EARTHQUAKE & PROGRESSIVE COLLAPSE DESIGN OF A REINFORCED CONCRETE STRUCTURE IN DUAL SYSTEM

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Key words: Dual system, seismic design, progressive collapse, technical regulations

Abstract: The building design to withstand the seismic action is, for the time being, well defined by the regulations in force. On the other hand, the building design or checking to prevent the progressive collapse is still in an early stage, trying to define itself. The object of this study is a suite of four reinforced concrete structures in dual system. The objective of the study is to check if a dual system building seismic designed complying with the Romanian codes has a good enough conformation to prevent the progressive collapse.

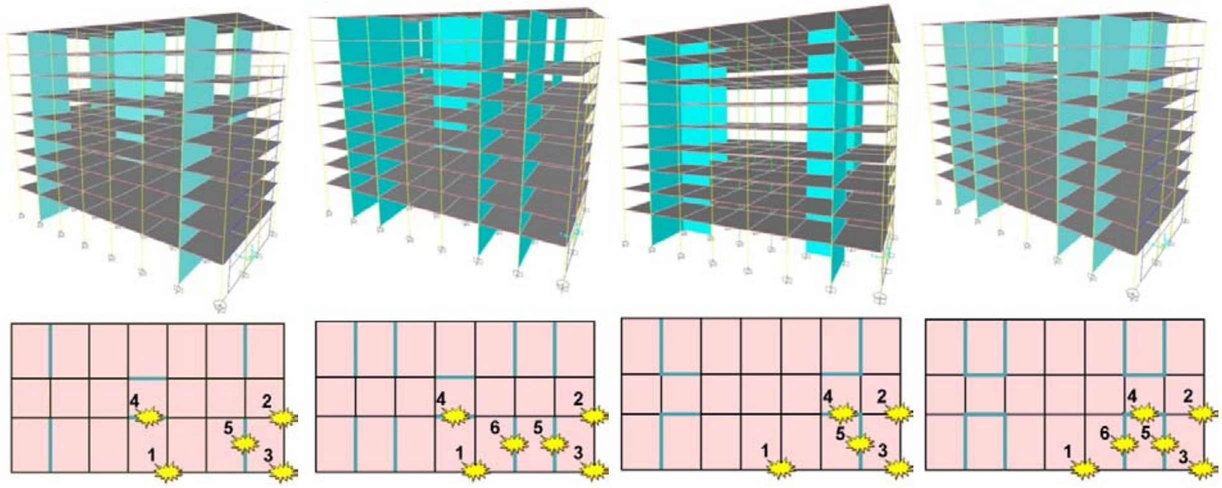
1. INTRODUCTION

Corley and others [4], have underlined that where there is a considerable seismic risk and/or an explosion risk, the dual system shall be also considered among other constructive systems.
The object of this study is a set of four dual system reinforced concrete structures, a ground level plus eight levels (nine levels high). The structures are theoretical but their dimensioning and the loads considered in the study comply with the technical regulations in force in Romania. The four study variants differ in number and in the way the interior structural walls are placed. Starting from a basic variant, by successive doubling the number of the walls along the two directions, one can obtain other three variants. Thus: (v_A) with four transversal walls and two longitudinal ones, representing the basic variant; (v_B) with eight transversal walls and two longitudinal ones – doubling the number of the transversal walls; (v_C) with four transversal walls and four longitudinal ones – doubling the number of the longitudinal walls; (v_D) with eight transversal walls and four longitudinal ones – doubling the number of both the transversal and longitudinal walls, that is in both directions.
The objective of the study is to determine if a dual-system construction, seismic designed complying with the Romanian technical regulations in force, has in the same time a good enough conformation to prevent progressive collapse. We have also in view to determine the influence of the number and position of the structural walls over the structural response for the progressive collapse. The calculations are care made in the elastic range.
Some recommendations from the international codes regarding the way the progressive collapse phenomena are approached will be also presented in the article.
The article is an extension of the following papers [10] and [2]

