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Earthquake Performance Analysis of Steel Structures with A3 Plan Irregularities

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Abstract: In earthquake engineering, a performance-based design method is used to determine the level of the expected performance of the structures under the earthquake effect. The 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 emerge under one certain earthquake effect.

In this study, the seismic behavior of steel structures with plan irregularities in the Turkey Building Earthquake Code in the 2018 (TBEC-2018) is investigated by the nonlinear static analysis methods. The selected steel structures are located in İzmir, Turkey. The Turkey Earthquake Code in 2018 is considered for assessing seismic performance evaluation of the selected moment-resisting frame steel building. Four different A3 type irregularity was investigated. The steel building with no irregularity in its plan. was selected as the structure of the reference. The performance goals of the five different steel structures are evaluated by applying the pushover and procedures of the TBEC-2018. The steel structures were compared by obtaining pushover curves for both the X and Y directions. The results show that the effects of A3 type irregularity should be not considered in design and buildings without irregularities are safer.

Keywords: Steel structures, nonlinear static pushover analysis, performance analysis, plan irregularity, A3 type irregularity

1. INTRODUCTION

In Turkey, there are many buildings at the border and under the border of earthquake safety. Accurate modeling of the seismic action is important to observe the real behavior of the structure under earthquake forces. In the Turkey Building Earthquake Code in 2018 (TBEC-2018), performance-based evaluations were to the fore by using advanced knowledge of earthquake engineering. Earthquake resistant design of steel structures has been developing in the last years by means of analytical and experimental results. Although structural steel is in many ways an ideal material for earthquake resistance, care should be taken in the design and detailing of framing. Earthquakes which affect the structure during its service life may sometimes be very destructive in Turkey and also in the whole world. Therefore, the subject of earthquake engineering and earthquake-resistant design is getting to be more important in the world in recent years. The latest Turkish building earthquake code was brought into force in 2018 to analyze the structures according to earthquake-resistant design concept. The necessity of having regular structural systems is emphasized in the TBEC-2018 while in some conditions it is unavoidable to apply. The plan irregularities in the TBEC-2018 code are: These, A1- Torsional Irregularity, A2- Floor Discontinuities and A3- Projections in Plan. The case where Torsional Irregularity Factor, which is defined for any of the two orthogonal earthquake directions as the ratio of the maximum relative stories drift at any stories to the average relative stories drift at the same stories in the same direction, is greater than 1.2. Floor Discontinuities: In any floor, the case where the total area of the openings including those of stairs and elevator shafts exceeds 1 / 3 of the gross floor area. The case where local floor openings which make the safe transfer of seismic loads difficult to vertical structural elements. The cases of abrupt reductions in the in-plane stiffness and strength of floors. A3 – Projections in Plan: The cases where dimensions of projections in both two perpendicular directions in plan exceed the total plan dimensions of that stories of the building in the respective directions by more than 20%

The studies-based irregularity procedures have been realized for the reinforced structures (Giannakouras and Zeris, 2019; Krawinkler and Seneviratna ,1998). The most common assessment procedures are explained in four main guidelines/codes which are Applied Technology Council (ATC-40), Federal Emergency Management Agency (FEMA 356), FEMA440 and TBEC-2018. TEC-2007 came into use in 2007.

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 (Jialiang and Wang, 2017; Inel et al. 2016, Çavdar and Bayraktar, 2014; Duan and Hueste, 2012). In this study, the nonlinear static pushover analysis is used to estimate the expected seismic performance of a regular steel building and four different irregular steel buildings. The buildings are moment resisting frame steel building. The 3D pushover analysis is performed by using the finite element program SAP 2000 (Wilson and Habibullah,1997). 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-2018 that has similarities with FEMA-356 guidelines.

