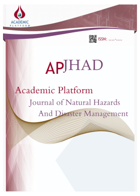

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Investigation of Effective Bending Rigidity Considering Different Code Approaches

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Abstract:

In the study, the nonlinear behavior of reinforced concrete (RC) structures was investigated considering effect of effective bending rigidity under seismic loads. The cross-sectional effective bending rigidity (EI_{eff}) of structural members was evaluated using different approaches of seismic design codes. The values of EI_{eff} given in Eurocode-8, Turkish Seismic Design Code (TSDC) 2007 and Turkish Building Earthquake Code (TBEC) 2018, were used in a case study and compared with the initial (uncracked) section rigidity. The nonlinear single mode pushover analysis was carried out to determine the nonlinear performance of a RC frame structure model in SAP2000. In nonlinear pushover analysis, the lumped plasticity and plastic hinge theory were used to define nonlinear behavior of the structural members. The plastic characteristics of structural members were also evaluated using moment-curvature relationship in Xtract. The dimension of cross-sections and reinforcing details were chosen considering the design requirements of TSDC 2007 and TBEC 2018. The structural performance of the RC frame models with different stiffnesses was compared with performance of the model in which initial rigidity used. The base reaction force vs. top displacement demand, story drifts, and plastic hinge mechanisms obtained from the analyses were selected as comparison criteria. It was observed in the analysis results that a remarkable difference occurred in force and displacement demand between the models using the different effective bending stiffnesses.

Key words: Effect of effective bending rigidity, nonlinear performance, reinforced concrete structure, pushover analysis

1. Introduction

Reinforced concrete (RC) structures might be exposed to different seismic effects during their service lives. Determination of the nonlinear behavior of these structures is the one of the most convenient ways to check structural safety. For this purpose, the structural behavior could be evaluated with different nonlinear analysis methods under the seismic effect [1-4]. To determine the proper analysis method for the nonlinear behavior of RC structures is very crucial. Pushover analysis is one of the most commonly used methods to evaluate performance of RC structures under earthquake loads [5-9]. In this method, the displacement demand of a structure is calculated by a monotonically incremental loading. This increase in seismic displacement demand should be proceeded until a reliable target displacement. Besides, the force distribution due to lateral earthquake load is taken into account in a compatible form of fundamental first mode on the structure at every story level [10-12]. In the last increment step of target displacement, demands of base shear force, top displacement, and story drifts are

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calculated to determine plastic deformations on each structural element. The plastic deformation intensity of each structural element is crucial for the assessment of RC structures in a nonlinear analysis. In this analysis, nonlinearity of each structural element affects directly the nonlinear behavior and performance level of RC structures. The nonlinearity of elements is defined by using plastic hinge theory with lumped plasticity. Plastic deformations are observed in a plastic hinge length at the both ends of structural elements. Additionally, it is assumed that the other parts of each structural element exibit elastic behavior [13].

On the other hand, cross-sectional properties and behavior of these elements should be known to define nonlinear behavior of RC structural elements. Moment-curvature (MC) relationship is one of the best theoretical approaches to represent the nonlinear behavior of RC elements [14-15]. Additionally, the moment-curvature relationships should be used with interaction surfaces of vertical structural elements (column, shear wall etc.). The interaction surfaces are evaluated according to the different levels of axial forces in a column or shear wall. Thus, the positive/negative effect of compression and tension forces can be taken into account by the cross-sectional analysis of a column or shear wall.

Additionally, flexural stiffness and ductility of a section can be determined using moment-curvature relationship [16]. The slope of MC relationship represents the effective bending rigidity (EI_{eff}) and is calculated by dividing the value of yield moment to the value yield curvature. Mander confined and unconfined concrete models which are one of the most commonly used models in literature to represent material behavior, are used in cross-sectional MC analysis [17]. The effect of confinement is considered for each different section.

In the study, twelve incremental single mode pushover analyses were carried out using the different values of EI_{eff} defined in different design codes. These stiffnesses were calculated according to Eurocode-8, Turkish Seismic Design Code for buildings 2007 and Turkish Building Earthquake Code 2018 (TSDC 2007 and TBEC 2018) [18-20]. Besides, Xtract [21], which is a commercial sectional analysis program was used to determine EI_{eff} of the sections and they were compared in pushover analysis. All pushover analyses were performed by using Sap2000 a commercial general finite element software [22]. According to the result of pushover analysis, the design code approaches were assessed by considering the variation of the structural demands and performances.

2. Numerical Modelling and Parametric Study

In the study, an incremental single mode pushover analysis is used to determine nonlinear displacement demand of structures under seismic loads. The displacement demand affects nonlinear deformations of structural elements directly. These deformations are evaluated using plastic hinge properties of each cross-section. Therefore, defining plastic hinge properties of cross sections is very important to determine nonlinearity of structures in pushover analysis. In this part of the study, modelling methodology is explained to create a numerical model in nonlinear analysis. In this research, twelve pushover analyses were applied to an eight-story RC structural frame model to determine effect of EI_{eff} on RC structures. In the analyses different EI_{eff} is used considering different code approaches to compare obtained results with the values obtained from Xtract. The analysis results are compared in terms of nonlinear force-displacement relationship, story drifts, plastic hinge rotation, and variation of first fundamental vibration mode of the structure.

