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Investigation of the Earthquake Performance of a Reinforced Concrete Shear Wall Hotel Using Nonlinear Methods

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Abstract: In the earthquake engineering, performance-based design method is used to determine the level of expected performance of the structures under the earthquake effect. Level of performance is related to the damage situation that could be occurred in the structure after the earthquake. In the performance-based structural design, it is predicted that more than one damage levels are emerged under one certain earthquake effect.

In this study, the seismic behavior of reinforced concrete shear wall hotel building collapsed during Van Earthquake, 2011, is investigated by the nonlinear static analysis. The selected reinforced concrete shear wall structure is located in Van, Turkey. The Turkish Building Earthquake Code in 2019 is considered for the assessing seismic performance evaluation of the selected reinforced concrete shear wall building. The performance goals of the reinforced concrete shear wall structure is evaluated by applying the pushover (Incremental Equivalent Earthquake Load Method) and procedures of the Code and nonlinear dynamic analysis. According to the code, the reinforced concrete shear wall hotel building is not expected to satisfy life safety performance levels. In this study, it is selected one collapsed building, because, it is tested reliability and usability of performance analysis method under design earthquake.

Keywords: Reinforced concrete shear wall structure, pushover analysis, nonlinear time history analysis, performance analysis, existing buildings.

1. INTRODUCTION

In Turkey, there are a large number of reinforced concrete building at the border and under the border of the earthquake safety. In addition, a large number of existing reinforced concrete shear wall building in first-degree seismic zone are needed seismic evaluation because noncompliance with the old code requirements, updating of codes, design practice of the building. The maintain and reinforcement of them is not possible respect of economic and technical reasons. Existing buildings earthquake safety evaluation of a more realistic form has been come in question. In the Turkish Building Earthquake Code in 2019 (TBEC-2019) [1], performance-based evaluations were to the fore by using advanced knowledge of earthquake engineering. Therefore, performance based design procedures have been investigated for the structures recently. There are several procedures for performance assessment in the literature. The most common assessment procedures are explained in four main guidelines/codes which are Applied Technology Council (ATC-40) [2], Federal Emergency Management Agency (FEMA 356) [3], FEMA440 [4] and TBEC-2019. TBEC-2019 came into use in 2007. Nonlinear dynamic analysis (NDA) is the most faithful analysis methodology between the all nonlinear analysis methods. However, static pushover analysis is happen significant due to its simple exercise check against to time history nonlinear analysis. Many articles have been published on performance evaluation of existing reinforced concrete buildings. The predominant building type which is mid-rise non-ductile reinforced concrete frames with hollow clay tile infill, thousands of which collapsed in a 'pancake' mode. The static pushover analysis may be less accurate for structures in which the story shear force vs. story drift relationships are sensitive to the applied load [6-7]. Another important point is that chapter 7 of TBEC-2019 entitled "Assessment and Strengthening of Existing Buildings" sets standards for performance assessment and rehabilitation of existing buildings [8]. Different procedures were developed the seismic deformation demands of multistory steel and concrete moment frames using nonlinear procedures based on spread hinge assumption [9].

There are many studies related to the performance analyses. These studies evaluated seismic performance of existing low and mid-rise reinforced concrete buildings by comparing their displacement capacities and displacement demands under selected ground motions experienced in the world [10-14].

In this paper, the pushover and time history nonlinear analysis are applied to forecast the expected earthquake performance of a reinforced concrete shear wall hotel building collapsed during Van (2011) earthquake, Turkey. The building is typical beam-column RC frame buildings with shear walls. The pushover and time history nonlinear analysis are realized by using the finite element Structural Analysis program SAP 2000 [15]. Beam and column components are modeled as nonlinear frame components with pileous plasticity by describing plastic hinges at both ends of beams and columns. Earthquake performance appreciate is realized in respect of the recently published TBEC-2019 that has likeness with FEMA-356 guidelines.

