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Investigation of ductility in high-rise RC wall buildings

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Abstract

Bearing wall structures (known as tunnel forms), are used in earthquake-prone areas because of their acceptable seismic performance and high construction speed. It should be mentioned that seismic codes did not specifically focus on these types of structures. As a result, tunnel form buildings are designed similar to structures including shear walls due to relevant codes. In this study, the seismic performance of high-rise tunnel form buildings have been investigated. For this purpose, three structures of 15, 20 and 25-story with this seismic system have been modelled and examined using fiber elements and nonlinear static and dynamic analysis are conducted on these structures. The focus of this study is on the ductility of the structures. The impact of axial force on the ductility ratio is investigated and the ductility demand is calculated for assumed structures.

Keywords: Bearing wall structure, Shear wall, Nonlinear static analysis (Pushover), Nonlinear dynamic analysis, Ductility, Axial force

Introduction

Tunnel form is a system in which both vertical and lateral loads are transferred to the foundation of the building through reinforced concrete walls and slabs, and the common bearing elements such as beams and columns are eliminated from the structure. Due to modular technical manufacturing methods, these structures are used widely in mass industry. High stiffness of seismic bearing system in comparison to other systems, high construction speed and being economical in mass projects are among the most positive features of this structural system. In recent years, this type of structure has been used in seismic-prone countries like Chile, Japan, Italy, Turkey and Iran.

Figure 1. RC wall system

Although this structural system has high resistance to earthquake excitations, there is insufficient information for their seismic response and design criteria. As a result, these types of buildings are designed mainly based on the methods recommended in relevant seismic codes for common shear walls. Actually, this is not a suitable approach because there are major differences between tunnel form buildings and common systems including shear walls due to their inherent characteristics.

In this paper, in order to study high-rise RC wall buildings, three structures of 15, 20 and 25-story with specific plan have been determined. These buildings are modelled in relevant software (ETABS v9.7.4) and analyzed using linear dynamic analysis approach (response spectrum). Shear walls and slabs are designed in accordance with the requirements of the ACI-318-05 code in the same software. In the next step, the studied structures were modelled in PERFORM-3D v4.0.3 software which is used for nonlinear analysis of structures. After modelling designed sections and defining necessary parameters for nonlinear analysis in this software, nonlinear static analysis known as pushover is performed and the main seismic concepts including response modification factor, performance point and ductility are investigated. We also have evaluated the impact of axial force on the ductility of structures. Finally, nonlinear time history analysis is performed using three proper pair of earthquake records to complete the seismic evaluation. In the last section, the ductility demand which is determined by pushover curve is calculated for the 15-story structure.

Introducing case studies

Three concrete structures with tunnel form system are modeled in Perform-3D software. A 15-story building is a real structure that was constructed in Iran. The 20-story and the 25-story buildings are hypothetical case studies with the plan similar to the 15-story building (Figure 2).The dimensions of building plans are approximately 23 meters in length (H1) and 21 meters in width (H2). The height of stories is 2.91 meters. Bearing walls are reinforced concrete with a thickness of 16, 18 and 20 centimeters. Figure (3) shows the facades of three-dimensional studied models.

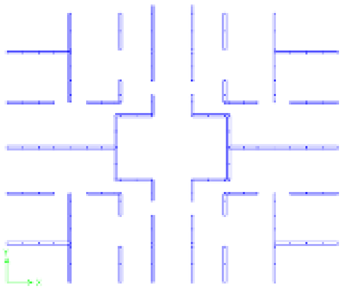

Figure 2. 15-20 and 25-story plan

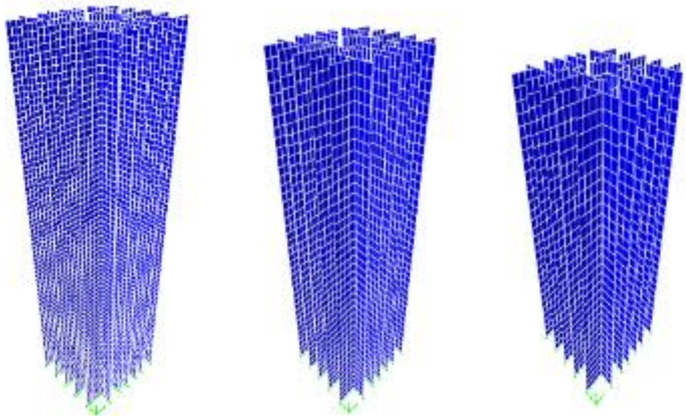

Figure 3. 3D facades of 15-20 and 25-story buildings

The model presented by Mander et al in 1988, has been used for modeling concrete behavior in compression for confined and unconfined concrete (Mander and Park, 1988). Moreover, elasticity module for concrete and steel have been considered respectively 250,000 and 2,100,000 kilograms per square centimeter.