2.THEORY

2.1. Performance Levels of Buildings Under Earthquake Effects According to TBEC–2018

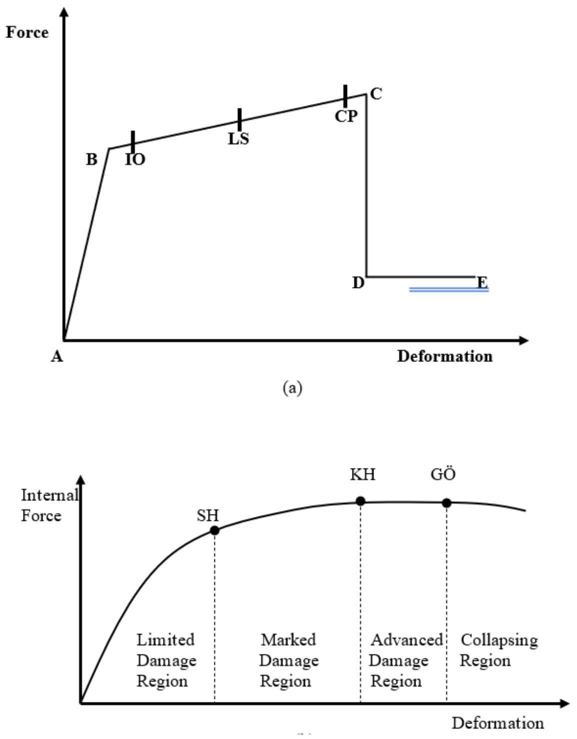
As shown in Fig. 1(a), five points labeled A, B, C, D, and E define force–deformation behavior of a plastic hinge. The values assigned to each of these points vary depending on type of element, material properties, longitudinal and transverse steel content, and axial load level on the element (TBEC,2018; ATC-40, 1996; FEMA-356, 2000). The definition of user-defined hinge properties requires moment-curvature analysis of each element. Mander model (Mander et all., 1988) 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-2018.

Similar to ATC and FEMA, three limit conditions have been defined for ductile elements on the cross section in TBEC-2018. These are Limited Damage Zone (LD), Controlled Damage Zone (CD) and Prevention Damage Zone (PD). Limited damage limit defines the beginning of the behavior beyond elasticity, safety limit defines the limit of the behavior beyond elasticity that the section is capable of safely ensuring the strength, and collapsing limit defines the limit of the behavior before collapsing. This classification does not apply to elements damaged in a brittle condition. Elements that the damages with critical sections do not reach LD are within the Limited Damage Region, those in-between LD and PD are within Controlled Damage Region, those in-between CD and PD are in Advanced Damage Region, and those going beyond PD are within Collapsing Region (Fig.1b).

3. METHODS

3.1. Description of Investigated Steel Buildings

The steel buildings are typical beam-column steel frame buildings. A typical floor plan is shown in Fig. 2 reference steel building which has no irregularity. The steel building has 7 spans in the X direction and 5 spans Y direction. The all-steel buildings were chosen 5 stories, first story is 4.0 m and other stories 3.0 m in height. Column dimensions in first and second stories are HE 400B profile and HE 360B profile for other stories. Beam dimensions in first and second stories are IPE 400 profile and IPE 360 profile for other stories. Secondary beams both X direction and Y direction were chosen IPE 270 profile. For the reference steel building 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.



(a)

(b)

Fig.1. Building performance levels according to TBEC-2018.

However, the validity of this approach is checked especially in cases of irregularities in the floor plans. According to the TBEC-2018, in the seismic zones, it shall be verified by the calculation that the floor systems can transfer the seismic loads safely between vertical structural elements. The dead load is G =4.78 kN/m2 for all the floors. The live load is Q= 4.9 kN/m2 for each floor except the top floor where the live load was considered as 2.25kN/m2. The steel structures are thought to be housing and its coefficient of live load addition is taken as n = 0.3. The steel structures are in İzmir 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. Three-dimensional finite element model of the regular steel building and of the steel buildings with A3 irregularities was prepared in SAP2000 structural analysis program shown in Fig. 3-7. The pushover analysis is performed by using the finite element method Structural Analysis Program-2000 (SAP2000). 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-2018 that has similarities with FEMA-356 guidelines.

