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The Effects of Placement and Cross-Section Shape of Shear Walls in Multi-Story RC Buildings with Plan Irregularity on Their Seismic Behavior by Using Nonlinear Time History Analyses

Mohammad Aminnia, Mahmood Hosseini

Abstract**—**Environmental and functional conditions, sometimes, necessitate the architectural plan of the building to be asymmetric, and this result in an asymmetric structure. In such cases finding an optimal pattern for locating the components of lateral load bearing system, including shear walls, in the building's plan is desired. In case of shear wall in addition to the location the shape of the wall cross-section is also an effective factor. Various types of shear walls and their proper layout might come effective in better stiffness distribution and more appropriate seismic response of the building. Several studies have been conducted in the context of analysis and design of shear walls; however, few studies have been performed on making decisions for the location and form of shear walls in multi-story buildings, especially those with irregular plan. In this study, an attempt has been made to obtain the most reliable seismic behavior of multi-story reinforced concrete vertically chamfered buildings by using more appropriate shear walls form and arrangement in 7-, 10-, 12-, and 15-stoy buildings. The considered forms and arrangements include common rectangular walls and L-, T-, U- and Z-shaped plan, located as the core or in the outer frames of the building structure. Comparison of seismic behaviors of the buildings, including maximum roof displacement and particularly formation of plastic hinges and their distribution in the buildings' structures, have been done based on the results of a series of nonlinear time history analyses, by using a set of selected earthquake records. Results show that shear walls with U-shaped cross-section, placed as the building central core, and also walls with Z-shaped cross-section, placed at the corners give the building more reliable seismic behavior.

Keywords**—**Vertically chamfered buildings, non-linear time history analyses, L-, T-, U- and Z-shaped plan walls.

I. INTRODUCTION

IN recent decades, behavior of the structures undergoing seismic forces has been drawn into attention and many researchers have put their efforts on designing the structures in such a way to achieve a reliable seismic behavior. Although, in recent earthquakes, the building structures, designed based on usual design criteria, have worked out appropriately in meeting criteria of Life Safety (LS) Performance Level (PL), the range of damages and the economic losses to the structures has been far beyond the expected levels. It is now well-known that the structures which are designed based on the common codes criteria would suffer from extensive damages subjected to severe earthquakes. Buildings with shear wall lateral load bearing system are not exceptions in this regard. The use of shear wall system, which is among the conventional load-bearing systems and shown to be economical in buildings up to 35 stories, is very common in multi-story buildings in earthquake prone countries.

In many cases, due to the limitations dictated by the architectural design of the building, its plan is asymmetric, and as a result shear wall may not be placed in a symmetrical setting. Investigations on the buildings' performance in past earthquakes show that the asymmetric buildings, either in plan or elevation are more vulnerable to earthquake than the symmetric ones [1], [2]. In recent years, many efforts have been made to assess the seismic responses of the asymmetric building structures, especially, their torsional responses. The asymmetric building structures have special characteristics in non-linear range which make it difficult to predict their behavior during an earthquake. Particularly with regard to reinforced concrete (RC) wall-frames buildings Jeong has expressed that the damage state probabilities of wall-frame structures designed to high PGA and ductility levels do not satisfactorily achieve the most favorable safety objectives [3]. Wdowicki J. and Wdowicka E. worked on three-dimensional static analysis of asymmetric shear wall structures with connecting and stiffening beams, and presented a method which is particularly and basically efficient at the preliminary design stage [4].

In case of asymmetric buildings it is quite logical to locate the walls in the building plan is such a way that the torsional effects become minimum. In spite of several researches on the seismic behavior of RC buildings with shear walls, and particularly their optimal seismic design, such as studies of Kaveh and Zakian [5], there are few studies on the optimal form and placement of shear walls in the plan of a building with asymmetric plan. Harne has done a comparative study of strength of RC shear wall at different location on a multi-storied residential building [6]. Mentioning that in spite of the existence of lots of literatures for design and analysis of shear walls, the decision about the location of shear wall in multistory building is not much discussed in any literature, he has focused on determining the solution for shear wall location

M. Aminnia is Graduate Student in Civil Engineering Department, School of Engineering, Tehran Central Branch of the Islamic Azad University (IAU), Tehran, Iran, (phone: +989124839954, e-mail: mohamadamn68@gmail.com).

M. Hosseini is Associate Professor in Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran (corresponding author, phone: +989128093102, fax: +982122803933, e-mail: hosseini@iiees.ac.ir).

in a multistory building. He has considered a 6-story reinforced concrete building placed in Nagpur, India, subjected to earthquake loading, with three different cases of shear walls positions and by using code-based simplified analysis has concluded that shear walls in middle bays of outer frames leads to better behavior of the building.

