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New Design Criteria in Performance Based Earthquake Engineering

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ABSTRACT
In order to increase the resistance of the building against earthquake effect in performance-based design, the main objective is to select a performance target as design criteria and to design the structure to meet this target. In the nonlinear analysis with finite element method, the formation of the plastic hinge can lead to great potential damage to the building, so they are one of the basic data to determine the state of the building. Accordingly, if the number of plastic hinges in the building is increased, the total horizontal load carrying capacity of the structure increases proportionally. Theoretically, when the structure of plane frame bearing system reaches a plus value of the degree of indeterminacy of the structure, the structure will reach the capacity to bear the largest final horizontal load. For this reason, in this study, in addition to the current design criteria in the relevant codes, it is aimed to increase the structure to the maximum load carrying capacity level by adding the new criterion: "to increase the number of plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by code". As a result of the studies conducted according to the new performance criteria presented, the load bearing capacity of the frame bearing system has increased by 50% compared to the current code results.

KEYWORDS: *Performance-based a seismic design, Yield moment, Plastic hinge, Static pushover analysis, Finite element method*

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1. INTRODUCTION

To date, in the building and construction industry, many codes, regulations and standards have been developed to make buildings less costly and secure. The establishment of the Performance Based Design (PBD) approach has been the most important factor in the development of these regulations. The PBD design ensures that the behavior of the structure during and after the earthquake is within the criteria expected from the structure. This design is based on the principle of designing the structure to meet this goal by selecting the performance target of the building at multiple ground motion levels and according to other design criteria. Performance criteria are directly related to the usage characteristics of the structure. Use immediately after the earthquake, ensuring life safety and reducing economic losses are the main criteria. Although PBD is in the regulations of many countries and is being developed continuously, it has not yet reached its full potential.

When displacement-based seismic design [1] became efficient, the PBD method against earthquakes [2] was developed on this basis. Basic information about PBD against earthquake was presented in [3] studies, high-rise structures [4,5] studies, and recent developments in this subject [6,7,8, 9]. The PBD method against earthquake has been extensively included in the relevant advanced regulations [10, 11].

In the study [12] of PBD against earthquake in addition to the current design criteria in the relevant regulations, it is aimed to increase the structure to the maximum load carrying capacity level by adding the criterion "to increase the number of plastic hinges to be formed in the structure as much as possible near theoretical value [14]". With the addition of the mentioned design criteria to the relevant PBD method, reaching the target performance (LS-Life Safety) has increased the carrying capacity of the structure by 7.64%.

As can be seen from the studies above, PBD studies against earthquake have not been evaluated by adding the criterion of "to increase the number of plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by regulation" and it will be discussed in the presented study.

2. PROBLEM IDENTIFICATION

The PBD method included in the current regulations [10,11,13] contains a number of design criteria to achieve the targeted performance of the structure. As it is known from theoretical studies [14], in plane frame bearing systems, when the degree of indeterminacy in the structure plus as many plastic hinges are formed, the load bearing capacity of the system is maximum. In this study, in addition to the Performance Based Design criteria in the current regulations it is aimed to increase the structure to the maximum load carrying capacity level by adding the new criterion "to increase the number of the plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by regulations". In this study, unlike the previous mentioned [12], it is aimed to keep the structure predominantly below the previously targeted performance. In other words, in short, more than 50% of the number of plastic hinges to be formed in the system must reach the predetermined target.

In this study, it is aimed to develop PBD method with the addition of new design criteria mentioned in current criteria.

In addition to the current design criteria in the PBD relevant regulations the new criterion, "to increase the number of plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by regulation", PBD layout, efficiency, related details, explanations, and comparative results with traditional PBD are presented in the following sections.

3. THE PERFORMANCE-BASED DESIGN PROCESS

Performance-based design process starts with selecting one or more design criteria expressed by the performance goal. Each performance target is the acceptable risk of structures being exposed to different levels of damage and as a result of the expression of losses that occur. Losses can be categorized in two types: structural or non-structural damage, as well as direct economic costs and loss of service costs.

Figure 3 shows a flow chart showing the basic steps in the performance-based design process.