2. PERFORMANCE LEVELS

In general, three factors are considered in the performance-based design approach. These are capacity, volition and performance. Capacity can be considered as a whole of elements; the structure of the building, type of material, section geometry etc. Under the influence of external forces such as earthquakes, without any reduction in their carrying capacities, the ability to deform (ductility) and to remain stable against loads (stiffness) are generally defined as capacity. Demand can be defined as displacement and sectional effects that the movements formed during the Earthquake are desired to be met from the structure. Performance is related to the extent to which the

capacity of the structure can meet the movements occurring during the Earthquake.
Performance Levels of Buildings to be Designed Under the Effect of Earthquake:

a) Uninterrupted Use Performance Level (UU); it is the building performance level where structural damage does not occur in building system elements or the damage is negligible.
b) Limited Damage Performance Level (LD); the building corresponds to the level of damage to the structural system elements, whereby a limited degree of damage or non-linear behavior occurs.
c) Controlled Damage Performance level (CD); in order to ensure life safety, the building bearing system corresponds to the level of controlled damage which is not very heavy.

d) Migration Prevention Performance Level; the building corresponds to the to the pre-cash situation where severe damage to the structural system elements occurs. Partial or complete migration of the building was prevented

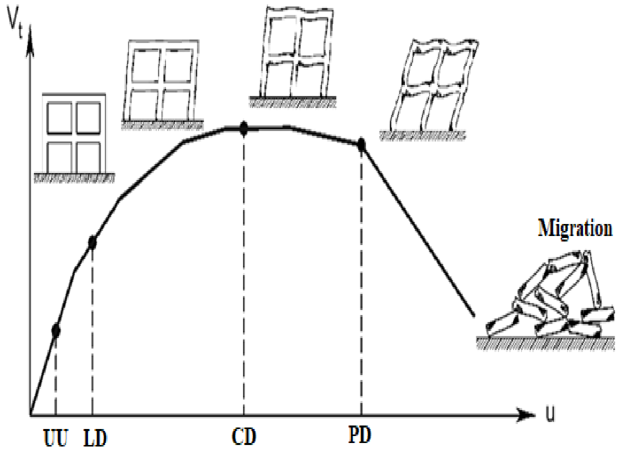


Fig.1. Building performance levels according to TBEC-2019

The definition of user-defined hinge properties requires moment-curvature analysis of each element. Mander model [16] for unconfined and confined concrete and typical steel stress-strain model with strain hardening for steel are implemented in moment-curvature analyses. The points B and C in Fig. 1 are related to yield and ultimate curvatures. The point B is obtained from SAP2000 using approximate component initial effective stiffness values as per TBEC-2019.

Moment-curvature analyses are carried out considering section properties and a constant axial load on the structural element. After the appropriate material properties are determined, structural element sections are modeled via XTRACT (2004) program [17]. In the section, two concrete models, confined and unconfined concretes, are used. The modeling is finished by inputting reinforced steels into defined section geometry. Thus, moment-curvature relations are determined after analyses.

Plastic hinge length is used to obtain ultimate rotation values from the ultimate curvatures. The plastic hinge length definition given in Eq. (1) is used:

$$L_p=0{,}08L+6f_ydb/40\geq 0{,}3f_ydb \quad (1)$$

In Eq. (1), Lp is the plastic hinge length, L is the distance from plastic hinge location to location of contraflexure, fy is yield stress longitudinal bar and db is the diameter of longitudinal reinforcement, respectively.

3. DESCRIPTION OF INVESTIGATED REINFORCED CONCRETE SHEAR WALL STRUCTURE

The building is typical beam-column reinforced concrete frame buildings with shear walls. A typical floor plan is shown in Fig. 2. Column dimensions in a story are 30x60, 25x60, 20x75 cm (Fig.2). The column dimensions in a defined position in the plan are the same in the other stories of the building. Longitudinal rebars are 8Ø14 for all columns. The longitudinal reinforcement ratio of these columns varies between 1.1% and 1.5%. The dimensions of all the beams in the building are the same as 25x60 cm. Beam longitudinal rebars are 3Ø14 on top and 5Ø14 in bottom for the residential building. Transverse rebars are Ø8/120 cm for columns and beams (Fig. 3). The reinforced concrete shear wall hotel building has 8 stories, stories first are 3.0 m and second stories are 3.5 m in height and other stories are 2.90 m (Fig.4). Framing of the building is irregular in plan where there are 4 axes in X-direction and 2 axes in Y-direction. Floor plan is not same for each story and first and second stories has an area of 87.65 m2 and other stories has an area of 115.92 m2. Slab thicknesses are 15 cm. For the buildings where the slabs act as rigid diaphragms on the horizontal axis, two horizontal translocations per floor and independence levels for the rotations around the horizontal axis will be considered. Independence levels of the floors will be defined for the center of mass of each floor and additional eccentricity will not be applied. The dead load is G =1.471 kN/m2 for all the floors except the top floor where the dead load was considered as G = 3 kN/m2. The live load is Q= 4.9 kN/m2 for each floor except the top floor where the live load was considered as zero. The structure is thought to be a hotel and its coefficient of live load addition is taken as n = 0.3.