In order to determine the performance level of the structural walls, the wall rotation along the plastic hinges should be measured. To this end, according to FEMA-356 guideline, Plastic hinge length is considered equal to the minimum value of half of the wall length and the height of the first floor (FEMA-356 2000). By defining the elements of the elastic rotation gage for walls in PERFORM-3D, the rotation value of these hinges are used to determine the performance level and evaluate the acceptance criteria. In addition, to simplify the story floor modeling, the diaphragm is assumed rigid and the wall connections to foundation are assumed as rigid restraints. Gravitational loads including dead and live ones are subjected to mathematical models according to the following table.

Table 1- Structural loading

Story type	Flooring dead load	Concrete slab dead load	Live load
Residential stories(t/m2)	0.22	0.325	0.17
Roof stories(t/m2)	0.15	0.325	0.17

The seismic mass of the building is placed concentrated at the center of the mass in each floor using the calculated dead loads including flooring, concrete slab weight and half of the weight of top and bottom walls plus the calculated live load according to the sixth issue of building national regulations (Sixth issue of building national regulations, 2006). According to Iranian code of practice for seismic resistant design of buildings, this mass is placed centrally in a point that has the 5% of eccentricity of the structure center of mass (Tehranizadeh et al., 2015) (Code, I. S., 2005).

NONLINEAR STATIC ANALYSIS RESULTS

Pushover curve

Pushover load pattern procedures which are proposed in FEMA-356 guideline are suitable for low rise structures, which their first mode is prevalent. In our study, mid-rise and high-rise structures are investigated. Therefore, pushover analysis based on ($m\times\Phi$) matrix corresponding to the first mode is inaccurate (m is the mass matrix and ϕ is modal shape matrix). Actually, higher modes in high-rise structures play significant role in structural seismic response. According to Chopra and Goel researches, higher modes in pushover analysis must be considered in tall buildings (Goel and Chopra, 2005).
In PERFORM-3D software, higher modes are considered in modal pushover analysis with a scale factor. In this method, scale factor for each mode is response spectrum acceleration (Sa) corresponding to the relevant period (T) from the response spectrum (B). In the project, response spectrum is considered due to Iranian code of practice for seismic resistant design of buildings. Finally higher modes are combined linearly with their calculated scale factors. For example, pushover curves for 15, 20 and 25 story buildings in (H1) direction are shown in figure (7), (8) and (9). In this figures, modal pushover results are compared with pushover curves resulted from nonlinear static analysis with uniform and triangle load patterns proposed in FEMA- 356 guideline.

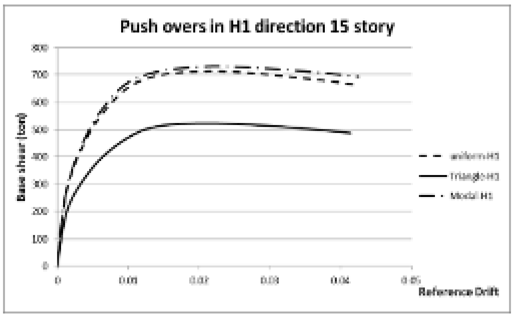

Figure 7. Comparing Modal pushover curves with uniform and triangle load distribution for the 15-story building

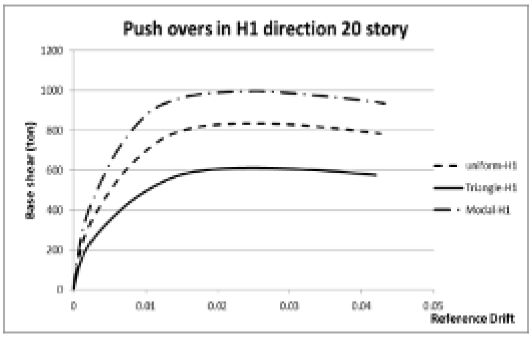

Figure 8. Comparing Modal pushover curves with uniform and triangle load distribution for the20-story building

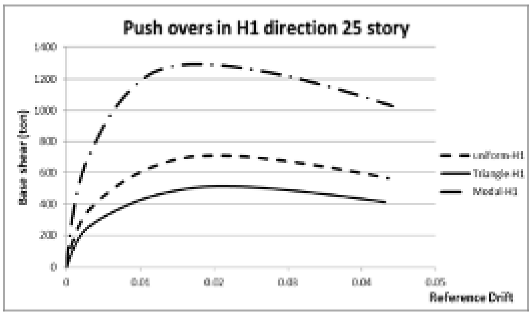

Figure 9. Comparing Modal pushover curves with uniform and triangle load distribution for the25-story building

According to figures, pushover curves based on modal load pattern have higher shear amount in comparison to conventional pushover patterns for each reference drift quantity. This shows modifications in pushover modal pattern toward conventional patterns for higher buildings.