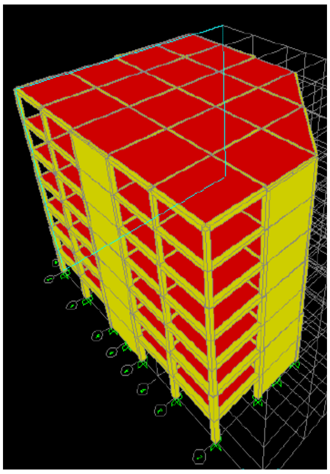
The ordinary pushover analysis method has the ability to accurately estimate the general seismic response in low- and mid-rise regular buildings, but it is not accurate in estimating the response of tall and, especially, irregular buildings. In fact, the effects of higher modes in these structures, lead to wrong estimation of their seismic responses by pushover analyses as reported by [7]. Regarding that, on the one hand, construction of mid- and particularly high-rise buildings is ongoing in many cities of the earthquake prone countries, especially in their large cities such as Tehran, and the regional and environmental conditions make many of these buildings asymmetric plan, on the other hand, the investigation on the asymmetric plan in this type of buildings and their more reliable and more economical design seems to be of great importance, particularly developing countries located in high seismic zones, such as Iran.

Based on the available technical publications, it can be said that many studies have already been conducted about the analysis and design of RC frames shear walls; however, the optimal placement of walls and their more appropriate cross-section shape, in buildings, especially those with asymmetric plan, have not been discussed thoroughly. As a result, in this study, an attempt has been made to find out the effect of placement as well as cross-section shapes of shear walls on the seismic response of multistory RC buildings, by modeling several mid-rise to relatively high-rise buildings with asymmetric plans, using walls of L-, T-, U- and Z-shaped cross-section. By performing a series of nonlinear time history analysis, by using the two- and three-component accelerograms of a set of selected earthquakes, and comparing the obtained seismic responses, particularly, the type and distribution of plastic hinges, it has been tried to find the more appropriate placement and cross-section shape of the walls among the eight considered patterns. Details of the study are briefly presented in the following sections.

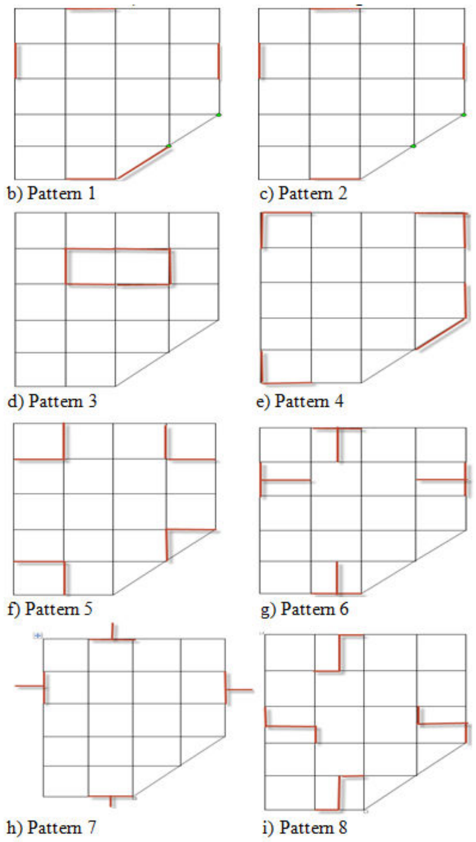
II. INTRODUCING THE CONSIDERED BUILDINGS AND VARIOUS SHEAR WALLS PLACEMENT-SHAPE PATTERNS

Fig. 1 illustrates a sample the considered chamfered RC building with eight various shear walls placement-shape patterns, considered for them to investigate the effect of shear walls placement and their cross-section shape in the seismic response of the building.

The general plan shown in Fig. 1 is very common for buildings which are located at corners of the city blocks. As the amount of setback at the corner of this building is more than 25% of the building plan dimension, it is categorized as an irregular plan according to the code. In all selected arrangements, an attempt has been made to equate the areas of the used walls in order to compare them, and in all cases an approximate span length of 5.5 m has been used. Also it has been tried to make center of mass and center of stiffness close to each other as much as possible to prevent the torsion effect. In patterns 3 and 5 some openings have been considered in the walls to create the required accesses. In placement 7 it has been assumed that there is an open area around the building. In all cases the height of the stories has been considered to be 3.0 m floor-to-floor.



(a) General view of the buildings



b) Pattern 1 c) Pattern 2

d) Pattern 3 e) Pattern 4

f) Pattern 5 g) Pattern 6

h) Pattern 7 i) Pattern 8

Fig. 1 Vertically chamfered building and its eight various shear walls placement-shape patterns

III. MODELING AND DESIGN OF THE CONSIDERED BUILDING

For design of the considered RC buildings with various shear walls placement-shape patterns they have been modeled in an appropriate computer program. Building’s location has been assumed to be in Tehran and the site soil to be of class C. The buildings have been considered to be for residential usage. Therefore, their importance category is moderate-importance. The specifications of the construction materials have been assumed as follow:

- Compressive allowable stress of concrete, f'c = 300 kgf/cm2
- Specific weight of concrete 2400kgf/m2
- Poisson's ratio of concrete, 0.2
- Modulus of elasticity of concrete, 25000MPa
- Steel barstype,ST-37

The used codes for design of the buildings include IBC-2003 for loading and ACI-318-05 for design of concrete sections. The sections considered for beams and columns of different stories of the 15-story buildings, as samples of the considered buildings of the study are as shown in Table I; more information of this type can be found in the main report of the study [9].