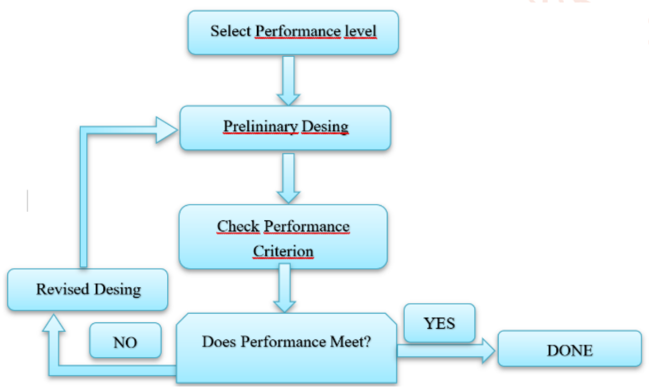


Figure 3: Performance-Based design process [12]

4. RESEARCH METHOD AND NUMERICAL MODELLING

An example reinforced concrete framed building under the effect of earthquake will be modeled by finite element method and performance evaluation will be examined using the nonlinear static pushover method. The analysis will be made as follows according to the TBEC 2019 regulation [11]. The geometrical dimensions of the sample building are given in Figure 4-1, and the seismic and ground parameters of the region in which they are located are given in Table 4-1. Seismic and soil parameters of the inhabited structure in this table, the structure's location (Turkey / Samsun / Atakum, Azerbaijan street, latitude: 41.328680, longitude: 36.279106), based on ground surveys previously conducted in this position earthquake ground motion level (DDR-2). In this location, it was obtained from the source [15] based on the previously made borehole information (by determining the local ground class ZC according to the plot of the ground borehole log and Vs velocities).

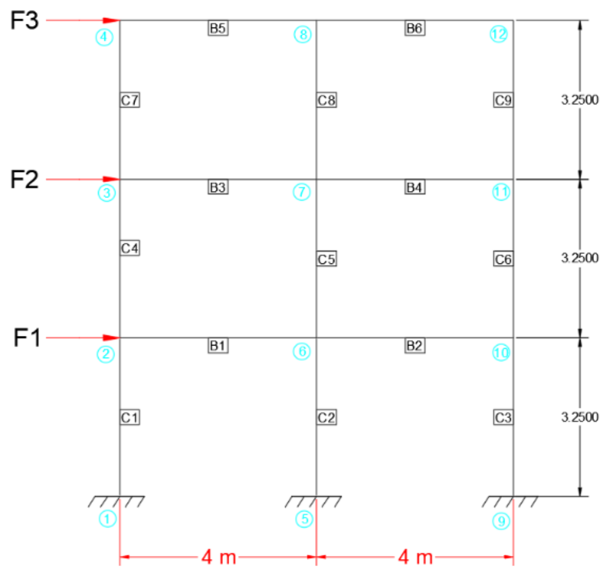


Figure 4-1: Frame system model.

Table 4-1: Material quality and seismic parameters

Material		*Mechanical Parameters*
Concrete	C25	$f_{ck} = 25\ N/mm^2$ $E: 30000\ N/mm^2$
Steel	S420	$f_{yk} = 420\ N/mm^2$ $E = 200000\ N/mm^2$
Earthquake and Soil Parameters		
Earthquake Ground Motion Level: DD-2 Local Ground Class: ZC Map spectral acceleration coefficient: $S_S = 0.507$ $S_1 = 0.179$ Design spectral acceleration coefficient: $S_{DS} = 0.658$ $S_{D1} = 0.269$ Spectrum corner period: $T_A = 0.082\ s$ $T_B = 0.408\ s$		

According to the above information, the sample building is pre-dimensioned [14, AASEM software] and obtained beam, column section, reinforcement in formations are given in Table 4-2.