Investigating the impact of axial load on ductility ratio

In this section, we have discussed the impact of axial load on ductility concept of tunnel form buildings. First a wall with specified characteristics is considered. This wall has the length of 4 (m), the height of 12 (m) and the width of 0.2 (m). It is assumed that the percentage of reinforcements in the wall is 2% (T 20 at 150 (mm)).

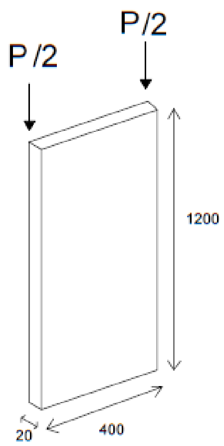

Figure 10: the wall characteristics (mm)

In the next step, an axial load posits on the wall, and the pushover curve is derived from conducting non-linear static analysis with a uniform pattern. Using bilinear approximation on pushover curve and obtaining required parameters, the ductility ratio of the wall is achieved. The relative ultimate displacement is considered 0.02. By increasing axial load on the wall, the above operations are repeated, and the ductility is calculated for axial loads with different values. The axial load is considered equal to 0.05 of axial capacity of the wall (P0) in the first step and with the increasing rate of 0.05 of the P0 in further steps. The axial capacity is calculated through the following equation:

$$P_0 = 0.85 \times f'_c \times (A_g - A_s) + A_s \times f_y = 2334.785\ (ton) \tag{1}$$

In table 2, the ductility ratio for two parameters of $(\frac{P}{P0})$ و $(\frac{(A_s - A_{s'})f_y + P}{t_w \times l_w \times f'_c})$ is calculated. $\frac{(A_s - A_{s'})f_y + P}{t_w \times l_w \times f'_c}$ is the parameter defined in FEMA-356 for nonlinear modelling of walls.

Table 2. Ductility ratio for different axial forces

P/P0	V0	delta m	delta y	µ	FEMA-356 coef.
0.05	211.51	0.02	0.009	2.18	0.058
0.1	231.45	0.02	0.009	2.27	0.117
0.15	254.25	0.02	0.008	2.39	0.175
0.2	271.05	0.02	0.008	2.48	0.233
0.25	287.04	0.02	0.008	2.49	0.292
0.3	300.14	0.02	0.008	2.50	0.350
0.35	313.23	0.02	0.008	2.40	0.409
0.4	324.03	0.02	0.009	2.31	0.467
0.45	330.58	0.02	0.009	2.29	0.525
0.5	336.03	0.02	0.009	2.24	0.584
0.55	338.9	0.02	0.009	2.19	0.642
0.6	339.7	0.02	0.009	2.12	0.700
0.65	340.49	0.02	0.010	2.03	0.759
0.7	337.71	0.02	0.010	1.95	0.817
0.75	337.07	0.02	0.011	1.80	0.876
0.8	332.94	0.02	0.012	1.68	0.934
0.85	330.38	0.02	0.013	1.53	0.992
0.9	321.09	0.02	0.014	1.43	1.051
0.95	310.62	0.02	0.015	1.34	1.109

As it is shown, the ductility ratio increased until the axial load reached 0.3 of P_0 and after that, it started to decrease. However, design regulations consider the allowable axial load equal to 0.35 of P_0. In other words, the increase in axial load after the certain value will cause the ductility of reinforced concrete wall to reduce (Figure 11).