TABLE I
THE SECTIONS CONSIDERED FOR BEAMS AND COLUMNS OF DIFFERENT STORIES OF THE CONSIDERED 15-STORY BUILDINGS

Section	Element Type	Number of pieces
B30×30	Beam	Stories 15, 14, 13
B35×35	Beam	Stories 12, 11, 10
B40×40	Beam	Stories 9, 8
B45×45	Beam	Stories 7, 6, 5
B50×50	Beam	Stories 4, 3
B55×55	Beam	Stories 1, 2
C35×35 – T16	Column	Stories 15, 14, 13
C35×35 – T20	Column	Stories 12, 11, 10
C40×40 – T20	Column	Stories 9, 8
C45×45 – T20	Column	Stories 7, 6, 5
C50×50 – T20	Column	Stories 4, 3, 2, 1

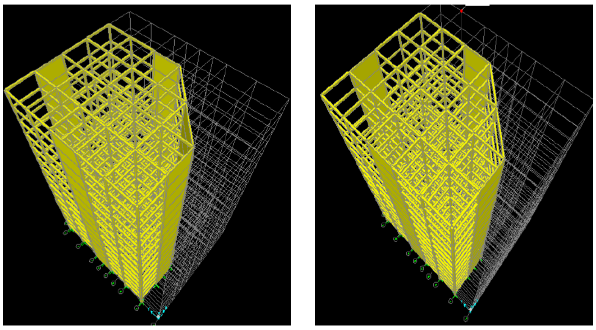
Fig. 2 shows the 3-D views of the computer models of the studied buildings with eight different placement-shape patterns of shear walls.

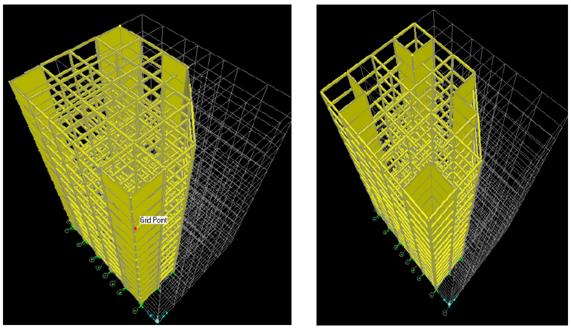
Fig. 3 shows the color-based presentation of stress ratios in the sample frames of the designed buildings, showing their proper code-based design.

It is seen in Fig. 3 that generally the stress ratios are less than 1.0. In the few cases which the ratios are beyond 1.0 it has been tried to limit them to 1.1 in design process. The fundamental periods of all of the designed buildings for eight placements of shear walls are given in Table II.

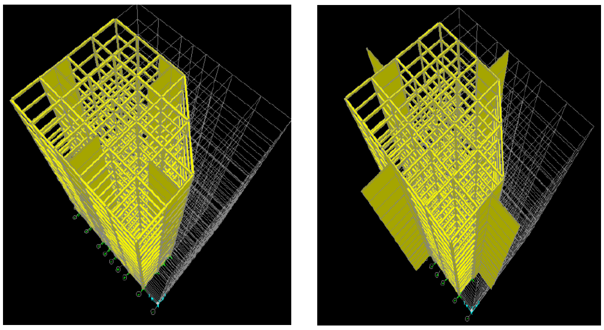
Mode shapes of the 15-story buildings for eight placements of shear walls are shown in Fig. 4.

It is seen in Table II that the fundamental periods of the buildings are significantly depended on the placement-shape pattern of the shear walls. For example in case of 7-story building the fundamental period varies from 0.42 sec for pattern 3 to 0.92 sec for pattern 1. Also it can be observed in Fig. 4 that in case of some patterns the first mode is basically lateral, while in case of some other patterns it is torsional.