2. STRUCTURE DESIGN. CALCULATION MODEL

The office building has a 4,50 m high ground floor and 8 levels, 3,0 m high each. It is a reinforced concrete construction [concrete C24/30 (fcd=18N/mm2, ftd=1,25N/mm2) and steel PC 52 (fyd=300N/mm2)]. The outer coverings are of curtain type wall, and the interior partition walls are made out of gypsum wallboard. The terrace is not practicable. The building is considered to be located in Bucharest, so that the design ground acceleration IMR 100 years is: a_g=0,24g, the peak period is: Tc=1,60sec, the ductility class is: H and for the importance class and exposure is: γI=1,20

The main technical regulations taken into consideration are: (i) CR2-1-1.1 Design Code for the Constructions with reinforced concrete structural walls; (ii) P100/2006-1 Seismic Design Code; (iii) STAS 10107/0-90 Calculation and configuration of the concrete, reinforced concrete and pre-stressed concrete structural elements; (iv) CR0 – 2005 Design Code. Bases of design for the structures in constructions
The structure has 7 spans (7 x 5,0 m) and 3 bays (7,0+5,0+7,0 m) occupying, in plan, an area of 665.00 m^2 and having a total height of 28,50 m. The dimensions of the columns are: 0,80m x 0,70 m and 0,85m x 0,75 m, and those of the beams are: 0,30 m x 0,50 m and 0,30 m x 0,60 m. The floors and the walls are 0,15 m thick.
The calculation models are made up spatially by one-dimensional elements – for the columns and for the beams and bi-dimensional – for the floors and for the structural walls. The structure is considered to be fixed at the supporting base, fig. 1.



a. model v_A (basic model) ***b. Model v_B*** ***c. Model v_C*** ***d. Model v_D***

Fig. 1 Design models, location of the structural walls

2.1 Dynamic characteristics.

The mass taken into consideration for the specific dynamic study comes from the dead load of the resistance elements and 40% from the service load. For each structure there were determined so many dynamic characteristics till the modal mass was attracted into vibration as close as possible to 100%. In the Table 1 there are presented some of the data obtained by using the SAP2000-V12 Program.

Table 1. Inherent vibration characteristics

Variant	**T 1** (s)	**Vibration 1**	**T 2** (s)	**Vibration 2**	**T 3** (s)	**Vibration 3**
v_A	1,1811	Longitudinal	0,7827	Transversal	0,7534	Torsion
v_B	1,2053	Longitudinal	0,6848	Torsion	0,6029	Transversal
v_C	0,8721	Longitudinal	0,7229	Torsion	0,7134	Transversal
v_D	0,7723	Longitudinal	0,6618	Torsion	0,5757	Transversal

On the whole, the variant v_A has a different dynamic behaviour from the other three variants. Doubling the number of the walls makes the mode 2 to be of the general torsion and the mode 3 of the transversal vibration. The doubling of the number of the walls on both directions (v_D) will lead to a decrease of the value of the fundamental period with about 35%.

2.2 Relative level displacements. Basic shear efforts

The objectives of this stage of the study are the following: to check the relative level displacements and to determine the percent to which the designed shear force at the base of the structure is taken over by the frame columns and by the structural walls. This checking is made for two limit states: (i) service limit state (SLS); (ii) ultimate limit state (ULS). The mechanic elements of the structural seismic response – efforts and displacements – were obtained using the modal calculation with design answering spectra. The values of the calculated displacements are, for all the studied cases, under the value of the allowed relative level displacement [9, 10]. The ratio to which the basic shear force is taken over by the frames varies between limits of 10% and 30% and the ratio to which the shear force is taken over by the structural walls varies within the following limits: 90% and 70%.

3. BRIEF PREZENTATION OF THE RECOMMENDATIONS IN SOME TECHNICAL REGULATIONS IN FORCE REFERRING TO THE PROGRESSIVE COLLAPSE

More authors, [1, 5], showed that in Europe the rooms are generally surrounded by bearing walls, while in the USA the living area are most often surrounded by partition walls which are not bearing walls. The ratio between the walls and the plates (meaning the rooms) for the constructions in the U.S.A. is small, representing about 1/3 from that characteristic for the buildings in Europe. Consequently, the fact that there are less vertical bearing elements for the constructions in the U.S.A. makes the problem concerning the building stability to be more acute than in Europe.