Table 4-2: Information of Column and Beam

Element	**Height (cm)**	**Width (cm)**	**Reinforcement**
Column	40	40	8ϕ16
Beam	50	30	3ϕ14 top and bottom

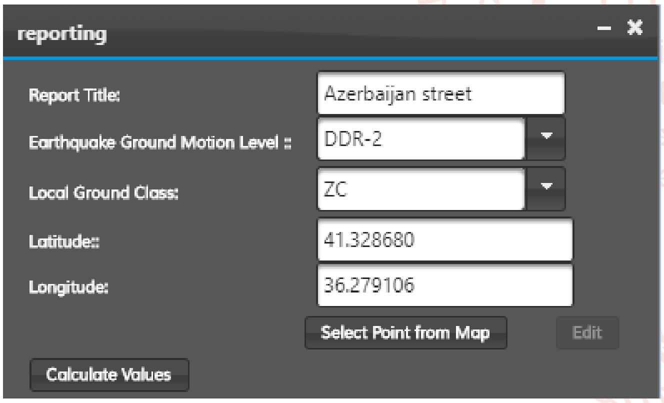
According to the graph of the ground borehole log and Vs velocities of the land from the soil analysis report made before in this location, the Local Ground Class is determined as ZC [11].

Table 4-3: Local Ground Classes

Local Ground Classes	Type of Ground	Average at the top 30 meters		
		$(V_s)_{30}[m/s]$	$(N_{60})_{30}$ $[darbe/30\,cm]$	$(c_u)_{30}$ $[kPa]$
ZA	Hard rocks	> 1500	-	-
ZB	Medium solid rocks	760 – 1500	-	-
ZC	Tight sand, gravel and hard clay layers or weak rocks with very cracks	360 – 760	> 50	> 250
ZD	Medium tight - layers of tight sand, gravel or very solid clay	180 – 360	15 – 50	70 – 250
ZE	Loose sand, gravel or soft - solid clay layers or profiles containing a total of more than 3 meters of soft clay layer (c_u <25 kPa) meeting PI> 20 and w> 40% conditions	< 180	< 15	< 70
ZF	Grounds requiring site specific research and evaluation: 1) Floors with a risk of collapse and potential collapse under the influence of an earthquake (liquefiable floors, highly sensitive clays, migrable weak cement floors, etc.), 2) Peat with a total thickness of more than 3 meters or clays with high organic content, 3) High plasticity (PI> 50) clays with a total thickness of more than 8 meters, 4) Very thick (> 35 m) soft or medium-solid clays.			

Seismic data for the four different levels of earthquake ground motion, is defined by the Earthquake Hazard Map of Turkey. These maps can be accessed from the website https://tdth.afad.gov.tr/

Local Ground Class ZC has been determined according to the earthquake ground motion level (DD-2) and the previous borehole information (based on the plot of ground drill log and Vs velocities) in this location according to the ground survey conducted earlier [15].



Received reports on the Turkey / Samsun / Atakum, Azerbaijan street; latitude: 41.328680, longitude: 36.279106 Map spectral acceleration coefficients (S_s , S_1) and design spectral acceleration coefficients (S_{DS} , S_{D1}) for DD-2 and DD-3 earthquake ground motion level It is stated below.

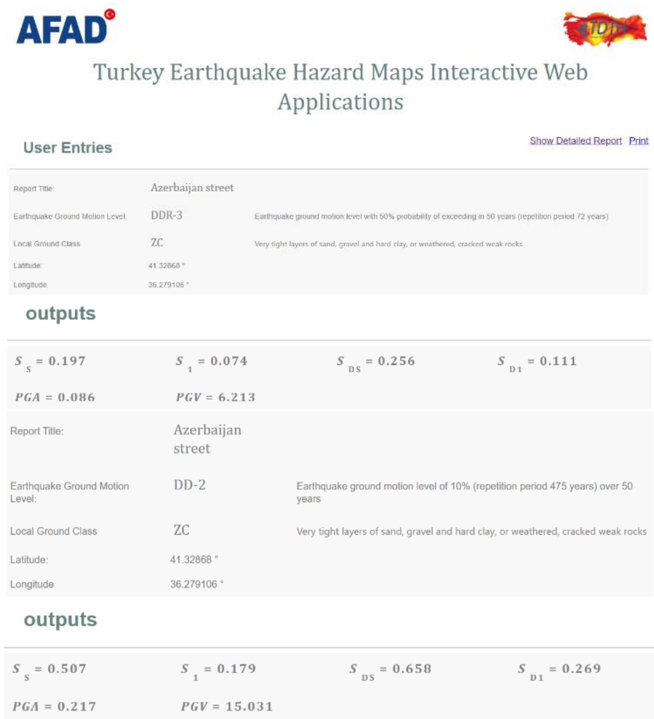


Figure 4-2: Turkey Earthquake Hazard Maps Interactive Web Applications

Since the structure usage purpose is Residential (Structure Usage Class) BKS = 3, (Structure importance factor) will be I = 1.0 (Table4-4)