Pattern 1 Pattern 2



Pattern 3 Pattern 4


Pattern 5 Pattern 6

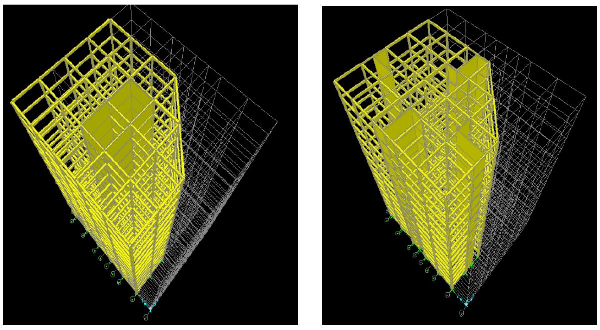

Pattern 7 Pattern 8

Fig. 2 The 3-D views of the computer models of the considered 15-story buildings

TABLE II
THE FUNDAMENTAL PERIODS OF DESIGNED BUILDINGS (IN SEC) FOR EIGHT PLACEMENT-SHAPE PATTERNS OF SHEAR WALLS

No. of Stories	**Placement-shape pattern number of shear walls**							
	1	2	3	4	5	6	7	8
7	0.92	0.91	0.42	0.44	0.52	0.48	0.61	0.43
10	1.41	1.40	0.76	0.73	0.86	0.85	0.98	0.71
12	1.73	1.72	1.03	0.94	1.13	1.12	1.36	0.98
15	1.87	1.85	1.12	1.03	1.31	1.29	1.48	1.13

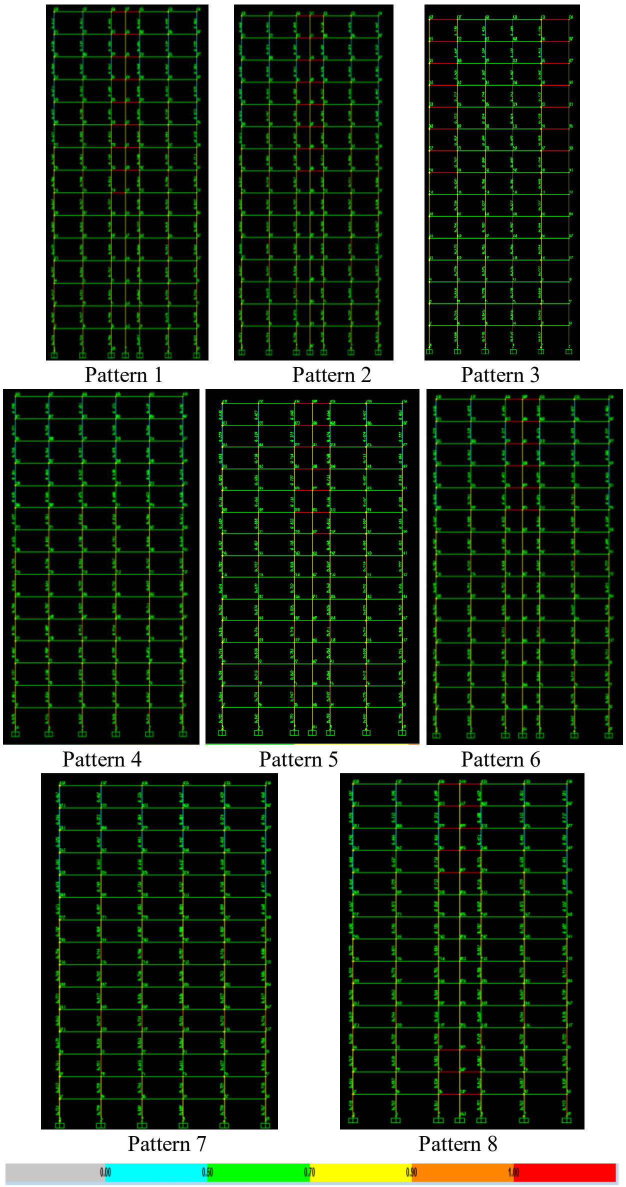

Pattern 1
Pattern 2
Pattern 3
Pattern 4
Pattern 5
Pattern 6
Pattern 7
Pattern 8

Fig. 3 Color-based presentation of stress ratios in some frames of the 15-story buildings

IV. NONLINEAR TIME HISTORY ANALYSIS OF THE BUILDINGS

To evaluate the seismic behavior of the designed buildings a series of nonlinear time history analyses (NLTHA) have been performed by using the two horizontal components of a set of selected earthquakes, [9], to be more compatible with the seismic design codes assumption with regard to far-field earthquakes. For this purpose characteristics of the plastic hinges have been considered based on ASCE-41-06 [8]. Both force-controlled and displacement-controlled plastic hinges have been used in columns, but for beams only displacement-controlled hinge have been considered. For shear walls the equivalent column sections have been used. Plastic hinges locations in columns and beams have been considered at 0.05 and 0.95 of the member length, and for each shear wall a plastic hinge has been considered at 0.05 of the wall height at its bottom. Seismic responses which have been considered for comparison include roof displacements, base shears, inter-story drifts and the plastic hinges of the buildings. Some samples of the response histories as well as the hysteretic curves, related to one of the 15-story buildings, as a sample of the studies buildings, are illustrated in Figs. 5 and 6.