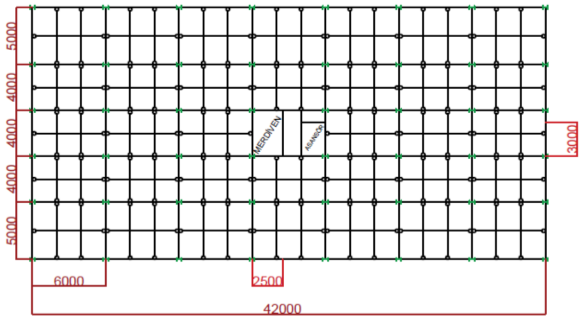
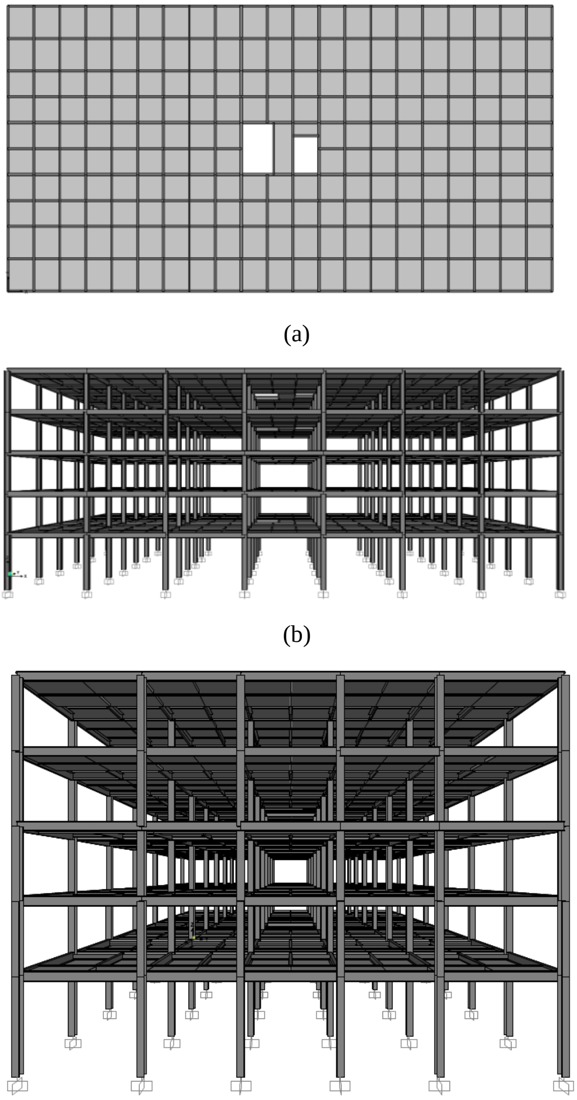


Fig. 2. Typical floor plan of the building.



(a)

(b)

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Fig.3. Plan view (a) XZ view(b) YZ view (c) of Regular steel building.