Table 4-4: Structure Use Classes and Structure Importance Coefficients

Structure Usage Classes	Purpose of the Building	Structure importance factor (I)
BKS =1	**Buildings that need to be used after the earthquake, buildings where people are present for a long time and intensely, buildings where valuable goods are stored and buildings containing dangerous substances** a) Buildings that need to be used immediately after the earthquake (Hospitals, dispensaries, health centers, fire brigade buildings and facilities, and other) b) O Schools, other educational buildings and facilities, dormitories and dormitories, military barracks, prisons, etc. c) Museums d) Buildings where toxic explosive and flammable properties are stored	**1.5**
BKS =2	**Buildings where people are concentrated** Shopping centers, sports facilities, cinema, theater, concert halls, places of worship, etc.	**1.2**
BKS =3	Other buildings BKS=1 and BKS=2 buildings that do not fall within the definitions given for Residences, offices, hotels, building type industrial buildings, etc.)	**1.0**

On base above information DTS parameter was taken from the Table 4-5 as following.

Table 4-5: Earthquake Design Classes (DTS)

DD-2 Earthquake Ground Motion Level Short Period Design Spectral Acceleration Coefficient (S_{DS})	Structure Usage Classes	
	BKS =1	BKS =2 3
$S_{DS} \leq 0.33$	DTS= 4a	DTS= 4
$0.33 \leq S_{DS} < 0.50$	DTS= 3a	DTS= 3
$0.50 \leq S_{DS} < 0.75$	DTS= 2a	DTS= 2
$0.75 \leq S_{DS}$	DTS= 1a	DTS= 1

Since Earthquake Design Class is **DTS = 2**, Structure Height is **H~N~=9.75m**, Structure Height Class **BYS = 7** will be determined (Table 4-6).

Table 4-6: Structure Height Class (TBEC-2019 Table 3.3)

Structure Height Class	Building Height Classes and building Height Ranges Defined by Earthquake Design Classes [m]		
	DTS = 1, 1a, 2, 2a	DTS= 3, 3a	DTS 4, 4a
BYS =1	$H_N > 70$	$H_N > 91$	$H_N > 105$
BYS =2	$56 < H_N \leq 70$	$70 < H_N \leq 91$	$91 < H_N \leq 105$
BYS =3	$42 < H_N \leq 56$	$56 < H_N \leq 70$	$56 < H_N \leq 91$
BYS =4	$28 < H_N \leq 42$	$42 < H_N \leq 56$	
BYS =5	$17.5 < H_N \leq 28$	$28 < H_N \leq 42$	
BYS =6	$10.5 < H_N \leq 17.5$	$17.5 < H_N \leq 28$	
BYS =7	$7 < H_N \leq 10.5$	$10.5 < H_N \leq 17.5$	
BYS =8	$H_N \leq 7$	$H_N \leq 10.5$	

Table 4-7: Performance Targets for New or Existing Structures According to Earthquake Design Classes

Earthquake ground motion level	$DTS = 1, 1a^{(1)}, 2, 2a^{(1)}, 3, 3a, 4, 4a$		$DTS = 1a^{(2)}, 2a^{(2)}$	
	Normal Performance Target	Evaluation / Design Approach	Advanced Performance Target	Evaluation / Design Approach
DD-3	–	–	IO	ŞGDT
DD-2	LS	$DGT^{(5)}$	LS	$DBS^{(3,4)}$
DD-1	–	–	LS	ŞGDT

Since the Earthquake Design Class is DTS = 2, DD-2 needs to meet the Life Safety (LS) performance target under the action of the earthquake ground motion.

Based on Earthquake Ground Motion Level DD-2 and Earthquake Design Class DTS-2 information, the performance target of the sample building is determined as Life Safety-LS from the relevant regulation [11].