2.1. The Model of Superstructure

Three dimensional (3D) numerical models of an eight-story RC structure, designed according to the minimum design requirements defined in TSDC 2007, are created. The dimensions of each cross-section, and reinforcement details of the structural elements are tabulated in Table 1. Moreover, reinforcement details of structural elements, and general layout and plan views of 3D numerical models are given in Figures 1 and 2 respectively.

Table 1. Material and section properties of superstructure

Name	Element	Concrete – Reinf.	Mod. of Concrete (MPa)	Mod. of Reinf. (MPa)	Yield Strength of Reinf. (MPa)	Dimensions (mm)	Long. – Trans. Reinforcement (mm)
C1	Column	C25 – S420	30000	210000	420	600x250	10Φ16–Φ10/100
C2	Column	C25 – S420	30000	210000	420	250x600	10Φ20–Φ10/100
C3	Column	C25 – S420	30000	210000	420	600x250	10Φ20–Φ10/100
B1	Beam	C25 – S420	30000	210000	420	250x500	6Φ16–Φ10/100
B2	Beam	C25 – S420	30000	210000	420	250x500	6Φ20–Φ10/100

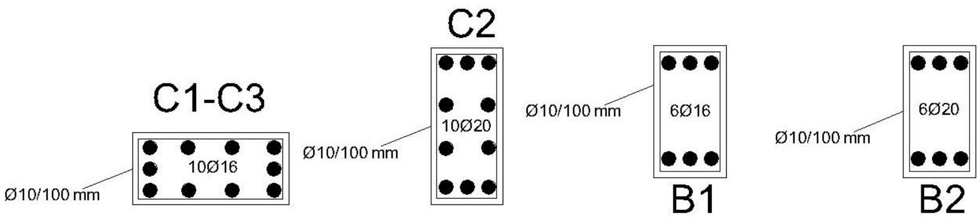

Figure 1. Reinforcement details of structural elements

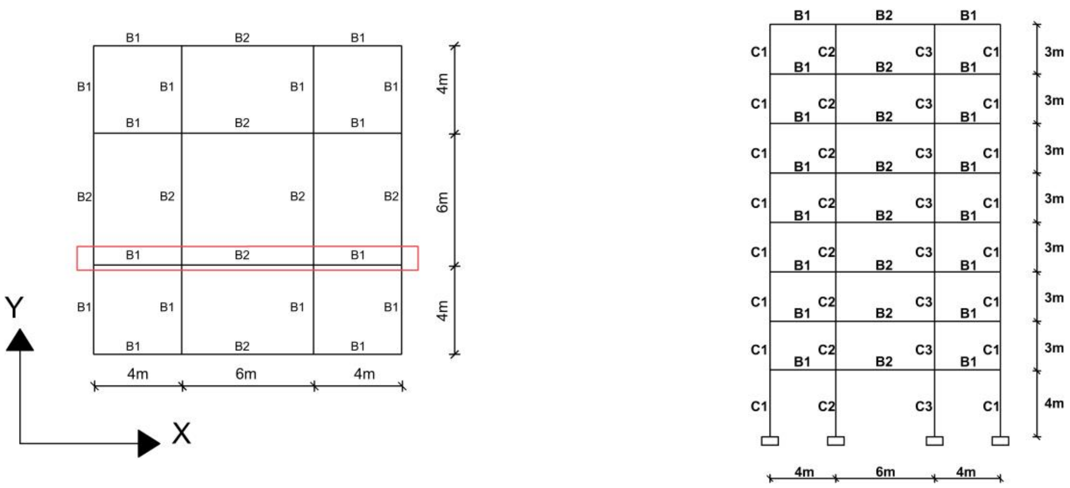

Figure 2. Plan view and general layout of structural model

It is assumed that all structural systems are constructed in a high seismic risk zone (first-degree). Therefore, they must a have high ductility. Moreover, soil conditions are considered as a Z4 soil class defined in TSDC 2007 for all structural models. In TSDC 2007, it is proposed that the peak ground acceleration (A_0) should have taken as 0.4g for the first-degree seismic risk zone. Elastic-perfectly plastic behavior is defined for the stress-strain relationship of steel reinforcement. Mander [17] confined and unconfined approaches are used for the nonlinearity of concrete material.

Plastic hinge properties of each cross section are calculated by considering reinforcing details. These plastic hinges are determined according to the moment-curvature relationship of each different cross-section assigned to the end points of structural elements. The frame in red box in Fig. 2 is selected as a reference axis to be able to compare analysis results. The moment-curvature relationships of all beam and column sections are given in Figure 3.