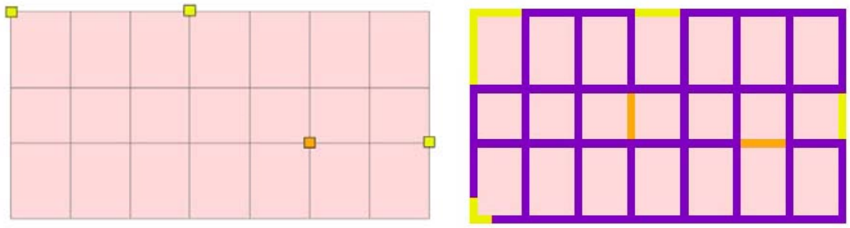
Eurocode 1 – Bases of design ENV 1991-1:1994 E, Section 2.1 Fundamental Requirements provides: • Avoiding, elimination or reducing the hazard. • Choosing the shape of the resistance structure that has a low sensibility to the considered types of hazard. • Choosing the shape of the resistance structure surviving the accidental removing of an individual element, of a limited part of the structure or the appearance of an acceptable localized failure. • Avoiding the structural systems that may collapse without any forewarning signs. • Anchoring the joining elements one to the other.

National Research Council of Canada, National Building Code of Canada (NBCC): Here we present some of the recommendations of this code: (i) Decreasing the length of the walls by adding some perpendicular „spine walls"; (ii) Reinforcing the floors in two directions so that to be able to take over the effects of an accidental removing of one wall placed on any direction.

Department of Defense (2003) Unified Facilities Criteria (UFC) 4-010-01: Minimum Antiterrorism Standards for buildings: One of the recommendations in this code refers to the necessity to calculate the columns and the walls – outside and inside – as if they were as long as the height of two floors.

Some of the most complete recommendations are in paper: *GSA - Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects - June 2003* [14]. Even if here there are indications for frame-structures and for structures with bearing walls presented separately. There are not provided recommendations for dual structures. For the framed-structures there are recommendations regarding the position of the columns that have to be considered as being removed, fig. 2,a. For the structures with resistance walls scenarios are proposed concerning the position and the length of the walls to be removed, fig. 2,b.

In view of taking into calculation the dynamic effects of the instant removing of one resistance element through a static analysis, it is proposed that the vertical loads on the failed structure to be double as compared with those acting on the intact structure.



a. *b.*

Fig. 2 Scenarios concerning the position of the removed resistance elements

In the Romanian technical regulations no recommendations are provided concerning the design or checking for the progressive collapse. Yet, there are some general recommendations in the *„Seismic Design Code P100-1/2006 – Design Provisions for Buildings”*, namely: (1) The structural simplicity implies the existence of continuous and strong enough structural system able to ensure a clear path, as direct as possible, non-interrupted for the seismic forces, irrespective their direction, up to the founding ground. The seismic forces that appear in all the elements of a building, as mass forces, are taken over by the floors – horizontal diaphragms and sent to the vertical structure, and from this they are transferred to the foundations and to the ground. The design shall ensure that no discontinuities will appear along this path. For instance, a large hole in the floor or the absence, from the floor, of the reinforcing bars collecting the inertia forces to send them to the vertical structure – also represent discontinuities. (2) The seismic design aims to provide the structure of the building with the appropriate redundancy. This will ensure that: *The failing of one single element or of one single structural tie do not expose the structure to the loss of its stability; *a plasticized mechanism is obtained with sufficient plastic zones, able to allow the exploitation of the resistance reserves of the structure and an advantageous dissipation of the seismic energy.

4. CHECKING THE STRUCTURES FOR THE PROGRESSIVE COLLAPSE

For the study regarding the determination of the dual structure sensitivity to progressive collapse, we have combined the recommendations for the framed-structures with those for the structures with walls.