Flexural rigidity is calculated for each member. Beams, columns and shear walls were modeled as frame elements which were connected to each other at the joints. Since the majority of buildings in Van, Turkey were constructed according to TEC-1975 [18], the selected building was designed according to this code, too. Because all the static projects are available, the reinforced-concrete properties of structural members are assumed to be known completely.

The pushover analysis is performed by using the finite element method Structural Analysis Program-2000 (SAP2000) [15]. Beam and column elements are modeled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. SAP2000 provides default or the user defined hinge properties options to model nonlinear behavior of components. In this study, user-defined hinge properties are implemented. Seismic performance evaluation is carried out in accordance with the recently published TBEC-2019 that has similarities with FEMA-356 guidelines.

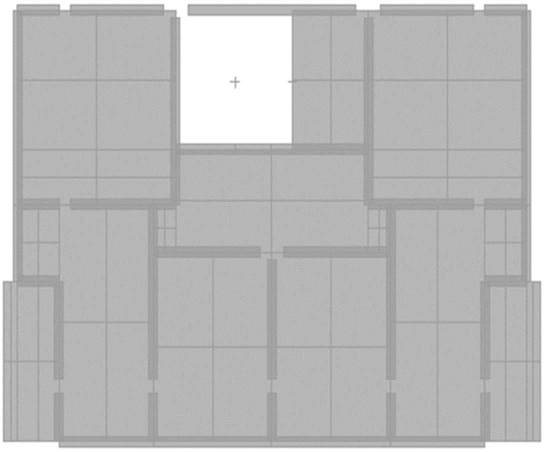
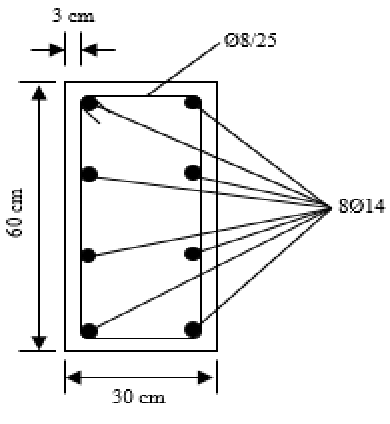
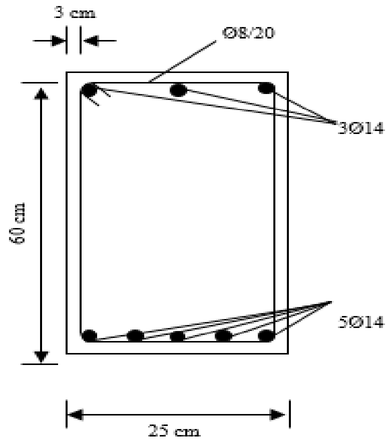


Fig. 2. Typical floor plan of the building.



a) 60x30 cm column



b) 60x25 cm beam

Fig. 3. Typical (a) beam and (b) column sections of building model.