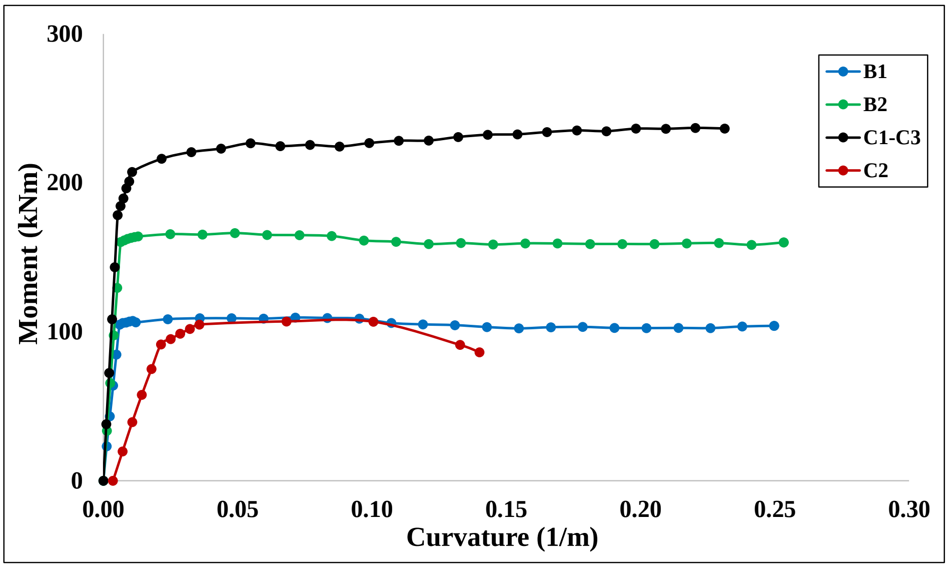

Figure 3. Moment-curvature relationships

The plastic hinge properties of beams (M3) are defined considering moment-curvature relationships. On the other hand, the flexural moment capacities are changed according to the axial force level (tension or compression) on the RC columns. Therefore, the plastic hinge properties of columns (P-M2-M3) are defined in accordance with interaction surfaces of columns. The axial forces are calculated by using interaction surfaces of columns in plastic zones. The interaction surfaces are obtained by using section designer module of SAP2000. In Sap2000, the moment-curvature analysis and the different interaction surfaces of columns are determined by using this module. During the pushover analysis, the SAP2000 software uses the default and adaptive axial forces obtained from interaction surfaces in the section designer module instead of user defined values. The interaction surfaces of columns are presented in Figure 4.

In nonlinear pushover analysis, the conventional load combinations used in linear analysis are not used to represent lateral loading procedure. In this method, the displacement demand of a structure is calculated by a monotonic incremental loading. This increase is seismic displacement demand should be proceeded until a reliable target displacement. Besides, the force distribution due to lateral earthquake load is taken into account in a compatible form of the fundamental first mode of the structure at every story level. In the last step of target displacement; the demand of the base shear force, top displacement, and story drifts are calculated to determine plastic deformations of each structural element. In pushover analysis, the initial conditions of superstructure are defined as a deformed model under the weight of superstructure. To perform these initial conditions, a nonlinear load case is defined by using the weight of superstructure (G+nQ) and checked the plasticity of RC structure. The dead loads, live loads and participation factor for live loads are denoted by using symbol G, Q and n, respectively. The value of n is assumed as 0.3 for the buildings. The pushover analysis is only carried out in the "X" direction of structures and the results are compared by considering plastic deformations of RC structures in this direction.