It was considered the removing, in turn, of one single structural element from the ground floor level that is three columns and two walls: (1) a column near the middle of the long side; (2) a column near the middle of the short side; (3) a corner column; (4) a wall parallel with the long side; (5) a wall parallel with the short side.

For the loadings the following combinations were considered:

- For the intact structure
  - specific dynamic study (1 x specific weight + 0,4 x service)
  - study of the displacements and efforts (1,35 x specific weight + 1,05 x service)
- for the structures where structural elements were removed:
  - specific dynamic study 2 x (1 x specific weight + 0,4 x service)
  - study of the displacements and efforts 2 x (1,35 x specific weight + 1,05 x service)

Thus, there have resulted 26 study cases: [4 intact structures + (2 structures x 5 removed elements for every structure) + (2 structures x 6 removed elements for every structure)]. The elements location and the order the comments are made are presented figure 1.

From the variables characterizing the structural response the following were chosen to make comparisons: the first two specific periods T1, T2, the vertical nodal displacement, the stress in the walls calculated according to Von Mises criterion. To make evident the influence of each mechanical variable we used the following type ratios:

$$\frac{\text{value of the mechanical variable at the structure with a removed element}}{\text{value of the mechanical variable at the intact structure}} = \text{C variable}$$

After the calculation of these coefficients for each type of structure and each case of the removed element, combinations shall be made in order to put into evidence the influence of the increased number of the walls.

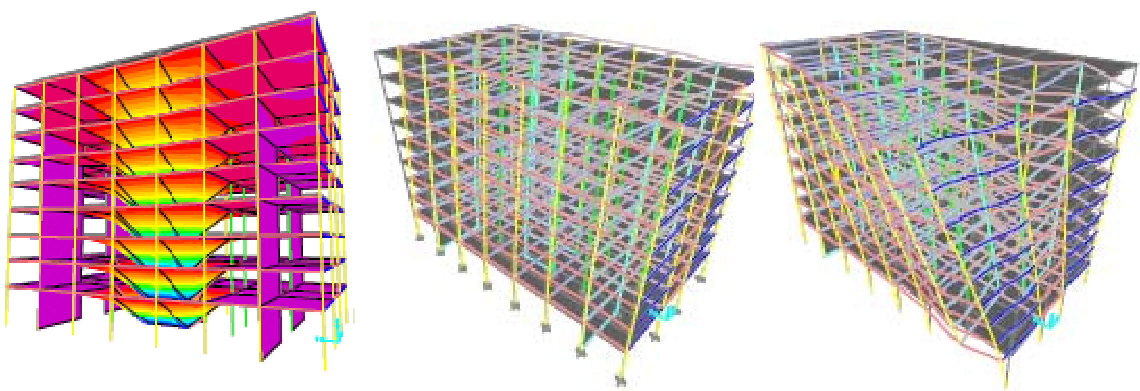
4.1 Structure v_A

Variant v_A represents the control variant – basic – having the fewest number of walls. The data are presented systematized in table 2.

Table 2 Variation coefficients of the mechanical variables determined for structure v_A

Case	$C_{mvariable}$				
	$C_{desplacements}$	C_{T1}	C_{T2}	$C_{SVM,\ wall\ on\ long\ side}$	$C_{SVM,\ wall\ on\ short\ side}$
Intact structure **v_A**	1,000	1,000 longitudinal	1,000 transversal	1,00	1,00
1-column on the long side	33,000	1,281	1,282	2,17	2,04
2-column on the short side	29,375	1,285	1,280	2,14	2,44
3-corner column	32,875	1,287	1,287	2,13	2,55
4-wall on the long side	52,500	1,474	1,280	2,73	2,02
5-wall on the short side	49,375	1,283	1,585 TORSION	2,04	3,47

The maximum vertical displacement is: 0,0834 m in case 4 – removing the wall parallel with the long side, placed immediately above it, fig.3,a.



a. Vertical displacements - case 4 ***b. Vibration mode 2 - Intact structure*** ***c. Vibration mode 2 - case 5***