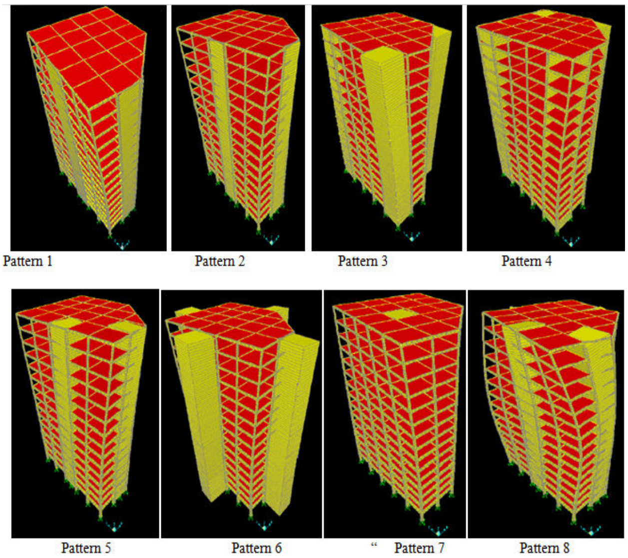
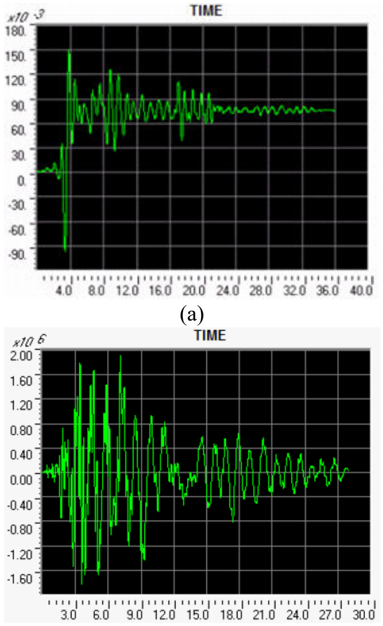

Pattern 1
Pattern 2
Pattern 3
Pattern 4
Pattern 5
Pattern 6
“ Pattern 7
Pattern 8

Fig. 4 Deformed shapes of 15-story building in its 1-st mode for eight placement-shape patters of shear walls

The nonlinear behavior of the sample 15-story building can be clearly seen in the roof displacement history shown in Fig. 5, and inter-story drift history, as well as the hysteretic loops, shown in Fig. 6.

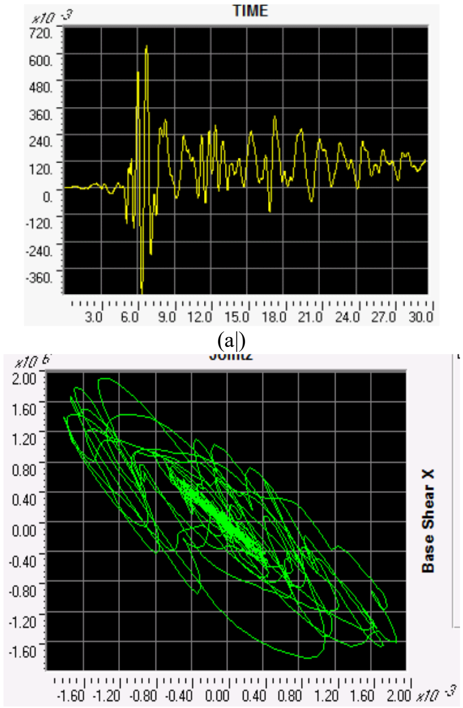
Types of plastic hinges and their distributions in some selected frames of the 15-story buildings for the eight considered shear wall placement-shape patterns are shown in Fig. 7; similar results for 7-, 10-, and 12-story buildings can be found in the main report of the study [9]. It is seen in Fig. 7 that in some cases the created plastic hinges are beyond Collapse Prevention (CP) PL, while is some other cases they are almost in LS PL, and even in some cases Immediate Occupancy (IO) PL. The difference in the PL of the created plastic hinges in cases of various placement-shape patterns is one of the main distinction factors between the considered patterns. On this basis, it can be said that the building with shear walls placement-shape pattern number 2, which is a very common pattern, has lower performance level in comparison with other patterns.



(a)

(b)

Fig. 5 Roof displacement (m) history (a), and base shear (kgf) history (b) of the sample 15-story building in X direction subjected to, respectively, Cape Mendocino and San Fernando earthquake



(a)

(b)

Fig.6 Time history of the inter-story drift (cm) of the 14th story (a) and hysteretic loops of story shear (kgf) versus inter-story drift of the 1st story (b) of the 15-story building in X direction subjected to, respectively, Whittier Narrows and San Fernando earthquake

To make a better comparison between the seismic responses of buildings with different number of stories and various shear wall placement-shape patterns, Tables III-VI show the average and maximum drift values, maximum base shear values, and maximum roof acceleration and maximum roof displacement values of the 7-, 10-, 12-, and 15-story buildings with the eight shear walls placement-shape patterns, obtained from the NLTHA by using the selected earthquakes. In these NLTHA once only the two horizontal components of the accelerograms have been considered to make the condition more compatible to the code assumption for the case of far-field earthquakes, and once more all three components have been considered to find of the effect of vertical ground excitation as well.