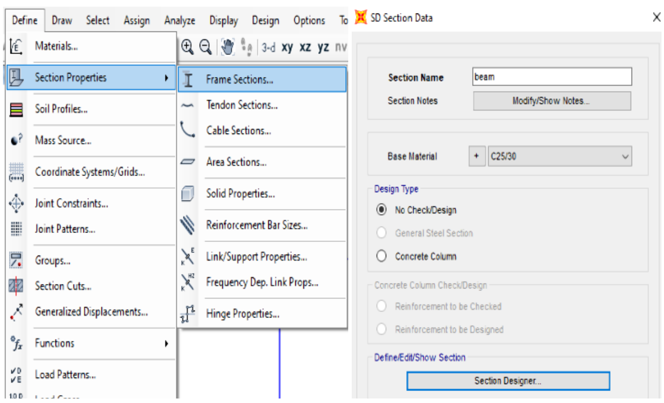
In accordance with this performance target, the plastic rotations of the sample building's columns and beams are calculated according to the formulas in the related table of the regulation [11]. In the presented study, the plastic rotations of the sample building columns and beams are calculated based on the mechanical properties of columns, beam sections, reinforcement, concrete in Table 4-1, 4-2.

5. RESEARCH METHOD AND NUMERICAL MODELLING

A. The Properties of Beam Plastic Hinge

In order to define the behaviour of plastic joints, the properties of the cross sections of the tested frame were calculated.

Entering the moment and curvature values of the beams into Sap 2000 software, after drawing the beam sections according to the minimum reinforcement conditions in the "Define / Section Properties / Frame Sections ... / SD Section Data / Section Designer ..." Moment and curvature values of the beam are determined (Figure 5-1):



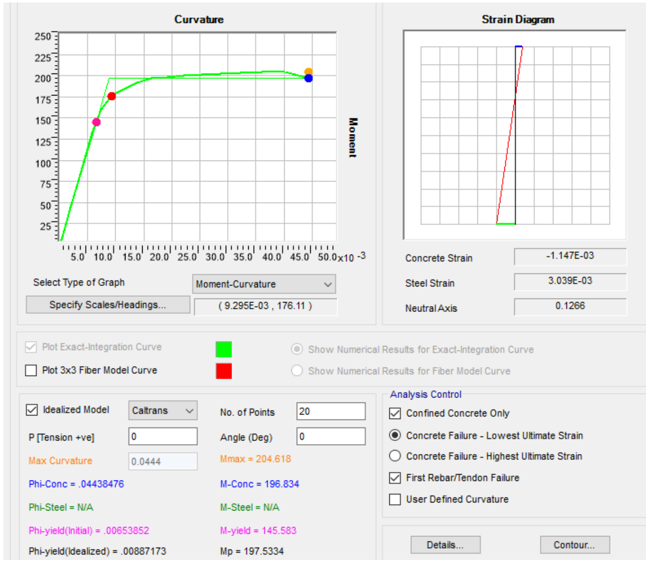


Figure 5-1: The values of Moment-Curvature at beam

As a result of the analysis (Figure 5-1)
$\Phi_u = 0.0444 \; \Phi_y = 0.006538$

Here Φ_u is max curvature, Φ_y is yield curvature show the total curvature before the collapse, taking into account the unit deformations of concrete and reinforcing steel and also the axial force acting on the section [11].

The length (Lp) of the plastic deformation zone, called the plastic hinge length shall be taken equal to half of the sectional dimension (h = 0.5 m) in the direction [11].
Lp = 0.5/ 2 = 0.25

Ls-is the shear length (ratio of moment / shear force in the section). Approximately half of the span can be taken in columns and beams [11].

For beams in the sample light presented
Ls = 4 / 2 = 2;

For the columns
Ls = 3.25 / 2 = 1.6;

The d_b value a represents the pull out of the reinforcement for the yielding state and shows the average diameter of the reinforcing steels attached to the support (at node or on foundation).
$d_b = 0.016$

In TBEC-2019 (Section 5.8) a η = 1 in beams and columns and η= 2 in shear wall [11].

f_{ye} and f_{cc} show the average (expected) compressive strength of concrete and the average yield strength of the reinforcement (Table 5-1) [17].