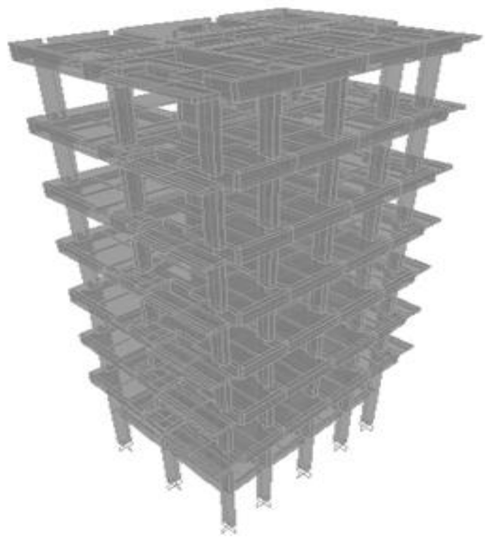
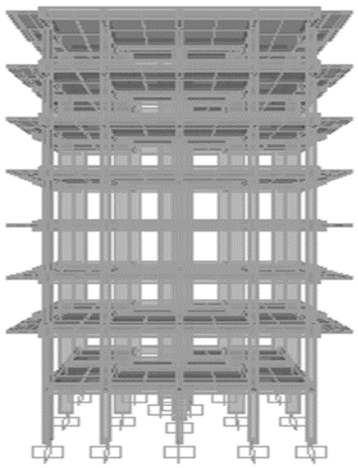
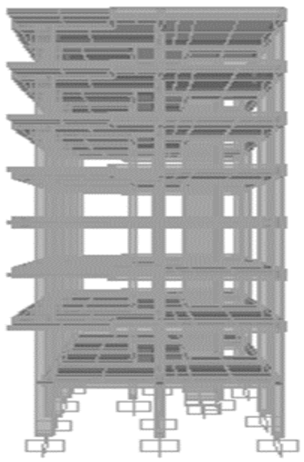


Figure. 4. 3-D finite element model of the reinforced concrete shear wall building



(a)



(b)

Fig. 5. (a) Typical X-Z sectional view (b) Typical Y-Z sectional view

The structure is in Van and in first-degree seismic zone. A design ground acceleration of 0.4g and soil class ZC that are similar to class C soil of FEMA-356 is considered in the analyses. The projected concrete class is C16 and projected reinforcing steel class is S420. The Young Modulus of concrete is 32000 MPa and reinforced steel is 205000 MPa. A reinforced concrete shear wall hotel building was analyzed in detail by performing pushover and nonlinear time history analyses according to the TBEC-2019. Three dimensional finite element model of the health building was prepared in SAP2000 structural analysis program shown in Fig. 4-5.

3.1.1. Performance Evaluation with Nonlinear Pushover Analysis

The aim of the nonlinear pushover analysis methods to be used for determining the structural performances of the buildings under seismic effect and for the strengthening analyses is enabling the measurement of the plastic deformation volitions regarding the ductile behavior and internal force volitions concerning the brittle behavior for a given earthquake. Afterwards, the magnitudes of the mentioned volitions are compared with the deformation and internal force capacities that are defined in TBEC-2019 and structural performance evaluation shall be conducted both at sectional and building level. According to TBEC-2019, to be able to use the pushover analysis, the number of floors of the building excluding the basement should not be above 8 and the torsional irregularity coefficient (η_{bi}) that is calculated in accordance with the elastic linear behavior without considering additional eccentricity should meet the condition $\eta_{bi} < 1.4$ for each floors. The torsional irregularity of the building is provided.

The building provides all these conditions, the nonlinear pushover analysis is utilized. Before incremental pushover analyses, a static analysis is done by taking into consideration vertical loads that is harmonic with the masses. This analysis is force controlled and the results of this study are assumed as initial conditions of incremental pushover analyses. The vertical loads in nonlinear static pushover analyses are assumed as follows:

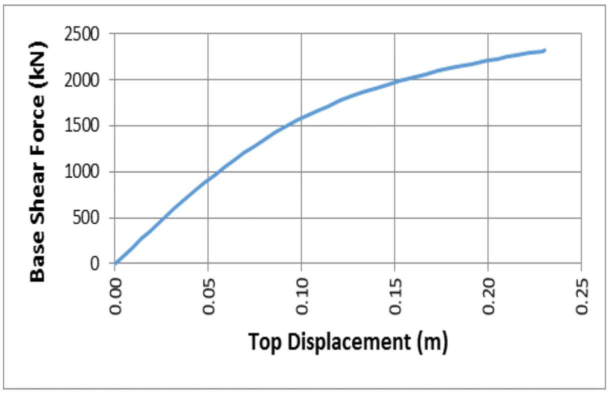
Vertical Load Combination (TBEC,2019)

$$G + nQ = G + 0.3Q \tag{2}$$

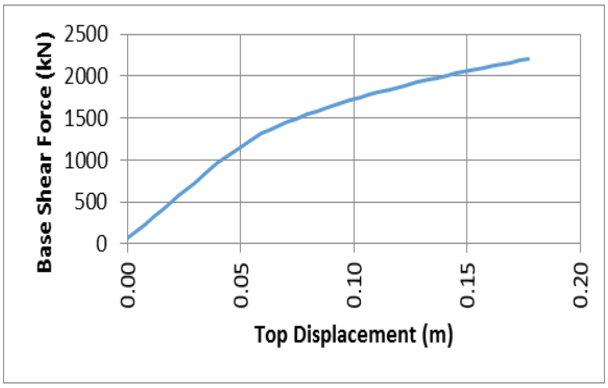
In Eq. (2), G is total dead load, n is the live load participation factor, Q is total live load stories of building, respectively.