It can be seen in Table III that depending on the shear walls placement-shape pattern, used in the 7-story buildings, the maximum drift value can vary between 0.30 cm and 0.87 cm, with the an average value ranging from 0.16 cm to 0.46 cm. Also it is seen in Table III that the maximum value of base shear force in 7-story buildings vary between 9.32E5 kgf to 4.10E6 kgf depending on the shear walls placement-shape pattern used in the building. Similar observations can be made by looking at the results shown in Tables IV-VI to 10-, 12-, and 15-story buildings. As the last set of the numerical results, Table VII shows the average and maximum drift values, maximum base shear values, and maximum roof acceleration and roof displacement values of the 15-story buildings with the eight shear walls placement-shape patterns obtained from the NLTHA by using the three components of the selected earthquakes to see if the consideration of vertical component of earthquake in combination of its horizontal components, which is the case for near-field earthquakes, does have any significant effect on the seismic responses.

Finally, comparing Tables VI and VII one cab observe that although the average drift values in case of three-component excitations is larger than those in case of two-component excitations, the maximum drift values are surprisingly smaller in case of three-component excitations. Table VII also shows that using the three-component excitations has a decreasing effect on the maximum base shear force values. The same is true with regard to maximum roof acceleration and maximum roof displacement values.

V. CONCLUSIONS

Based on the numerical results, obtained from NLTHA of 7- to 15- story RC buildings with eight different shear walls placement-shape patterns, by using two- and three-component accelerograms of the selected earthquakes, and comparing the seismic responses of the buildings, the following conclusions can be made:

- Depending on the shear walls placement-shape pattern used in the building design the response values, either drifts or base shear forces, may vary in a wide range, so that the maximum value may be several times larger than the minimum value. This drastic change of the seismic responses for different shear walls placement-shape pattern is also true for the formation of plastic hinges.