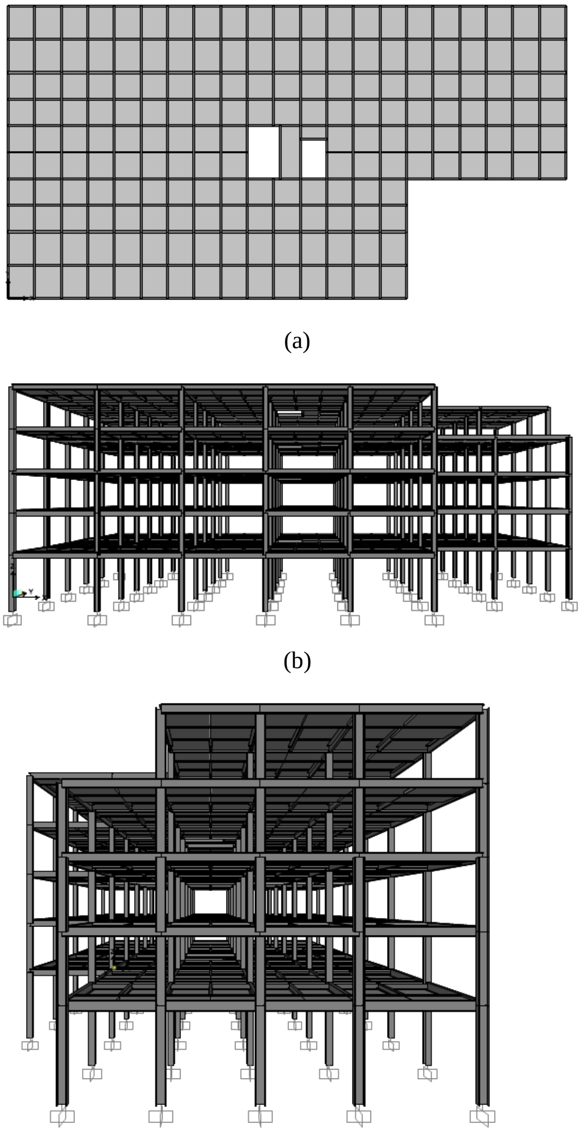

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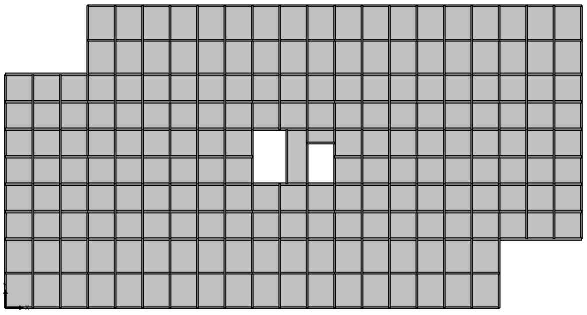
Fig.4. Plan view (a) XZ view(b) YZ view (c) of Model 1 steel building.



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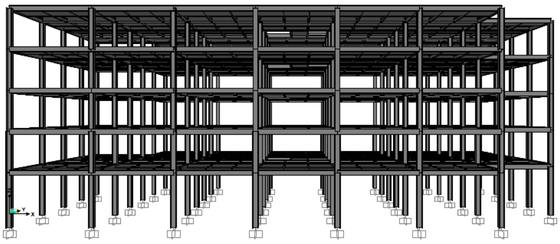

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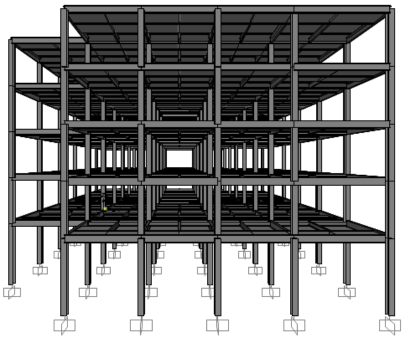

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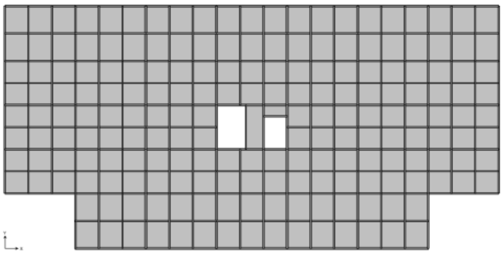
Fig.5. Plan view (a) XZ view(b) YZ view (c) of Model 2 steel building.



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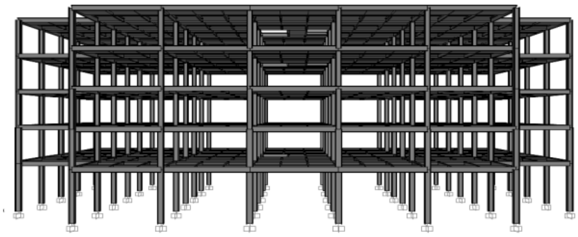

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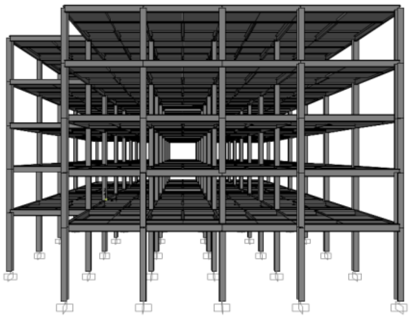
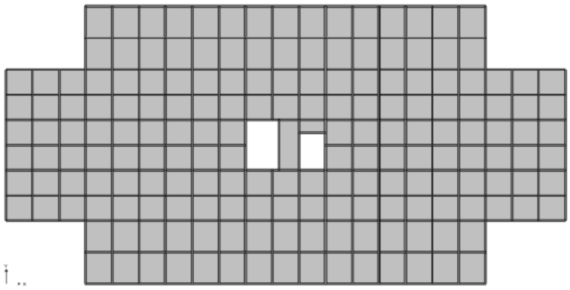


(c)

Fig.6. Plan view (a) XZ view(b) YZ view (c) of Model 3 steel building.