The plastic hinge places are assumed and defined on the two ends of the column and beams elements constituting the bearing system. Plastic hinge length is assumed to be half of the section depth of elements as recommended in TEC (2007). It is seen from Fig. 6 that static pushover curvature is obtained by analyzing bearing system under the vertical loads and proportional incremental interval seismic loads for soil class Z3. Design earthquake is converted to spectrum curve and modal displacement demand is determined and performance points are determined by TBEC-2019 as seen in Fig. 7a-b. The plastic hinges are obtained by pushing again the bearing system up to this demand. It is seen in Fig. 7a-b that, in case

the incremental repulsion analysis is conducted via applying the Incremental Equivalence Seismic Load Method, the "modal capacity diagram" belonging to the primary (dominant) mode the coordinates of which are defined as "modal translocation – modal acceleration" shall be derived. The modal translocation volition belonging to the primary (dominant) mode shall be set taking the elastic behaviors spectrum and the modifications applied on this spectrum for different exceeding probabilities together with the mentioned diagram into consideration. In the final step, the translocation, plastic deformation (plastic rotation) and inner force volitions that corresponds to the modal translocation volition shall be calculated.



(a)



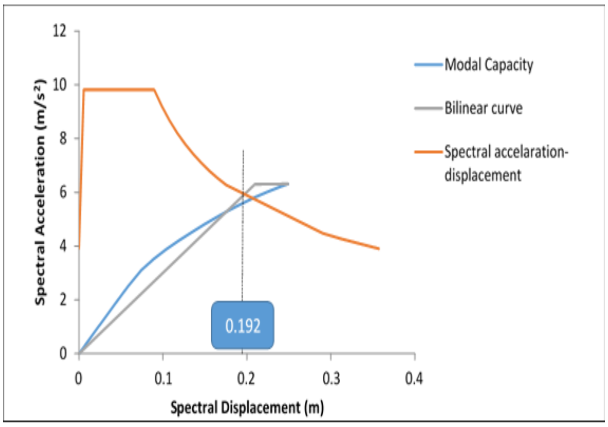
(b)

Fig. 6. Capacity curves for X direction (a) and Y direction (b) by pushover analysis for 8-story buildings.

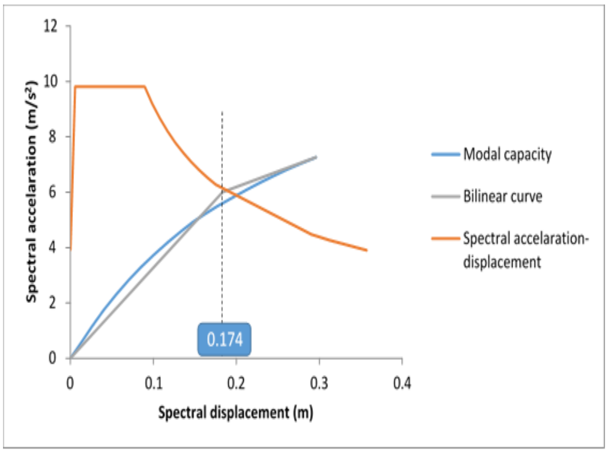
The pushover analysis of the selected structure is actualized under design earthquake (10% in 50-year hazard level) as proposed in the TBEC-2019. Nonlinear static pushover analyses are determined by SAP2000. A design performance level is a statement of the desired structural behavior of a building. After determination of damage regions of sections, the performance level of the building is controlled. It is seen from Fig.8 that the hinges through the structure after pushover analysis is under design earthquake (10% in 50-year hazard level).