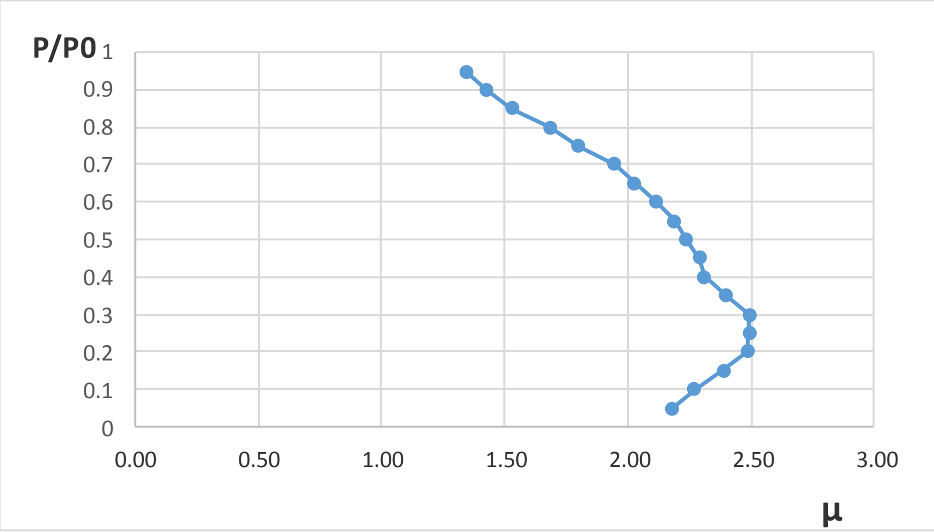

Figure 11. The process of ductility variations for different axial force values for concrete shear wall

The ductility study is done for an assumed shear wall according to previous issues. We like to extend this concept for tunnel form buildings. For this purpose, the 15-story building in this project is considered and the axial loads of this building is increased with specific pattern. After conducting modal pushover analysis in H2 direction in each step of loading, the changes in ductility ratio due to FEMA-356 coefficient is investigated. In FEMA-356, axial load parameter is considered for two following states:

$$\frac{(A_s - A_{s'})f_y + P}{t_w \times l_w \times f'_c} \leq 0.1 \quad \text{و} \quad \frac{(A_s - A_{s'})f_y + P}{t_w \times l_w \times f'_c} \geq 0.25$$

Based on the analysis done for the case study, the increase of axial load parameter up to 0.3 augments the ductility ratio and after that leads it to decrease (Figure 12).

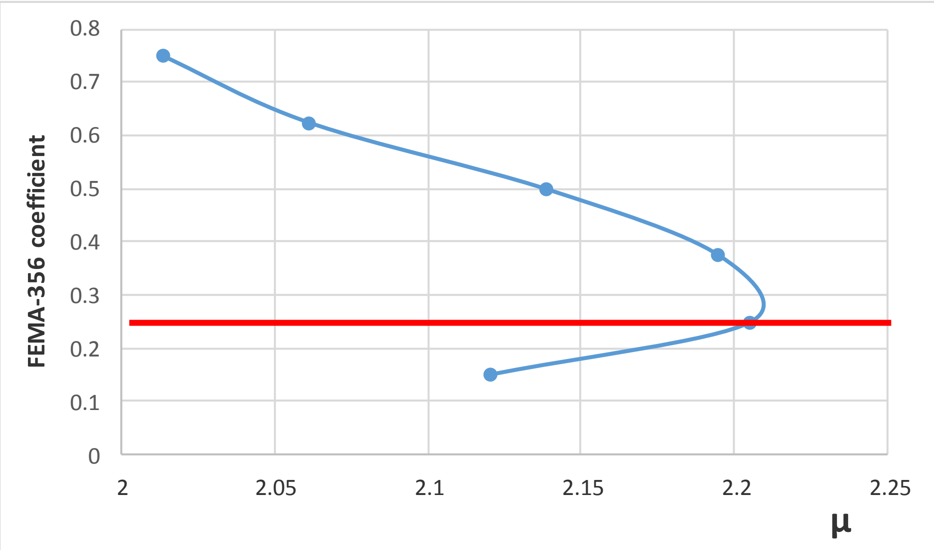

Figure 11. The ductility variations for different axial load values according to regulation for the 15-story building

Based on the diagram, the certain value of FEMA356 coefficient for this building is 0.25. This issue demonstrates that in our 15-story RC wall building, the increase of the axial load after a certain value results a decline in ductility of the structure.

NONLINEAR DYNAMIC ANALYSIS RESULTS
Earthquake record selection

In this study, three pair of records are used to perform a dynamic analysis. Towards that end, 22 pair of records introduced in (FEMA-p695) guideline related to soil type C (similar to soil type II of Iranian code of practice for seismic resistant design of buildings) are surveyed and three pair of records which had the most accordance with the standard design spectrum have been selected. Their features are written in table (3) (FEMA, 2009).

The selected pair of records are scaled to find more coordination with standard design spectrum and used in the analysis. This scaling is done by the help of Iranian code of practice for seismic resistant design of buildings.