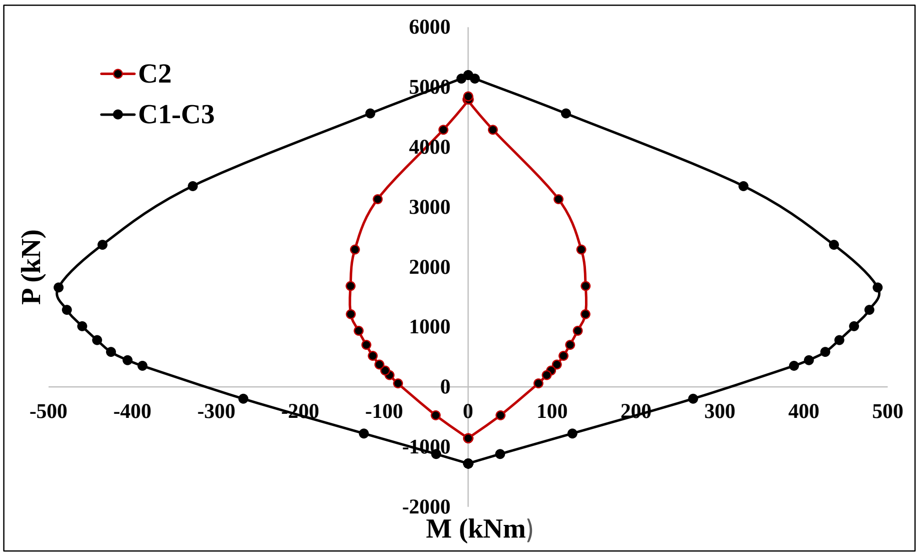

Figure 4. Axial force (P, kN)-moment (M, kNm) interaction surfaces

2.2. Parametric study

The EI_{eff} of cracked sections is a very crucial parameter in nonlinear analyses. That parameter is defined as different values in different earthquake design codes. The aim of this study is to determine different EI of cracked sections considering earthquake code approaches. Moreover, values of EI_{eff} are compared to the values obtained from Xtract program. In the study, the EI of cracked section are calculated by considering the values defined in TSDC 2007, Eurocade-8, and TBEC 2018 seismic codes. The cracked-section EI is defined as a constant value for frame beam and column elements in Eurocode-8. In TSDC 2007, the EI_{eff} for a frame beam element is constant like others. For the column elements, this value must be calculated between 0.4-0.8 of initial rigidity according to the axial load level of columns. The envelope value of axial force obtained from the mode superposition method is taken account into to determine EI_{eff} value of TSDC 2007. The envelope axial loads are calculated by using the sufficient number of modes in which the participation ratio of mass is or above %95. In Xtract program, the value of EI_{eff} can be calculated by a step by step solution for all beam and column elements. In the section analyses any axial load level can be taken into account for all column sections. The moment-curvature relationships are used when these values are calculated in Xtract. In every step of sectional analysis, the deformation of reinforcement, confined and unconfined concrete are controlled according to a limit deformation which is defined for failure mode of the material. In TBEC 2018, the design EI_{eff} values used in a design of a new building are defined in section 4 (Design Principles of Strength Based Design of The Structures under Earthquake Effect) and these values are constant for frame elements such as columns and beams. However, the performance EI_{eff} values used in a seismic performance evaluation of an existing building are calculated by using Eqs. 1 and 2. These equations are defined by performing the moment-curvature analysis in section 5 (Assessment and Design Principles of Displacement Based Design of the Structures under Earthquake Effect). In Eq. 1, L_s, M_y and θ_y represent the shear span (can be assumed as the half of span), yield moment, and rotation respectively. The compressive strength of concrete and yield strength of reinforcements are defined by using f_{ce} and f_{ye}. In Eq. 2, $\emptyset_y$, h and d_b indicate the yield curvature (obtained from moment-curvature analysis), height of the section and average diameter of tension reinforcement, respectively. The coefficient η is a constant value and should be accepted for a frame element such as column and beams as 1. Each EI_{eff} value for Xtract and other earthquakes codes is given as a ratio of initial rigidity in Table 2.

$$EI_{eff} = \frac{M_y}{\theta_y}\ \frac{L_S}{3} \tag{1}$$

$$\theta_y = \frac{\emptyset_y L_s}{3} + 0.015\eta\left(1+1.5\times\frac{h}{L_s}\right) + \frac{\emptyset_y d_b f_{ye}}{8\sqrt{f_{ce}}} \tag{2}$$

Table 2. Material and sectional properties of superstructure

Name	Initial EI (kNm^2)	EI_{eff} of Eurocade-8	EI_{eff} of TSDC 2007	Design EI_{eff} of TBEC 2018	Performance EI_{eff} of TBEC 2018	EI_{eff} of Xtract
C1	135000	0.5	0.48-0.62	0.7	0.06	0.33-0.35
C2	23438	0.5	0.78	0.7	0.12	0.34
C3	135000	0.5	0.74	0.7	0.06	0.36
B1	78125	0.5	0.4	0.35	0.05	0.22
B2	78125	0.5	0.4	0.35	0.06	0.32

As it can be seen in the Table 2 that the performance approaches of TBEC 2018 are very conservative compared to the other values of EI_{eff}. It can be said that an accurate performance assessment cannot be determined by using these performance EI_{eff} values. Probably, the results of pushover analysis could be irrational compared to the other results. Therefore, in the study the design EI_{eff} values of TBEC 2018 are used due to being a more realistic assumption than the performance EI_{eff} values. These values are defined in structural models when pushover analyses are carried out in Sap2000. The nonlinear force-displacement relationship obtained from pushover curves, story displacements and drifts, plastic hinge rotation, and variation of first fundamental vibration mode of structure are selected as parameters to make a comparison between analysis results.

3. Results

3.1. Pushover curves

In the study, the pushover curve is used to explain the relationship between base shear force and roof displacement in a nonlinear analysis. In numerical analysis, displacement and force demand of structures which are obtained from pushover curves are compared in Figure 5, 6 and 7. Moreover pushover curves are also used to determine performance level of the each numerical model. In the analysis, four different EI_{eff} ratio according to the initial EI obtained from different design codes, are used and compared using pushover analysis. Firstly, only the EI_{eff} of beams are changed while the columns are considered as having a constant value of EI (initial value). Secondly, only the EI_{eff} of columns are changed as the EI_{eff} of beams are accepted as constant value (initial EI). In last part of the study, the calculated EI_{eff} calculated from design codes and obtained from Xtract are used for both beams and columns. The results obtained from the analyses are compared in Figure 5, 6 and Figure 7.