Fig. 3 Variant v_A for walls location

In case 5 – removing the wall parallel with the short side, the vector characteristic for the vibration mode two changes from bending to torsion and the increase of its inherent period is the highest. Studying the displacements for the cases when a column is removed one can find out that the effect of the removing of the column from the long side – 0,0528 m, and the effect of the removing of the corner column – 0,0526 m are practically equal. In this variant – where the walls are the fewest in number – speaking about the vertical displacements, the influence of the removing the walls is with about 60% higher than the influence of the column removing

4.2 Structure v_B

As in this variant the structure has eight walls parallel with the short side, they can be removed and then one can read the values both for the wall to the interior and for that placed to the exterior. Consequently, six cases will be studied and the results can be chosen both for the exterior and interior walls. The data read on the interior wall are given between parentheses – table 3.

Doubling the number of the transversal walls will lead to the modification of the vibration vector of the mode 2 even since the structure is intact. This is of the torsion type as compared to the transversal vibration in model v_A. The specific vibration modes keep their own shapes in all studied cases. The maximum displacement is for the case 4 – removing the longitudinal wall and it has the following value: 0,0814 m.

Table 3 Variation coefficients of the mechanical variables determined for structure v_B

Case	$C_{variable}$				
	$C_{displacements}$	C_{T1}	C_{T2}	$C_{SVM,\ wall\ on\ long\ side}$	$C_{SVM,\ wall\ on\ short\ side}$
Intact structure **v_B**	1,00	1,000 longitudinal	1,000 torsion	1,00	1,00
1-column on the long side	42,83	1,28	1,28	2,21	1,94 (2,21)
2-column on the short side	39,08	1,28	1,28	2,13	2,29 (2,20)
3-corner column	43,50	1,27	1,28	2,13	2,34 (2,02)
4-wall on the long side	67,83	1,47	1,28	2,70	2,04 (2,54)
5-wall on the short side, exterior	63,33	1,28	1,42	1,99	2,90 (3,08)
6-wall on the short side, interior	62,50	1,28	1,33	2,47	2,98 (2,70)

The removing of the wall parallel with the long side has its maximum effect on the period of the fundamental mode increasing the longitudinal vibration. The removing of the wall parallel with the short side, placed to the exterior, has the maximum effect on the period of the mode 2 increasing the torsion type vibration.

4.3 Structure v_C

Variant v_C has are 4 longitudinal walls and 4 transversal walls – double the number of the walls on the longitudinal direction as compared to the variant v_A. The data are presented synthetically in table 4.

For this variant the following remarks can be made:

(1) the maximum vertical displacements are at the case 1 – removing the column from the long side – 0,0535 m;

(2) the minimum vertical displacement is at the case 4 – removing a longitudinal wall – 0,0105 m;

(3) at the case 5 – removing the wall parallel with the short side, the roof tie-bar joint has both vertical displacement – 0,0153 m, and transversal displacement – 0,021 m;

Tabel 4 Coeficienți de variație a mărimilor mecanice determinate pentru structura v_C

Case	$C_{variable}$				
	$C_{displacements}$	C_{T1}	C_{T2}	$C_{SVM,\ wall\ on\ long\ side}$	$C_{SVM,\ wall\ on\ short\ side}$
Intact structure **v_C**	1,000	1,000 longitudinal	1,000 torsion	1,00	1,00
1-column on long side	33,475	1,280	1,278	1,88	2,17
2-wall on the short side	29,190	1,284	1,278	2,15	2,28
3-corner column	32,625	1,286	1,283	2,19	2,55
4-wall on the long side	6,56	1,410	1,299	2,49	4,12
5-wall on the short side	9,313 displ. Also transversally	1,415 TORSION	1,507 TORS+TRANSV	3,81	3,13

(4) the vibration vector changes at the case 5 - removing the wall parallel with the short side even from the fundamental mode which is now torsion, the vector of mode 2 is made out of a vibration composed out of the torsion and bending, fig. 4;

(5) a special remark can be made regarding the position of the walls where the maximum Von Mises unit effort appears, namely: (a) at the case 2 - removing the column on the short side, the maximum unit effort is in the longitudinal wall opposite the column speaking about the symmetry transversal axis, fig. 5; (b) at the case 3 – removing the corner column, the maximum unit effort is also in a longitudinal wall opposite the column, as compared to the diagonal, fig. 5.