Table 3- records used in this study

Significant Duration (Sec)	PGA (g)	Duration (Sec)	Component	Earthquake				No.
				Station	Name	Year	M	
11.65	0.266	45.3	HEC000	Hector	Hector Mine	1999	7.1	**1**
9.66	0.337	45.3	HEC090					
11.015	0.219	30	ARC000	Arcelik	Kocaeli, Turkey	1999	7.5	**2**
10.275	0.15	30	ARC090					
10.49	0.21	28	PEL090	LA-Hollywood Stor	San Fernando	1971	6.6	**3**
11.16	0.174	28	PEL180					

Investigating the ductility demand

The ductility ratio which has been investigated earlier in this study, is the quantity which is determined by pushover analysis. The other important issue in seismic evaluation is ductility demand. With a view to seismic surveys in recent years, there are different methods to obtain the ductility demand of structural systems especially moment frames (Alam et al., 2012) (Kia and Yahyaei, 2004).

Based on one of these researches about reinforced concrete frames, the ductility demand for each floor is the ratio of maximum relative inter story displacement derived from dynamic nonlinear time history analysis to inter story yield displacement derived from nonlinear static analysis. To calculate the ductility demand in this study, the ultimate displacement is considered as the maximum relative inter story displacement (Alam et al., 2012) (Kia and Yahyaei, 2004). To assess the inter story yield displacement, first we conduct a modal pushover analysis. By creating structural sections for each story, the force-displacement equation could be achieved. Hence, the bilinear approximation could be accomplished, and the yield displacement could be calculated for each story. It should be noted that in bilinear approximation on force-displacement curve of each story, the ultimate displacement is considered in life safety level.

By dividing the maximum relative inter story displacement of each record to yield displacement calculated for each story, the ductility demand for each record in 15-story building is calculated which is illustrated in figure 12.

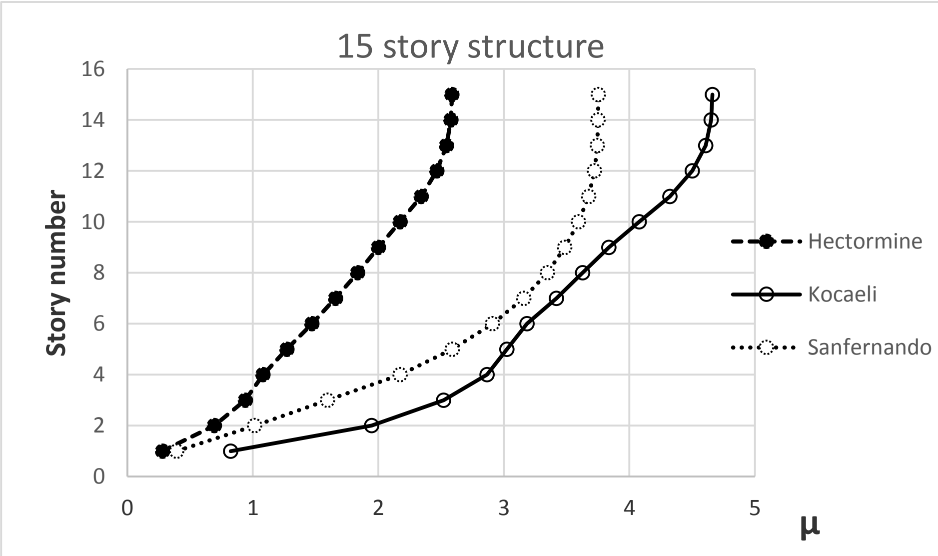

Figure 12. Ductility of stories calculated from applied records for the 15-story structure

It is obvious from the diagram that the ductility of the building has the direct relation with the number of stories. In other words, the maximum ductility of the structure which is as same as the critical value, is happened in the last story. However, in the studies carried out in case of ductility of stories for moment frames, the critical ductility usually happens in lower stories. In RC wall buildings which have lower ductility capacity, this critical value is occurred in upper stories. The numerical ductility value is obtained between 1 and 4.8.

Conclusion

In this study, three high rise RC wall buildings were examined and the nonlinear static and dynamic analyses are performed. The nonlinear static analysis with participation of higher modes is done. The impact of axial load on ductility ratio is investigated. It is shown that ductility ratio is increased in shear wall buildings through augmentation of axial load to the certain point, and then it is decreased after that critical point. Finally, the nonlinear dynamic analysis is conducted on assumed building and the ductility demand is investigated in each story of it. It is concluded that this concept has direct relation with the number of stories in 15-story building.

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