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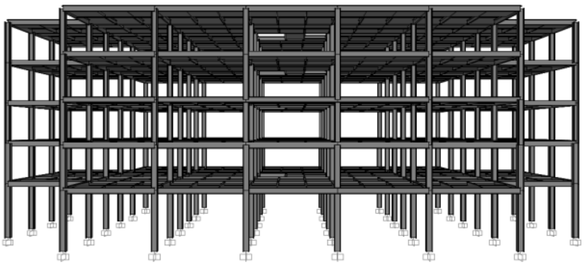

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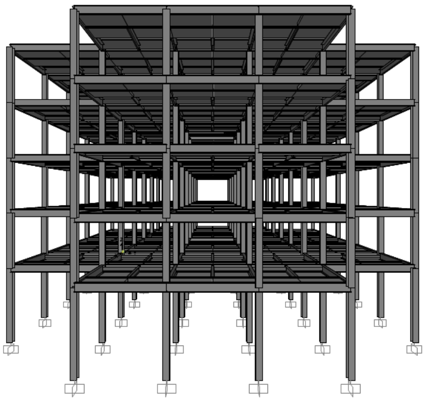


(c)

Fig.7. Plan view (a) XZ view(b) YZ view (c) of Model 4 steel building.

3.2. 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-2018 and structural performance evaluation shall be conducted both at sectional and building level.

According to TBEC-2018, to be able to use the pushover analysis, the torsional irregularity coefficient (ηbi) that is calculated in accordance with the elastic linear behavior without considering additional eccentricity should meet the condition $\eta bi < 1.4$ for each floor. The torsional irregularity of the buildings is provided.

Moreover, in accordance with the earthquake taken into consideration, the ratio of the active mass of the primary (dominant) vibration mode was calculated taking the linear elastic behavior as a basis point to the total mass of the building (except for the masses of the basement floors covered by the rigid frames) should be above 0.95 (TBEC, 2018). Because 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 are 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, 2018)

$$G+nQ=G+0.3Q \tag{1}$$

In Eq. (1), G is total dead load, n is the live load participation factor, Q is total live load stories of building, respectively.

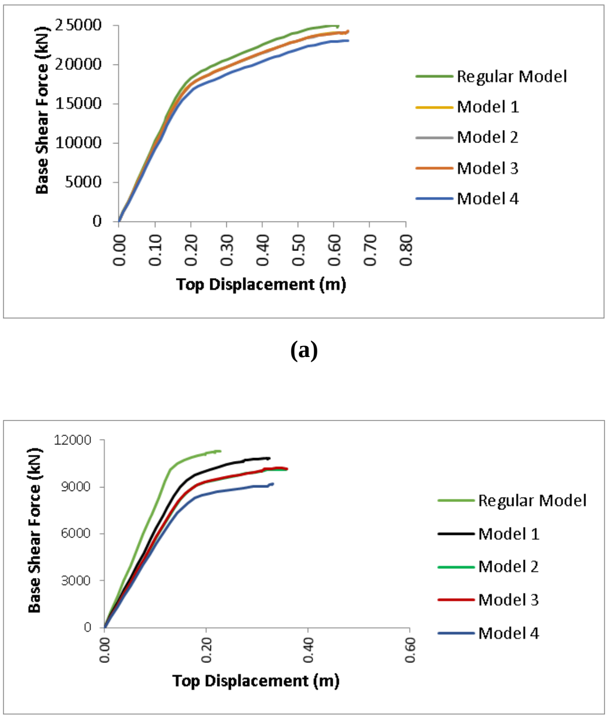
The pushover analysis of the selected structures is actualized under DD-2 (design earthquake) (10% in 50-year hazard level) as proposed in the TBEC-2018. Nonlinear static pushover analyses are determined by SAP2000. A design performance level is a statement of the desired structural behavior of a building. After determination of damage regions of sections, the performance. levels of the steel buildings are controlled. It is seen from Fig.8 that the based shear force and top displacements through the steel frame structures of models of in the X and Y direction after pushover analysis is under design earthquake (10% in 50-year hazard level).