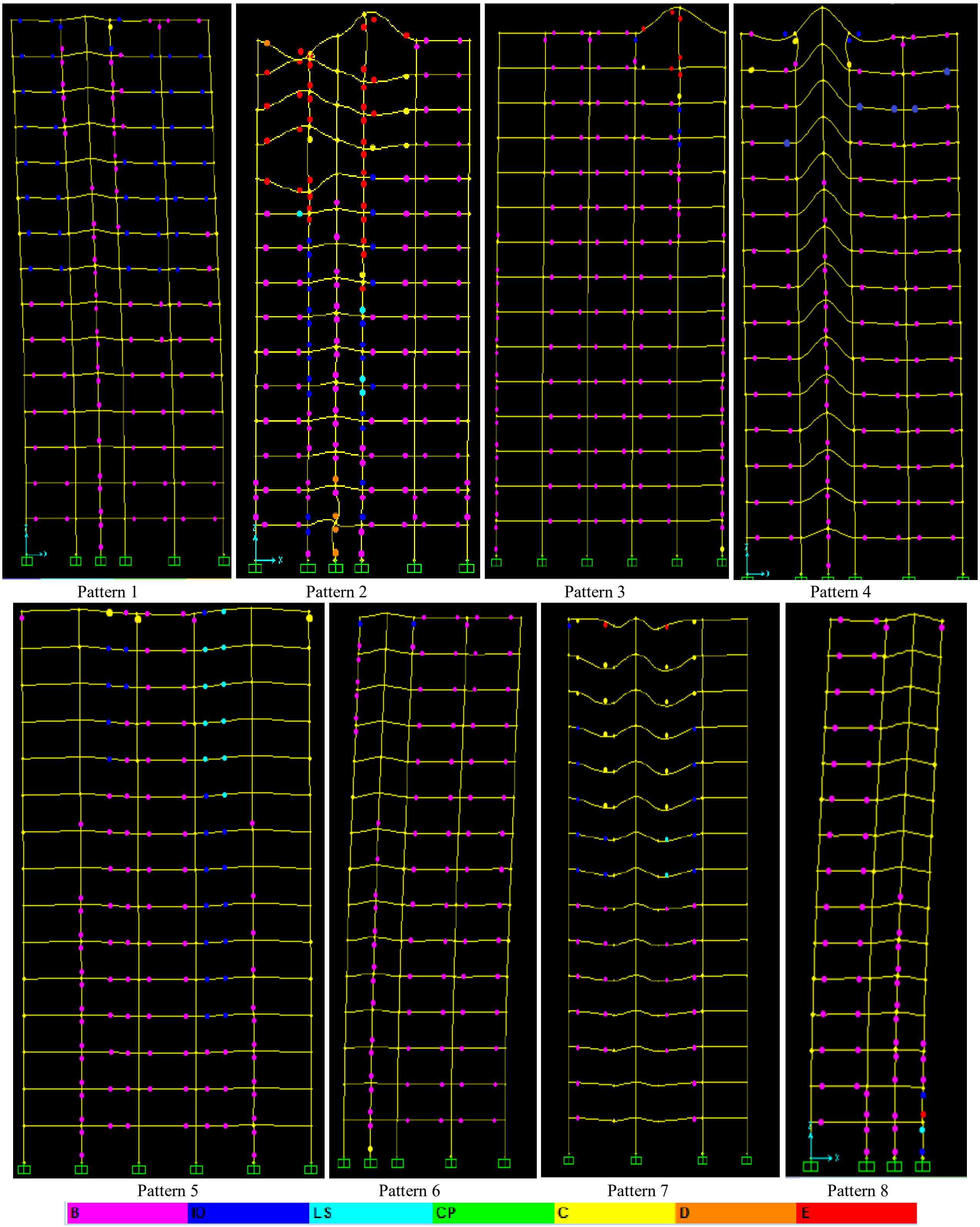

Pattern 1
Pattern 2
Pattern 3
Pattern 4
Pattern 5
Pattern 6
Pattern 7
Pattern 8

Fig. 7 Samples of types and distributions of plastic hinges in beams, columns and walls of selected frames of the15-storiesbuildings in the worst conditions

TABLE III
Average and Maximum Drift Values, Maximum Base Shear Values, and Maximum Roof Acceleration and Roof Displacement Values of the 7-Story Buildings with the Eight Shear Walls Placement-Shape Patterns Obtained from the NLTHA

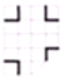
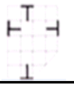
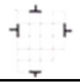
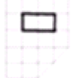
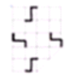
Pattern Response								
Av. Drift (cm) in X and Y directions	0.39	0.37	0.19	0.26	0.33	0.20	0.46	0.17
	0.37	0.36	0.18	0.23	0.31	0.19	0.17	0.16
Max. Drift (cm) in X and Y directions	0.58	0.55	0.34	0.48	0.69	0.38	0.87	0.31
	0.56	0.53	0.33	0.45	0.58	0.37	0.24	0.30
Max. Base Shear (kgf) in X and Y directions	1.03E6	9.32E5	3.8E6	3.47E6	3.78E6	2.80E6	4.1E6	3.3E6
	1.05E6	9.56E5	3.4E6	3.46E6	3.41E6	2.80E6	2.4E6	3.2E6
Max. Roof Acc. (g) in X and Y directions	0.40	0.43	0.54	0.61	0.68	0.54	0.87	0.58
	0.39	0.44	0.53	0.57	0.63	0.53	0.46	0.56
Max. Roof Disp. (cm) in X and Y directions	16.0	10.0	7.3	11.0	12.0	6.8	15.0	5.2
	10.0	9.7	8.3	8.9	10.0	6.6	5.1	5.5

TABLE IV
Average and Maximum Drift Values, Maximum Base Shear Values, and Maximum Roof Acceleration and Roof Displacement Values of the 10-Story Buildings with the Eight Shear Walls Placement-Shape Patterns Obtained from the NLTHA

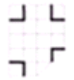
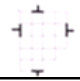
Pattern Response								
Av. Drift(cm) in X And Y directions	0.47	0.44	0.37	0.37	0.44	0.46	0.40	0.18
	0.46	0.43	0.34	0.36	0.42	0.47	0.26	0.17
Max. Drift (cm) in X and Y directions	0.79	0.71	0.64	0.61	0.85	0.84	0.69	0.33
	0.77	0.77	0.59	0.57	0.85	0.86	0.35	0.32
Max. Base Shear (kgf) in X and Y directions	1.60E6	1.36E6	2.78E6	3.01E6	3.00E6	3.08E6	2.00E6	2.05E6
	1.60E6	1.66E6	2.79E6	3.02E6	3.07E6	3.20E6	2.65E6	2.04E6
Max. Roof Acc. (g) in X and Y directions	0.42	0.40	0.78	0.71	0.78	0.77	0.54	0.49
	0.43	0.41	0.70	0.72	0.78	0.78	0.68	0.49
Max. Roof Disp. (cm) in X and Y directions	24.0	18.0	19.0	21.6	17.7	15.0	23.0	11.4
	23.0	17.5	19.0	16.5	17.5	13.5	12.0	10.8

TABLE V
Average and maximum drift values, Maximum Base Shear Values, and Maximum Roof Acceleration and Roof Displacement Values of the 12-Story Buildings with the Eight Shear Walls Placement-Shape Patterns Obtained from the NLTHA