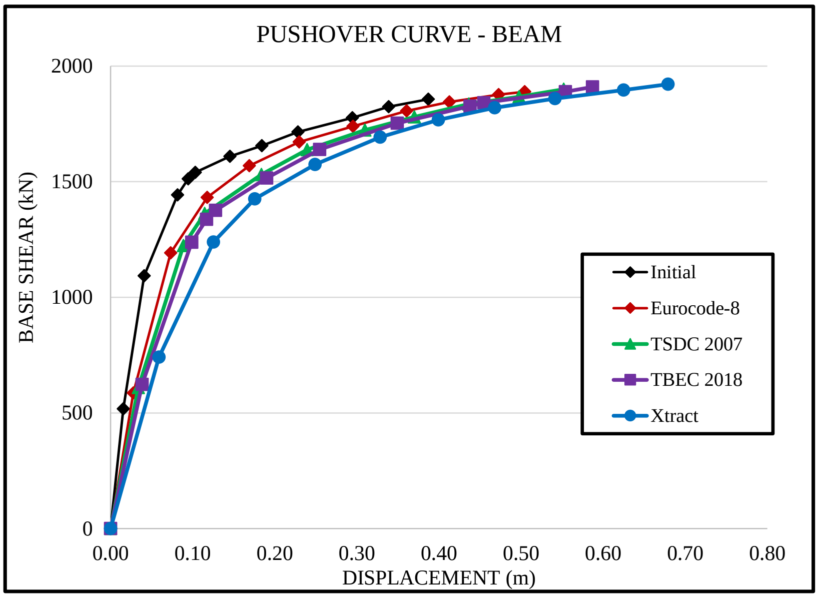

Figure 5. Pushover curves for model changed EI of only beams

When the analysis results are compared, the nonlinear force and displacement demand increases when calculated EI_{eff} obtained from Xtract is taken into account in the nonlinear analysis. Additionally, yield force and displacement change in different design code approaches. As it can be seen in the figures, the force and displacement demand of structural models using the EI_{eff} of different design codes become approximately similar. However, these demands are conservative with respect to the results of the structural model using the EI_{eff} of Xtract. Therefore, all the structural models reach to failure due to larger force and lesser displacement demand when the results of structural model using the EI_{eff} of Xtract are compared. It can be said that the models of Xtract show more ductile behavior with respect to the other structural models considering force and displacement demand.

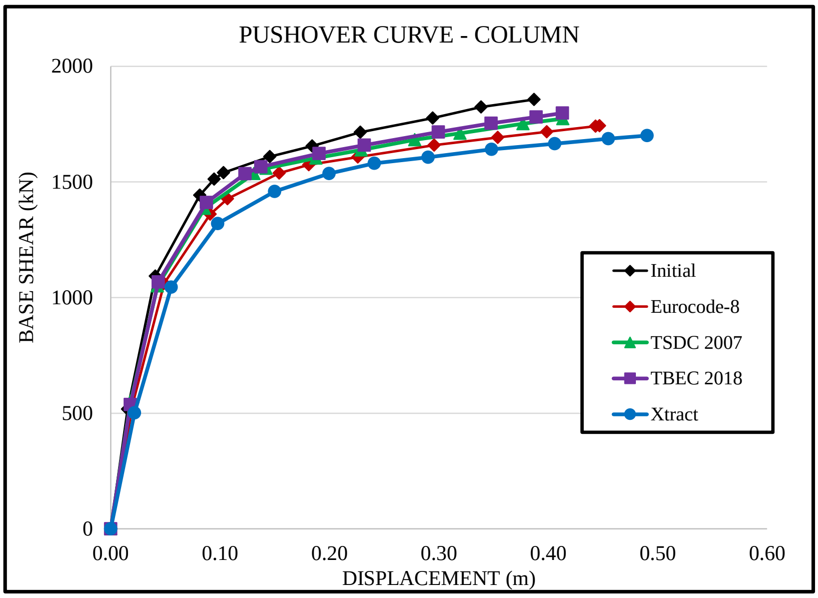

Figure 6. Pushover curves for model changed EI of only columns

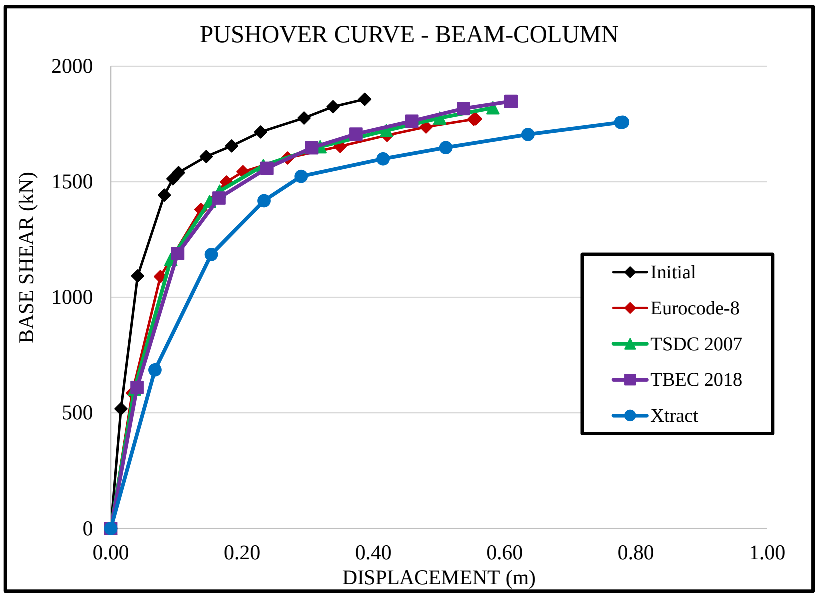

Figure 7. Pushover curves for model changed EI of both beam and columns

3.2. Structural demands

The results of pushover analyses are presented in Table 3. The difference in base shear, roof displacement, displacement ductility, and period of fundamental mode for different structural models are tabulated Table 3 considering different code approaches. Determination of target displacement values is the most crucial part of the nonlinear analysis. The plastic deformations of RC elements obtained from nonlinear analysis are calculated according to that target displacement values. These plastic deformations are used to determine the accurate nonlinear performance level of structures. Target displacements are calculated by means of measuring horizontal deflection value at the top of structures. The variations between structural models are shown for models whose EI_{eff} is changed for beams, columns, both beam and columns separately. As it is expected, the combined use of the effective bending stiffnesses of columns and beams leads to increase in the first free vibration period of the structures. Similarly, the displacement demand increases due to the use of EI_{eff} for beams and columns together for each structural model.

