK	OK
8-9	OK	Not OK	OK
6-7	OK	Not OK	Not OK
2-5	OK	Not OK	OK
1	OK	Not OK	OK
Levels	Gravitational - Case of a central column failure		
	$M_{Ed} < M_{Rd}$ Support 1	$M_{Ed} < M_{Rd}$ Support 2	$M_{Ed} < M_{Rd}$ Midfield
10	Not OK	Not OK	OK
8-9	OK	OK	OK
6-7	OK	OK	OK
2-5	OK	OK	OK
1	OK	OK	OK

Nonlinear static analysis (pushover) was chosen to perform in good condition for RC frame structures in ETABS [15]. This analysis involves the gradual annoyance of displacements on the structure until it forms a plastic mechanism. As it grow the structural displacements as gradually develops plastic hinges. Plastic hinges used are of two types: beams plastic hinges (joints bending moment M_3) and columns plastic hinges (joints M_3 bending moment and axial force P), defined at both ends of elements. To define the performance ranges the plastic hinges rotations were definite based on the requirements of FEMA 273. For columns plastic hinges the moment-axial force interaction curve must be defined and will be introduced by points. The push-over analysis involves two assumptions: a situation where the structure is loaded by gravity load; a situation where the structure is progressively loaded horizontally. This hypothesis run after the first one. The maximum number of steps and the number of null steps are the parameters which control the run time. Reaching the maximum number of steps or null steps the analysis stops. The meaning of null steps is that a plastic hinge yield and determined the yielding of other plastic hinges.

4. Nonlinear Static Analysis Responses Interpretation

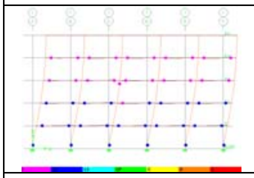
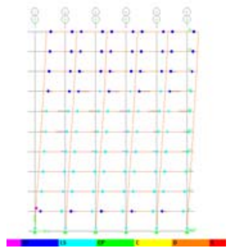
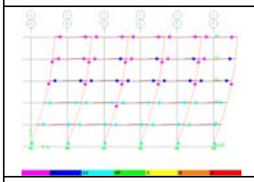
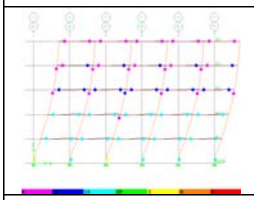
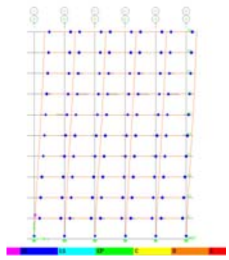
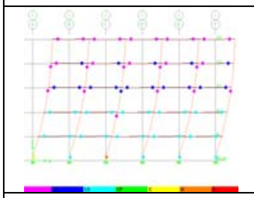
The initial unaffected structures - Following the analysis it was found that:

- Structures were properly conformed because the plastic hinges occurs first at the beams edges and then at the columns bases;
- Until the target displacement is reach there are not occurred plastic hinges to compromise the safety of the buildings (the most requested items arrive to stage LS = Life Safety).
- The structures develop plastic hinges for C – collapse stage for not much larger

displacement than the target displacements.

- The analysis of the three scenarios for generating local collapse (removing the corner, marginal and central columns) is justified. Just several steps of each case are shown in this paper.

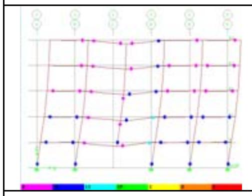
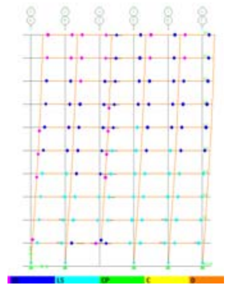
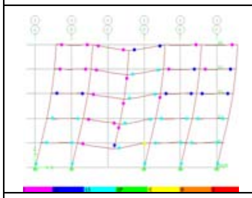
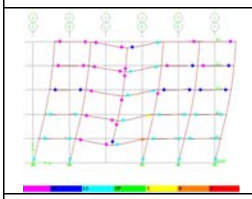
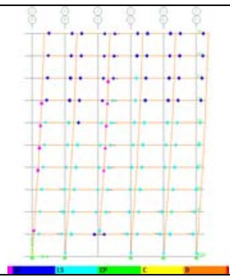
Plastic hinges occurrence for the initial structures Table 11

5 levels	10 levels
	
Step 5 $d = 0{,}090m < d_t = 0{,}1$	
	
Step 7 $d = 0{,}162m > d_t = 0{,}$	Step 6 $d = 0{,}25m < d_t = 0{,}27$
	
Step 8 $d = 0{,}175m > d_t = 0{,}1$	
	
Step 9 $d > d_t$	Step 7 $d = 0{,}31m > d_t = 0{,}27$

The case of removed central column - Following the analysis it was found that:

- At the column base (the column above the removed column) plastic hinge occurs from the first step (step 2 d = 0.024 m);
- At the beams above the removed column plastic hinges occurs corresponding to stage LS-CP (Life Safety-Collapse Prevention) before reaching the target displacement;
- If the beams reach near the limit of CP or exceed, the structure is likely to have a progressive collapse;
- Once reaching the target displacement in the beam above the removed column C plastic hinges occurs corresponding to collapse stage.