According to TBEC-2019, the buildings that satisfy the conditions mentioned below can be agreed to be in Life Safety (LS) performance level provided that the brittle damaged components, if any, are strengthened:

(a) As the result of the calculations made for each earthquake direction applies on each floor, at most 30% of the beams except for the secondary ones (that does not take place in the horizontal load-bearing system) and at most the proportion of the columns defined in “paragraph b” can exceed the Advanced Damage Zone.



(a)



(b)

Fig. 7. Spectral acceleration, spectral displacement and Modal Capacity curves for X (a) and Y direction (b).

(b) The total contribution of the columns in the Advanced Damage Zone to the shear force that is borne by the columns in each floor should not exceed 20%. For the top floor, the ratio of the total shear forces of the columns in the Advanced Damage Zone to the total shear forces of all the columns at that floor can be at most 40%.

The performance levels, MN, GV, and GÇ are considered as specified in this code and several other international guidelines such as FEMA-356 and ATC-40 (Fig. 1). Displacement volition estimates for earthquakes with probability of exceedance of 10% in 50 years are compared for MN, GV and GÇ displacement capacities. For any floor, if these ratios not exceed targeted performance level’s ratio, it is concluded that the building is sufficient for MN under design earthquake.

It can be seen from the result under soil class Z3 design earthquake of the pushover analysis through the X and Y direction (Fig.7a-b) that building does not collapse before reaching the push target. The maximum base shear force and maximum displacement in X−direction and the maximum base shear force and maximum displacement in Y−direction obtained from the pushover analysis of Z3 design earthquake are 2320 kN, 0.23 m, 2203 kN and 0.17 m, respectively. It is concluded from nonlinear static pushover analysis under design earthquake that according to displacement target of the building, the building provided LS rating in the view of LS level targeted in TBEC-2019. According to TBEC-2019, the reinforced concrete shear wall building is expected to satisfy LS performance levels under design earthquake. In each floor, the ratio of the beams provided targeted performance level to total beam number in this floor and the ratio of the shearing forces of the columns provided targeted performance level to total floor shear force are determined.

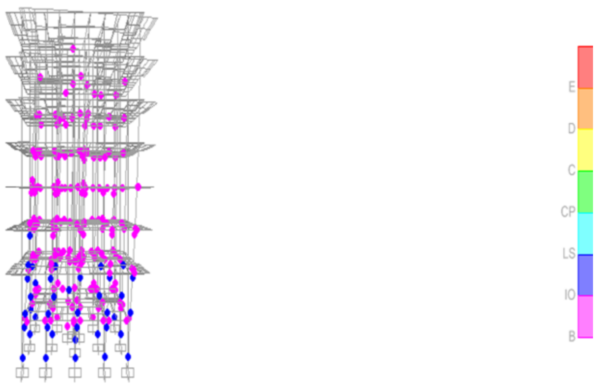
3.1.2. Performance Evaluation with Nonlinear Time History Analysis

It is assumed that nonlinear time history analysis defines structure behavior ideally because of the seismic loads directly applied to structure. The aim of nonlinear time history analysis is integration of equations of the motion of the system step by step by taking into consideration of nonlinear behavior of bearing system. It is calculated for each time increment that displacement, plastic deformation, internal forces occurred in the system and maximum values of them during earthquake.

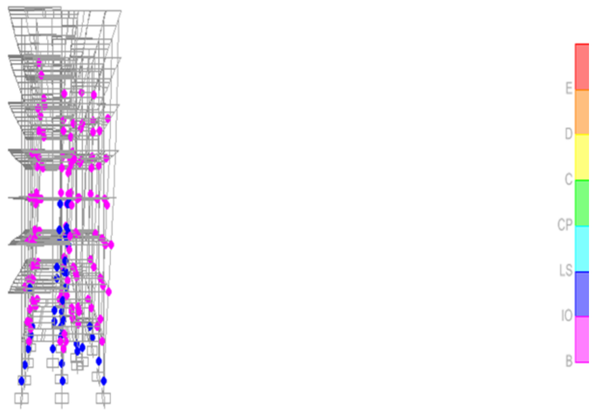
In addition to the static pushover analysis, in this study, performance evaluation of the selected building also is determined with nonlinear time history analysis, comparatively. Because the building is in Van provincial border, horizontal component of Van earthquake (Fig.9) is taking into consideration. The responses of the structure are computed via using the Newmark's method.