Table 3. Variation of structural demands

Model		Initial	Eurocode-8	TSDC 2007	TBEC 2018	Xtract
Beam	Base Shear (kN)	1857	1890	1900	1910	1922
	Roof Disp. (m)	0.39	0.50	0.55	0.59	0.68
	Period T (s)	1.25	1.55	1.67	1.75	1.97
	Ductility	3.8	4.2	4.8	5.1	5.5
Column	Base Shear (kN)	1857	1743	1774	1798	1701
	Roof Disp. (m)	0.39	0.45	0.41	0.41	0.49
	Period T (s)	1.25	1.41	1.33	1.32	1.54
	Ductility	3.8	4.2	4.8	4.7	5.1
Beam-Column	Base Shear (kN)	1857	1773	1821	1849	1759
	Roof Disp. (m)	0.39	0.56	0.58	0.61	0.78
	Period T (s)	1.25	1.71	1.75	1.82	2.26
	Ductility	3.8	3.2	3.9	3.7	4.1

Additionally, as the displacement demand increases, the displacement ductility decreases due to combined use of EI_{eff} for beam and columns. As it can be seen in Table 3, the EI_{eff} of columns is more effective on the dynamic characteristics and seismic demand of the structure with respect to the EI_{eff} of beams. On the other hand, the first free vibration periods of the structural models using the performance EI_{eff} of TBEC 2018 change between 4-6 s. Moreover, the displacement demand is found to be between 1-2 m. The level of displacement demand and first free vibration period prove that the use the performance EI_{eff} of TBEC 2018 causes unreasonable analysis results for a multi-degree structural system. Therefore, the performance approach of EI_{eff} in TBEC 2018 should be revised considering dynamic characteristics and structural demands.

3.3. Story drifts

Story drift is calculated by dividing the difference between horizontal deflection of top and bottom of a story to the height of this story. The variations of story drifts and displacements are shown in Figure 8, 9 and 10.

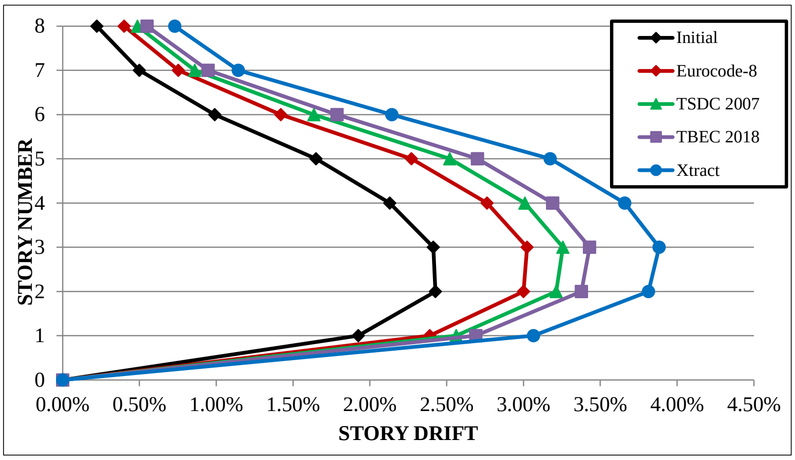

Figure 8. Story drifts for model changed EI of only beams

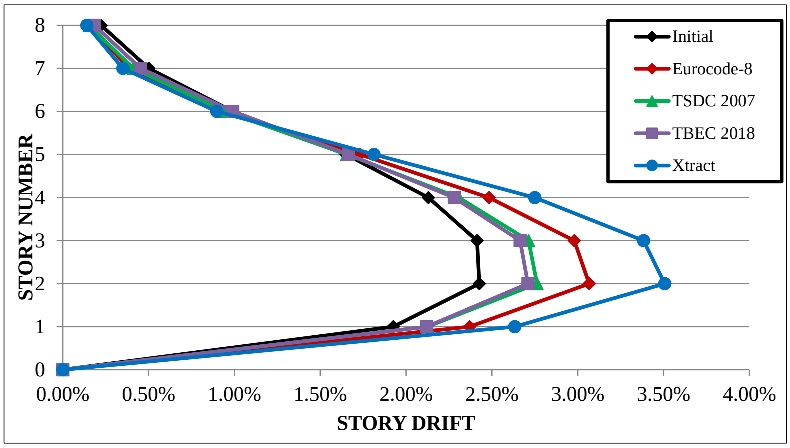

Figure 9. Story drifts for model changed EI of only columns

The story drift is one of the most direct parameters to make an assessment about the nonlinear performance level of a structure. In different earthquake design codes of different countries, some limitations are defined for story drifts while determining performance level of structures. The limitations of TSDC 2007 are used in this study and defined for immediate occupancy (IO), life safety (LS) and collapse prevention (CP) performance levels as 2%, 3% and 5%