Since A3-projections plan irregularity was examined in the study, all values related to the structure were taken as the same but this irregularity value was changed. In comparison to the regular model, the maximum base shears forces decreased by 18% in the X direction and by 26% in the Y direction. The highest decrease. in the X direction was determined in Model 4, while the highest. decrease in the Y direction was determined in Model 4.

According to TBEC-2018, 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.

(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%.



(a)

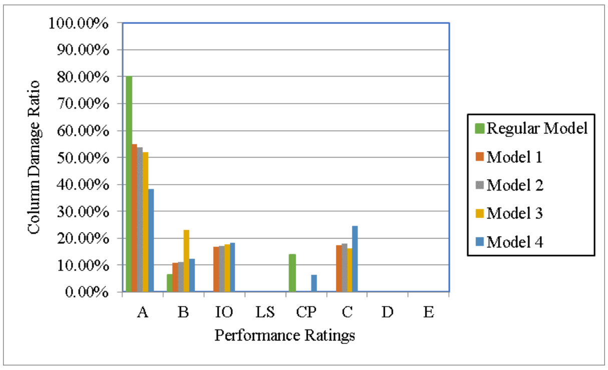
(b)

Fig. 8. Comparison of pushover curves for X and Y direction for different steel models.

The performance levels, LD, CD, and PD 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 a probability of exceedance of 10% in 50 years are compared for LD, CD, and PD displacement capacities. For any floor, if these ratios do not exceed the targeted performance level's ratio, it is concluded that the building is sufficient for CD under design earthquake.

It can be seen from the result under soil class ZC design earthquake of the pushover analysis through the X and Y direction (Fig.9a-b). It is concluded from nonlinear static pushover analysis under design earthquake that according to displacement target of the building, the buildings provided CD rating in the view of LD level targeted in TBEC-2018. According to TBEC-2018, the regular model is expected to satisfy LD performance levels, but irregular models are not expected to satisfy LD performance levels under design earthquake.

The highest decrease in the X direction was found in Model 4, while the highest decrease in the Y direction was found in Model 4. As Model 1, Model 2 and Model 3 had symmetry, the values for. the X and Y directions were highly close to each other. As the center of rigidity will get further away from the center of mass in irregular structures, the torque will create additional shear forces on vertical load-bearing structures. These will affect the earthquake resistance of the structure negatively.



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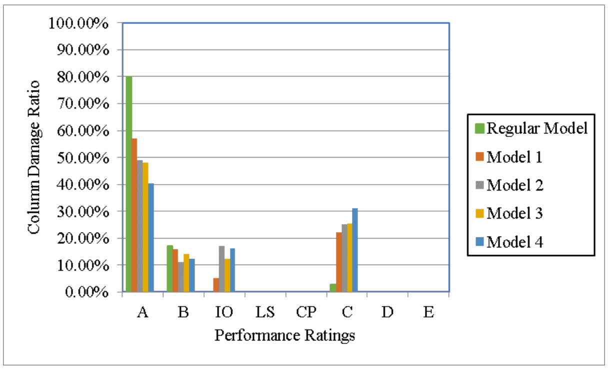

(b)

Fig.9. Columns performance levels of (a) X direction (b) Y direction of the steel building obtained by pushover analysis.

4. CONCLUSIONS

This paper investigates the seismic performance of five different buildings designed according to the provisions of TBEC-2018. 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-2018. The performance levels, LD, CD, and PD 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-2018 were used to determine global displacements of the building corresponding to the performance levels considered above. Displacement volition estimates for an earthquake with probability of exceedance of 10% in 50 years are compared for LD, CD, and PD 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 structures. Pushover analysis is not only useful for evaluating the seismic performance of the structures, however, could also be helpful for selecting seismic details that are more suitable for withstanding the expected inelastic deformations. According to TBEC-2018, the regular model is expected to satisfy LD performance levels but irregular models are not expected to satisfy LD performance levels under design earthquake.

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