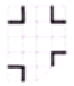
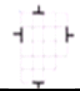
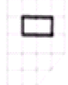
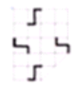
Pattern Response								
Av. Drift(cm) in X And Y directions	0.33	0.30	0.30	0.29	0.33	0.28	0.41	0.23
	0.32	0.31	0.24	0.30	0.34	0.29	0.31	0.24
Max. Drift (cm) in X and Y directions	0.52	0.57	0.45	0.47	0.61	0.46	0.70	0.43
	0.51	0.58	0.39	0.46	0.60	0.47	0.51	0.44
Max. Base Shear (kgf) In X and Y directions	1.2E6	1.17E6	2.42E6	2.33E6	2.32E6	1.97E6	2.12E6	2.58E6
	1.3E6	1.21E6	2.47E6	2.36E6	2.32E6	2.22E6	2.78E6	2.59E6
Max. Roof Acc. (g) in X and Y directions	0.38	0.37	0.52	0.54	0.51	0.50	0.78	0.55
	0.39	0.38	0.54	0.56	0.52	0.54	0.61	0.55

TABLE VI
Average and Maximum Drift Values, Maximum Base Shear Values, and Maximum Roof Acceleration and Roof Displacement Values of the 15-Story Buildings with the Eight Shear Walls Placement-Shape Patterns Obtained from the NLTHA

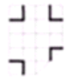
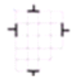
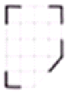
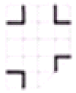
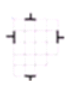
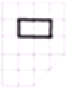
Pattern Response								
Av. Drift(cm) in X And Y directions	0.45	0.46	0.30	0.31	0.47	0.42	0.32	0.28
	0.46	0.44	0.27	0.30	0.48	0.41	0.19	0.29
Max. Drift (cm) in X and Y directions	0.87	0.88	0.49	0.48	0.83	0.84	0.66	0.49
	0.89	0.76	0.50	0.51	0.84	0.85	0.28	0.50
Max. Base Shear (kgf) In X and Y directions	1.44E6	1.32E6	1.92E6	1.89E6	1.82E6	1.85E6	1.75E6	1.84E6
	1.46E6	1.33E6	1.76E6	1.88E6	1.85E6	1.87E6	1.47E6	1.83E6
Max. Roof Acc. (g) in X and Y directions	0.47	0.45	0.69	0.64	0.72	0.72	0.65	0.68
	0.49	0.46	0.62	0.65	0.72	0.73	0.51	0.69
Max. Roof Disp. (cm) in X and Y directions	33.0	27.5	23.0	23.0	28.0	22.0	21.0	15.0
	30.5	23.0	21.0	22.0	27.5	21.5	12.0	14.8

TABLE VII

AVERAGE AND MAXIMUM DRIFT VALUES, MAXIMUM BASE SHEAR VALUES, AND MAXIMUM ROOF ACCELERATION AND ROOF DISPLACEMENT VALUES OF THE 15-STORY BUILDINGS WITH THE EIGHT SHEAR WALLS PLACEMENT-SHAPE PATTERNS OBTAINED FROM THE NLTHA BY USING THREE COMPONENTS OF THE EARTHQUAKE EXCITATIONS TO INCLUDE THE EFFECT OF VERTICAL GROUND ACCELERATION

Pattern **Response**								
Av. Drift(cm) in X And Y directions	0.36	0.40	0.31	0.35	0.50	0.48	0.46	0.25
	0.36	0.41	0.30	0.36	0.50	0.46	0.28	0.24
Max. Drift (cm) in X and Y directions	0.53	0.62	0.44	0.50	0.75	0.72	0.72	0.40
	0.52	0.63	0.42	0.52	0.74	0.69	0.34	0.39
Max. Base Shear (kgf) In X and Y directions	8.40E5	8.5E5	1.73E6	1.49E6	1.57E6	1.50E6	1.33E6	1.58E6
	8.77E5	8.6E5	1.78E6	1.50E6	1.59E6	1.53E6	1.36E6	1.62E6
Max. Roof Acc. (g) in X and Y directions	0.41	0.44	0.67	0.65	0.67	0.66	0.61	0.58
	0.39	0.43	0.60	0.65	0.69	0.68	0.59	0.58
Max. Roof Disp. (cm) in X and Y directions	22.0	17.0	20.0	21.0	27.0	24.0	21.0	12.0
	23.0	16.0	18.0	21.5	26.0	23.7	14.0	11.0

- Shear walls with Z-shape and T-shape cross-section, placed in the outer frames of the building skeleton, result in more reliable seismic behavior of RC asymmetric multi-story buildings, using walls with Z-shape cross-section may create some architectural limitations.
- Applying three-component accelerograms instead of two-component ones, to take into account the near-field earthquake excitations, may result in smaller seismic response values.

Finally, it should be noted that the present study was conducted with some limitations, such as considering only one plan shape for all buildings; using the same beams and columns in all buildings of the same story number, regardless of the shear walls placement-shape pattern; using the same thickness for all shear walls in all buildings; excluding the effects of openings in shear walls; and discarding the effect of soil-structure-interaction. Therefore, to achieve more general conclusions further research is required, without the mentioned limitations.

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