respectively. The difference in story drifts obtained from different structural models are calculated according to the story displacements. The difference in story drift ratios is more apparent when the EI_{eff} values of beams are only used. The design code approaches are very similar to determine story drift ratios. Therefore, the displacement demand of each structure in which the EI_{eff} of design codes are used, are approximately same. Additionally, the story drift ratios in the structural model using the EI_{eff} of seismic codes are conservative when the results of structural model with the EI_{eff} of Xtract are compared. According to the results of story drifts, it can be deduced that the structure can reach to the different performance level because of application of the different EI_{eff} assumptions. In addition, the EI_{eff} obtained from the Xtract could be a more realistic to reach to the accurate performance of structures. Besides, as it can be seen in the Figs. 8, 9 and 10 that the most critical values of story drift ratios occur on the first three stories of the structures in which the first free vibration period is dominant.

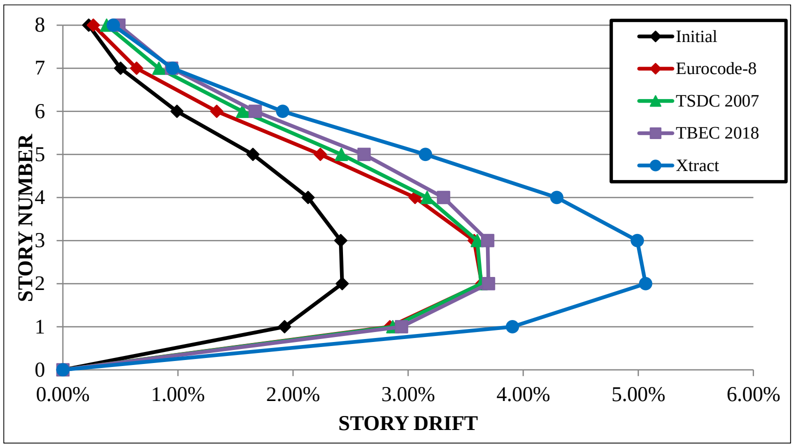

Figure 10. Story drifts for model changed EI of both beam and columns

3.4. Plastic Hinge Mechanisms

In earthquake design codes, column-beam connections are defined as one of the most crucial parts of a structure under seismic loads. To prevent brittle collapse, there are some special design rules for these connections. The strong column - weak beam analogy is generally proposed to be able to make a more ductile design for RC structures. In the study, analysis results showed that this analogy couldn't be provided due to different approaches of design codes. Moreover, some new plastic hinge mechanism can be observed in a structural system according to the values of EI_{eff}. By means of using different EI_{eff} approaches, these plastic hinge rotations can increase when the results are compared. For instance, the differences in plastic hinge formation mechanisms are shown in Figure 11. As it can be seen in Figure 11, the structural models reach to the failure mechanism with a different number of plastic hinges. In addition, the plastic deformation levels of plastic hinges are different according to the use of the different EI_{eff}. The color of pink is used to represent the yield deformation of structural elements. The color of blue, turquois and green represent the performance of immediate occupancy (IO), life safety (LS) and collapse prevention (CP), respectively. According to the results of pushover analysis, the number and distribution (%) of the plastic hinges are presented for beams and columns in Table 4. The number and distribution of plastic hinges are classified in accordance with the performance levels defined in the seismic design codes.

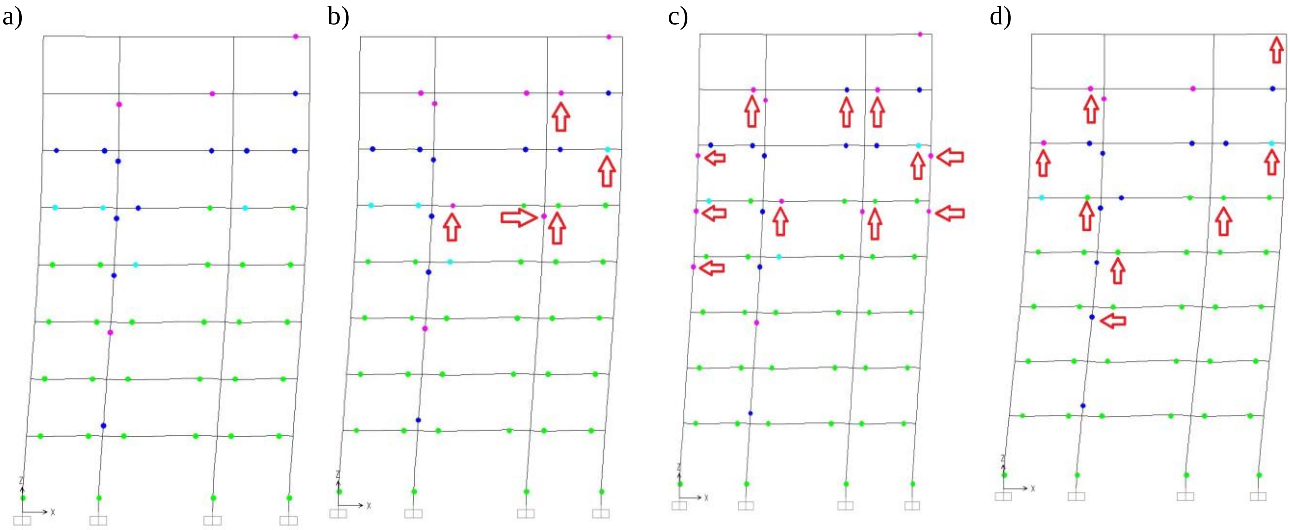

Figure 11. Plastic hinge formation a) Eurocode-8 b) TSDC 2007 c) TBEC 2018 d) Xtract