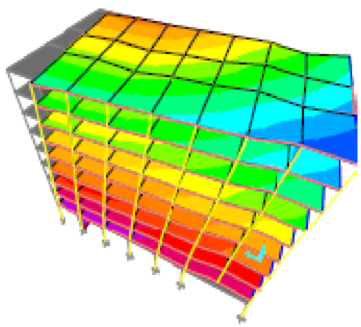


Fig. 4 Mode 2 - case 5 (v_C)

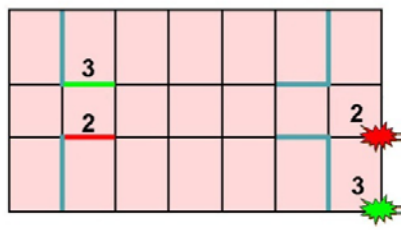


Fig. 5 SVM- Efforts – cases 3,4 (v_C)

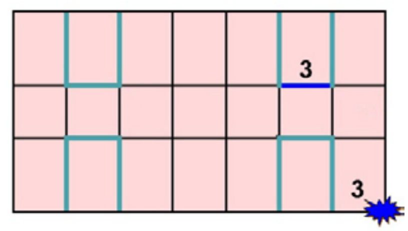


Fig. 6 SVM Efforts – case 6 (v_D)

4.4 Structure v_D

The variant v_D has the greatest number of walls – 4 longitudinal and 8 transversal walls – double as the basic variant, v_A. As in this variant the structure has eight walls parallel with the short side, both a wall placed to the interior and one placed to the exterior are removed. Consequently, six cases will be studied. The data are summarized in table 5. Besides the wall the column in common with the wall, on the perpendicular direction, was also removed from the model.

Tabel 5 Coeficienți de variație a mărimilor mecanice determinate pentru structura v_D

Case	$C_{variable}$				
	$C_{displacements}$	C_{T1}	C_{T2}	$C_{SVM,\ wall}$ on long side	$C_{SVM,\ wall}$ on short side
Intact structure **v_D**	1,000	1,000 longitudinal	1,000 torsion	1,00	1,00
1-column on the long side	32,50	1,279	1,278	2,04	2,40
2-column on the short side	29,00	1,283	1,278	2,29	2,29
3-corner column	32,31	1,284	1,281	2,20	2,49
4-wall on the long side	2,81	1,325	1,340	2,57	5,98
5-wall on the short side-exterior	7,50	1,368	1,400	7,78	3,06
6-wall on the short side -interior	7,12	1,363	1,332	7,94	3,03

In this walls placing variant, the vertical displacement is very small (0,0045) m for the case 4 – removing a wall parallel with the long side. The eigenvectors do not change their shape. The maximum values of the Von Mises unit efforts are for the cases 5 and 6 – removing a wall parallel with the short side - exterior and interior.

We mention that, when removing the corner column, the wall parallel with the long side over the longitudinal symmetry axis, where the column was removed, is loaded, fig. 6.

5. VARIANTS COMPARISON

The data are summarized in table 6 where the symbols have the following significance:

- m –minimum value of the coefficient for the variable studied on the case;
- mm – minimum value of the coefficient for the variable studied on all variants;
- M – maximum value of the coefficient for the variable studied on the case;
- MM – maximum value of the coefficient for the variable studied on all variants.