Table 5-1: Average strength of the material.

Concrete(C25)	$f_{cc} = 1.3 f_{ck} = 1.3 \cdot 25 = 32.5$
Rebar(S420)	$f_{ye} = 1.2 f_{yk} = 1.2 \cdot 420 = 504$

In accordance with the equations in TBEC-2019 Section 5.8, by using the Φ_u and Φ_y values, plastic hinge length(L_p) ,shear span (L_s), pullout reinforcement (d_b) the permitted plastic rotation limits and yield rotation according to various cross-section damage limits are calculated as follows in the reinforced concrete column elements where plastic deformations occur [11].

➢ Plastic Rotation Limit

The allowable plastic rotation limit for the Collapse Prevention (CP) Performance Level was calculated in accordance with the equations specified in TBEC-2019 (Section 5.8).

$$\theta_P^{(CP)} = \frac{2}{3}\left[(\Phi_u + \Phi_y)L_p\left(1 - 0.5\frac{L_p}{L_s}\right) + 4.5\Phi_u d_b\right] = \frac{2}{3}\left[(0.0444 + 0.006538)0.25\left(1 - 0.5\frac{0.25}{2}\right) + 4.5 \cdot 0.0444 \cdot 0.016\right] = 0.010$$

The permitted plastic rotation limit for the Life Safety (LS) Performance Level has been calculated based on the values defined in the Immediate Occupancy (IO) performance level [11].

$$\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0076$$
$$\theta_P^{(IO)} = 0$$

➢ Yield Rotation

Plastic hinge yield rotation is calculated below according to the equation in TBEC-2019 Section 5.4 [11].

$$\theta_y = \frac{\Phi_y L_s}{3} + 0.0015\eta\left(1 + 1.5\frac{h}{L_s}\right) + \frac{\Phi_y d_b f_{ye}}{8\sqrt{f_{cc}}}$$

$$= \frac{0.0065 \cdot 2}{3} + 0.0015 \cdot 1\left(1 + 1.5\frac{0.5}{2}\right) + \frac{0.0065 \cdot 0.016 \cdot 32.5}{8\sqrt{504}} = 0.0064\,m$$

As seen in Figure 5-2, it is possible to express the behavior of an element by determining the coordinates of some points on the curve (such as B, C, D and E). Then, the moment-rotation angle relation of the cross-section known as the stress-strain relationship can be obtained. This curve is idealized in the Figure shown in Figure 5-2 by accepting the amount of reinforcement in the section and certain deformation values for the reinforcement as limit values [18].

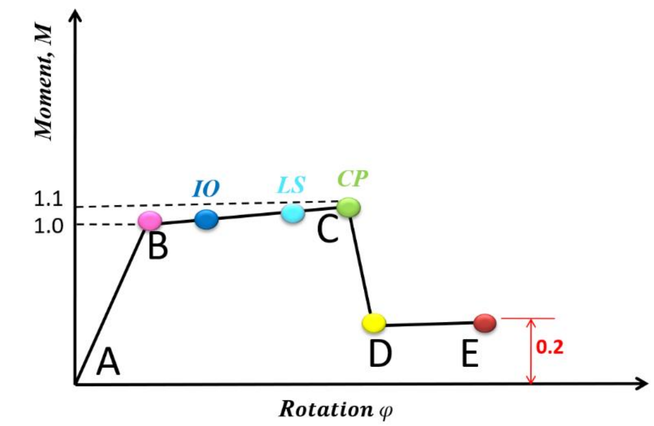


Figure 5-2: Typical Moment-Curvature curve of reinforced concrete element

Based on the Moment-rotation relations (Figure 5-1), according to the value of My = 145.583kNm (My = Myield), the yielding moment (Mb, Mc, Md, Me) in accordance with the performance levels in the above graphical relationship values are calculated as follows:

$$M_y = 145.583\,kNm$$
$$M_B = M_y = 145.583\,kNm$$
$$M_C = M_y + 0.1M_y = 145.583 + 0.1 \cdot 145.583 = 160.14\,kNm$$
$$M_D = 0.2M_y = 0.2 \cdot 145.583 = 29.12\,kNm$$
$$M_E = M_D = 0.2 \cdot 145.583 = 29.12\,kNm$$