Table 4. The plastic hinge distribution of beams and columns for each performance level

	Level of plastic hinge	Beam		Column		Number of plastic hinge for failure of structure
		Number	%	Number	%	
Eurocaode-8	Yield	2	4	2	4	48
	IO	7	15	4	8	
	LS	4	8	0	0	
	CP	25	52	4	8	
TSDC 2007	Yield	5	10	3	6	51
	IO	5	10	4	8	
	LS	4	8	0	0	
	CP	26	51	4	8	
TBEC 2018	Yield	4	7	7	13	55
	IO	6	11	4	7	
	LS	3	5	0	0	
	CP	27	49	4	7	
Xtract	Yield	3	6	1	2	49
	IO	5	10	6	12	
	LS	2	4	0	0	
	CP	28	57	4	8	

When the results of plastic hinges are compared, the strong column-weak beam approach is achieved due to the fact that most of the plastic hinges are formed in the beams. The plastic deformation of columns using the EI_{eff} of TSDC 2007 and TBEC 2018 are larger than the plastic deformations of other models. However, the number of plastic hinge mechanisms on beams is less than the other structural models in which different approaches are used. Therefore, the structural model using the EI_{eff} of Xtract can be accepted as the most ductile model because it reaches to the largest displacement demand with the least number of plastic hinges. Besides, the behavior of structural model using the initial EI is approximately elastic and reaches to a failure mechanism with only two plastic hinges.

4. Conclusions

In the study, the nonlinear behavior of reinforced concrete (RC) frames considering effect of effective bending rigidity under seismic loads is investigated. The cross-sectional effective bending rigidities (EI_{eff}) of structural members are determined using different approaches of seismic codes (Eurocode-8, TSDC 2007 and TBEC 2018). Twelve incremental single mode pushover analyses are carried out using the different values of EI_{eff}. The structural performance of RC frames with different stiffness is compared. Base reaction vs. force-top displacement demand, story drifts, plastic hinge mechanisms, periods, ductility, and roof displacements obtained from the analysis are selected as the comparison criteria. The effect of EI is seemed that different approaches of codes can cause a different assessment for same structures in nonlinear analysis. As the EI_{eff} decreases due to the code assumptions, performance levels of structures changes in numerical models negatively. Moreover, the numerical model whose EI_{eff} value calculated with Xtract program has more displacement capacity than other numerical models whose EI_{eff} defined according to the relevant design codes. From the analysis results, the following conclusions can be deduced:

1) When the pushover curves are compared, structural systems exhibit different displacement and force demands. The numerical model whose EI calculated with Xtract is less rigid than the other models. The most rigid model becomes the one EI_{eff} is not considered. The models on which EI_{eff} is considered only on beams or columns performed very similar behavior when the criteria of EuroCode-8, TSDC 2007, and TBEC 2018 are taken into account. On the other hand, those results remained between the results of initial EI and Xtract analysis.

2) It is seemed that the roof displacement and the displacement demand become bigger as the rigidity of structure decreases. Besides, the greatest displacement demand occurs in a numerical model whose EI_{eff} calculated with Xtract. This numerical model represents more ductile behavior than the others as well. While the minimum roof displacements were obtained from the models in which EI_{eff} is disregarded, the results obtained from seismic code approaches stayed between that values.

3) The story drifts can reach critical limit values with different assumptions of EI_{eff}. The difference in story drifts between numerical models decreases at the top of structures. The critical difference generally occurs at the first three stories. The results of story drifts can be observed apparently when the EI_{eff} of only beams are changed.

4) When the effect of EI_{eff} is taken account into in a nonlinear analysis, it is observed that some beam mechanism may change to column hinge mechanism for the numerical models. Plastic hinge rotations can reach high values with the increase in displacement demands. The differences between models are more apparent when the EI_{eff} of columns and beams are changed concurrently.

5) When the periods of the structural systems are evaluated, along with the decrease in EI_{eff} values the periods increase dramatically due to decrease in rigidity of the system. As the maximum period was observed in the models on which EI_{eff} values calculated by Xtract, the minimum value was obtained on the model EI_{eff} was not considered.

In the study, it is deduced that the structural performance of load bearing systems changes significantly according to use of different EI_{eff}. The important variations are observed on periods, ductility, roof displacements, and base shears of the building as well. The relevant seismic codes used in this study become generally conservative in this regard. However, the results obtained from TBEC 2018 seem meaningless since it gives very small EI_{eff} values. Moreover, according to the analysis results, it is seen that EI_{eff} values of columns have a more significant effect then beams on the system. Lastly, while calculating the EI_{eff} values, the axil load on column members should be taken into account since it affects moment-curvature behavior of the sections significantly.

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