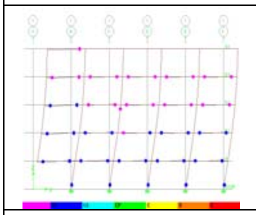
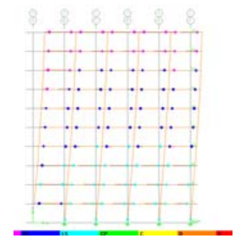
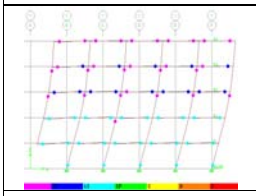
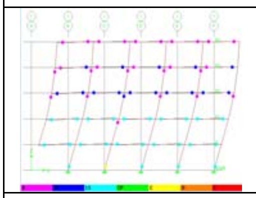
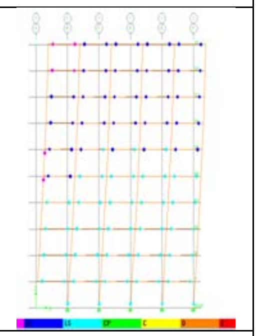
Plastic hinges occurrence for removed central column case Table 12

5 levels	10 levels
	
Step 5 $d = 0{,}086m < d_t = 0{,}$	
	
Step 6 $d = 0{,}145m = d_t = 0{,}$	Step 7 $d = 0{,}219m < d_t = 0{,}2$
	
Step 8 $d = 0{,}175m > d_t = 0{,}$	Step 8 $d = 0{,}363m > d_t = 0{,}2$

The case of removed corner column - Following the analysis it was found that:

- Structure behaves properly until the target displacement, the most requested structural elements arrive to stage LS = Life Safety;
- After exceeding the target displacement next item to be damaged is the marginal (central) column, as can be seen in step 9 where d = 0.175 m, at the column base and a C-collapse plastic hinge occur.

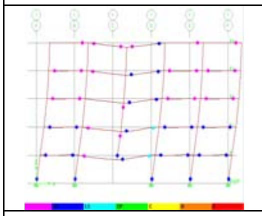
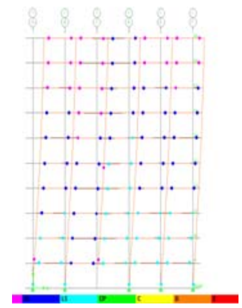
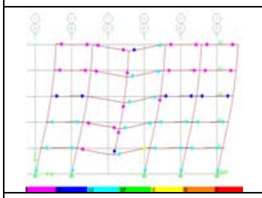
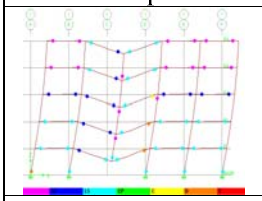
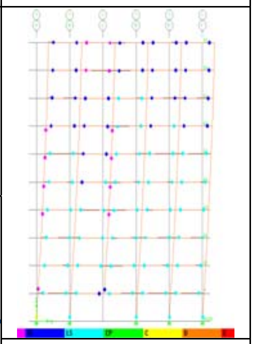
Plastic hinges occurrence for removed corner column case Table 13

5 levels	10 levels
	
Step 6 $d = 0,033m < d_t = 0,$	
	
Step 8 $d = 0,162\ m > d_t = 0$	Step 6 $d = 0,263m < d_t = 0,$
	
Step 9 $d = 0,175m > d_t = 0,$	Step 8 $d = 0,324\ m > d_t = 0$

The case of removed marginal column - Following the analysis it was found that:

- As well as the disposal of the center column at the base of the column above the column removed the plastic hinge occurs (step 2 with d = 0.024 m);
- In the beams above the removed column plastic hinges occurs corresponding to LS-CP stage (Life Safety-Collapse Prevention) before reaching the target displacement;

Plastic hinges occurrence for removed marginal column case Table 14

5 levels	10 levels
	
Step 6 $d = 0,068m < d_t = 0,1$	
	
Step 7 $d = 0,144m < d_t = 0,$ collapse	Step 7 $d = 0,251m < d_t = 0,$
	
Step 8 $d = 0,107m < d_t = 0,1$	Step 9 $d = 0,364\ m > d_t = 0,27$

- In step 7 d = 0.144 m <d_t = 0.145 m, at the beam above the removed column plastic hinges occurs to C - collapse stage. Immediately in the next step, this beam and the one above it reaches point D (section suffered major irreversible degradation and retains only a residual strength);
- Compared to the situations described above (removing the corner column and removing central column), the case where the marginal column is damaged is the worst.

5. Final Considerations

- The linear and nonlinear static analysis found that higher structure (10 levels) has a better behavior in all three studied damage scenarios than the lower one (5 levels).
- After removing the columns a redistribution of moments in the beams, adjacent to removed columns, were observed. The tensile fiber is reversed in these elements so that when the mid span bottom bending moments becomes larger and (in many cases) exceeds the bending moment capacity of the section. The mode of failure was characterized by splitting the bottom longitudinal reinforcement.
- In the case of marginal removed column the level relative displacements are larger and are no longer in accordance within the allowable values prescribed by codes.
- The joints above the removed columns have smaller displacement for 10 levels building than those with lower height (5 levels).
- After removing the columns on the ground floor, the beams deflections fall within acceptable limits ($f \leq f_{adm}$=0.0125 m), aside from the case of marginal column removal at 5 levels building.
- Nonlinear static analysis (pushover) allows to have a clearer picture of the behavior of structures.
- Analyzing the damaged structures by comparison, for 5 levels building, it can be seen that when the corner column is removed, the structure has a behavior similar to the original (undamaged). The problems start to occur when eliminating marginal column because in the beams above it plastic hinges occurs suitable to stage C - Collapse before reaching the displacement target. In addition, in the column above the one removed several plastic hinges occurs which reach up to the stage LS = Life Safety.
- Structures with 10 levels have a better behavior, but also removing the marginal column is the worst case (similar with the 5 levels structure).

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