It is seen from Fig.10 that plastic hinges occurred through X and Y-directions as a result of nonlinear time history analysis. It can be seen from Fig. 10 that these hinges are concentrated on collapsing mechanism the Y direction. Because at the downstairs collapsing mechanism is occurred, the structure does not act its mission and it is collapsed completely.

When the analysis results are investigated, it is concluded from nonlinear time history analysis that according to damage conditions of elements, the building does not provide life safety (LS) rating in TBEC-2019. The existing residential building is far from satisfying the expected performance levels. The performance level of the building is determined as collapse (CO).



(a)



(b)

Fig. 8. The plastic hinges occurred through the X (a) and Y (b) directions of the building for design earthquake after pushover analysis.

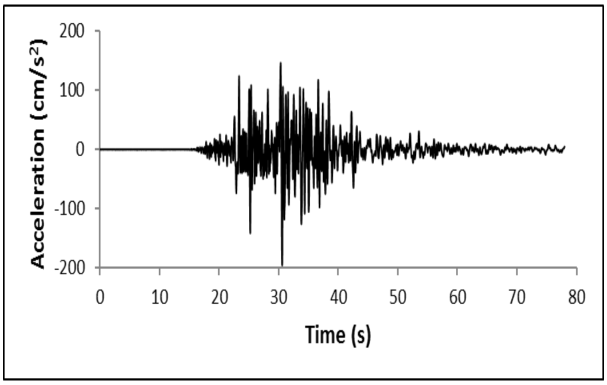


Fig.9. Acceleration time history of Van earthquake (NS6503), 2011.

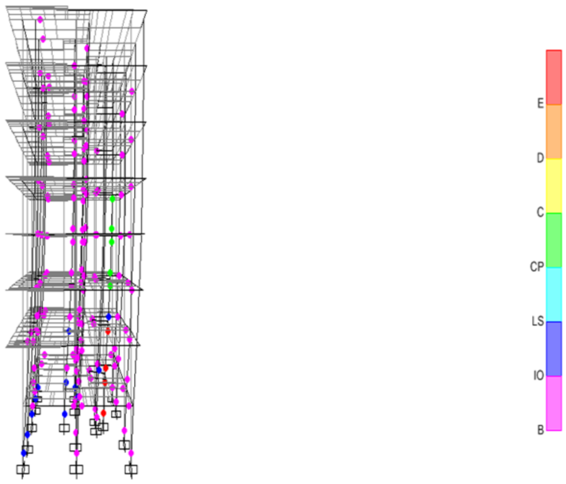


Fig. 10. The plastic hinges occurred through the YZ directions of the building for nonlinear time history analysis.

4. CONCLUSIONS

This paper investigates the seismic performance of an eight-story reinforced concrete shear wall hotel building designed according to the provisions of TEC-1975. The Pushover analysis was used to evaluate the seismic performance of the building. Performance evaluation is performed using the current Turkish Building Earthquake Code, TBEC-2019. The performance levels, MN, GV, and GÇ are considered as specified in this code and several other international guidelines such as FEMA-356 and ATC-40. Pushover analysis and criteria of TBEC-2019 were used to determine global displacements of the building corresponding to the performance levels considered above. Displacement volition estimates for earthquake with probability of exceedance of 10% in 50 years are compared for MN, GV and GÇ displacement capacities**.**

The pushover analysis is a simple way to explore the nonlinear behavior of the buildings. The results obtained in terms of pushover volition, capacity spectrum and plastic hinges gave an insight into the real behavior of structure. Pushover analysis is not only useful for evaluating the seismic performance of the structure, however, could also be helpful for selecting seismic details that are more suitable for withstanding the expected inelastic deformations. According to TBEC-2019, the reinforced concrete shear wall building is expected to satisfy life safety (LS) performance levels under design earthquake. Pushover can provide reasonably accurate estimation of the performance level when the reinforced concrete shear wall building is not the severely damage. While the building is serious collapsed, the pushover analysis underestimated the building performance, regardless of the lateral load distributions.

It is concluded from nonlinear dynamic analysis of the structure to the scaled ground motion that according to damage conditions of elements, the building does not provide life safety (LS) rating in TBEC-2019. The building is far from satisfying the expected performance levels.

In addition to these, the results from linear analysis and pushover analysis show lower damage ratios for the first story beams and columns than those of the nonlinear dynamic analysis.

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