Tabel 6 Comparații

Coefficient	Vari-ant	**Case – removed element**				
		1- column long side	**2**- column long side	**3**-corner column	**4**-wall long side	**5**- wall on short side - exterior/interior
C displacement	v_A					
	v_B	M	M	M	MM	M
	v_C					
	v_D	m	m	m	mm	m
C T1	v_A	M	M	M	M	
	v_B		m	m		mm
	v_C					MM change the vector
	v_D	m			m	
C T2	v_A	M	M	M	m	MM change the vector
	v_B			m		
	v_C	mm	m			change the vector
	v_D				M	m
C SVM in wall long side	v_A			m	M	
	v_B	M	m			m
	v_C	mm			m	
	v_D		M	M		MM
C SVM in wall short side	v_A		M	M	m	M
	v_B	mm	(m)	(m)		m
	v_C					
	v_D	M			MM	

6. FINAL REMARKS

The study had the following objectives: (i) to find if a dual system seismic designed construction complying with the Romanian technical regulations in force is, in the same time, well designed to prevent the progressive collapse as well; and (ii) to find out the influence of the number and of the position of the structural walls over the structural response for progressive collapse**.** The object of this study is a set of four dual system reinforced concrete structures, ground level plus eight levels (nine levels high). The four study variants differ in number and in the way the inside resistance walls are placed. The calculation hypotheses for the progressive collapse were: (1) only one resistance element was removed from the structure; (2) the loads on the structure having a removed element are double as compared with those on the intact structure; (3) it is a static calculation in the linear elastic domain.

1. The structures in dual system are designed and checked for the seismic actions applying the technical regulations in force in Romania. The level relative displacements range within the allowed values both for the service limit state and for the ultimate limit state, in all studied variants of placing the structural walls. The doubling of the number of the walls in both directions (v_D as compared to v_A) brings about a decrease of the fundamental period with about 35%.
2. Based on the study carried out for the progressive collapse, the following comments can be made:

   a) Removing a column:

   - Practically, the vertical displacements are the same for all variants and for all cases respectively. The variation is not significant: the maximum value is

0,0528 m in variant v_A and in case 1-removed column from the long side, and the minimum value is 0,0464 m in variant v_D and in case 2- removed column from the short side. The vertical displacements in the cases when a column from the long side or the corner column was removed have about the same values in all variants of the walls location.

- The increasing of the fundamental period as well as that for the vibration mode two is about the value of 1,28. The vibration vectors of the intact structure remain the same they do not change irrespective the removed column.
- The increasing of the values of the unit efforts – Von Mises - in the structural walls when removing the columns varies between 1,88 (at the wall on the long side, in variant v_C and case 1-column on the long side) and 2,55 (at the wall on the short side, in variants v_C or v_A in case 3-corner column). In fact, the removing of the corner column has the greatest influence, in all wall patern variants, on the walls parallel with the short side.
- In certain wall pattern variants, when removing the columns, the maximum Von Mises values of the unit efforts are not in the walls near the removed columns but on the opposite side of the structure.

We consider that for the studied wall placing variants, the influence of the removing of only one column does not bring about major disturbances in the structural response.

b) Removing a wall:

- The maximum vertical displacement for all studied variants and cases (0,0836 m), is noticed al variant v_A case 4-removing the wall on the long side. The minimum vertical displacement is at variant v_D, also case 4 (0,0045 m). The highest influence, of all variants and of all cases, is at variant v_B and at the same case 4 where the increase is 67,83 times the one of the intact structure.
- Case 5-removing the wall parallel with the short side has the greatest influence on the inherent dynamic response, both in increasing the natural periods and in changing the eigenvector. We consider it is the most significant influence.
- Variant v_D (where the number of the walls is maximum and double as compared to variant v_A), it has a maximum influence in respect of increasing the Von Mises unit effort. In case 4 – when removing a wall parallel with the long side, the maximum influence is over the wall parallel with the short side; in case 5- removing a wall parallel with the short side, the maximum influence is over the wall parallel with the long side.

The influence of the walls removing is significant. The removing of one wall parallel with the long side influences the vertical displacements and the unit efforts in the walls parallel with the short side. Removing a wall parallel with the short side influences the inherent dynamic response both by increasing the values of the natural periods and, especially by changing the eigenvibration vector; it also has influence over the unit effort in the walls parallel with the long side.

ACKNOWLEDGEMENT: *This work was supported by CNCSIS –UEFISCSU - project number 362/2007, PN II – IDEI code 8/2007).*

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