In accordance with the equations $\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0076$ and $\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0076$ specified in TBEC-2019 (Section 5.8), the angle of rotation ($\varphi_B, \varphi_C, \varphi_D, \varphi_E$)for the points B, C, D, E suitable for the yield moment values (M_B, M_C, M_D, M_E)according to performance levels in the graphical relationship in Figure 5-2 are calculated below.

$$\varphi_y = \Phi_y \cdot L_p = 0.006538 \cdot 0.25 = 0.0016\,rad$$
$$\varphi_B = \varphi_y = 0.0016 \text{ rad}$$
$$\varphi_C = \varphi_B + \theta_P^{(LS)} = 0.001635 + 0.0113 = 0.0092 \text{ rad}$$
$$\varphi_D = \varphi_C = 0.0092\,rad$$
$$\varphi_E = \varphi_B + \theta_P^{(CP)} = 0.001635 + 0.01534 = 0.0117\text{rad}$$

Moment/SF

$$B = M_B/M_y = 145.583/145.583 = 1$$
$$C = M_C/M_y = 160.14/145.583 = 1.1$$
$$D = M_D/M_y = 29.12/145.583 = 0.2$$
$$E = M_E/M_y = 29.12/145.583 = 0.2$$

Rotation /SF

$$B = \varphi_B/\varphi_Y = 0.001635/0.001635 = 1$$
$$C = \varphi_C/\varphi_Y = 0.012935/0.001635 = 5.6286$$
$$D = \varphi_D/\varphi_Y = 0.012935/0.001635 = 5.6286$$
$$E = \varphi_E/\varphi_Y = 0.016975/0.001635 = 7.1714$$

For the points B, C, D, E by calculating the values above, the hinge properties calculated as multiples of the yield rotation and yield moment in the SAP 2000 software "Frame Hinge Property data for beam" Tab (Figure 5-3) was entered.

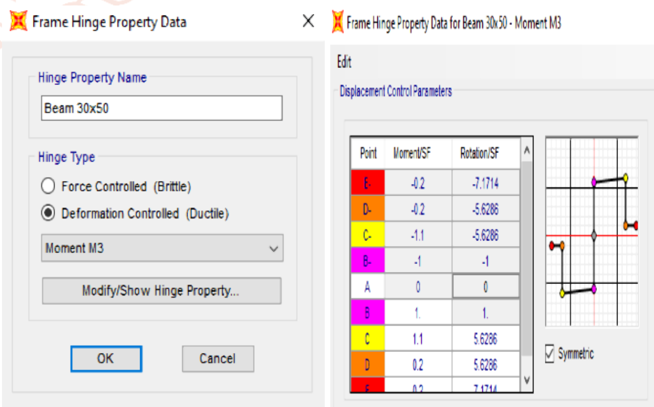


Figure 5-3: Visual illustration of frame hinge property Data for Beam -Moment M3

Since there is no axial force in beams, moment is defined as M3 joint. Plastic hinge properties are determined in the structure elements whose moment-curvature relations and yield surfaces are determined in accordance with the data entry method in SAP2000 software. It is accepted that element deformations are concentrated at the ends and plastic joints are defined in these sections.

SAP2000 in plastic hinge definitions for frame elements FEMA-356 (Federal Emergency Management Agency) and ATC-40 (Applied Technology Council) Plastic hinge approaches prepared by can be automatically taken into sections.

Since the relevant part of TBEC-2019 should not be added here in SAP2000 20.0 version, the related formulas ($\theta_P^{(LS)}$ *and* $\theta_P^{(CP)}$) Angle of rotation ($\varphi_B, \varphi_C, \varphi_D, \varphi_E$) and the relevant yield moments(M_B, M_C, M_D, M_E) were manually entered.

B. The Properties of Column Plastic Hinge

In columns, entering the moment and curvature values into the software is different than the beams. Entering moment and curvature values of columns into Sap 2000 software in "Define/Section Properties/Frame Sections.../ SD Section Data/ Section Designer..." after column sections are drawn according to minimum reinforcement conditions moment and curvature values of the column drawn with the tab are determined (Figure 5-4):

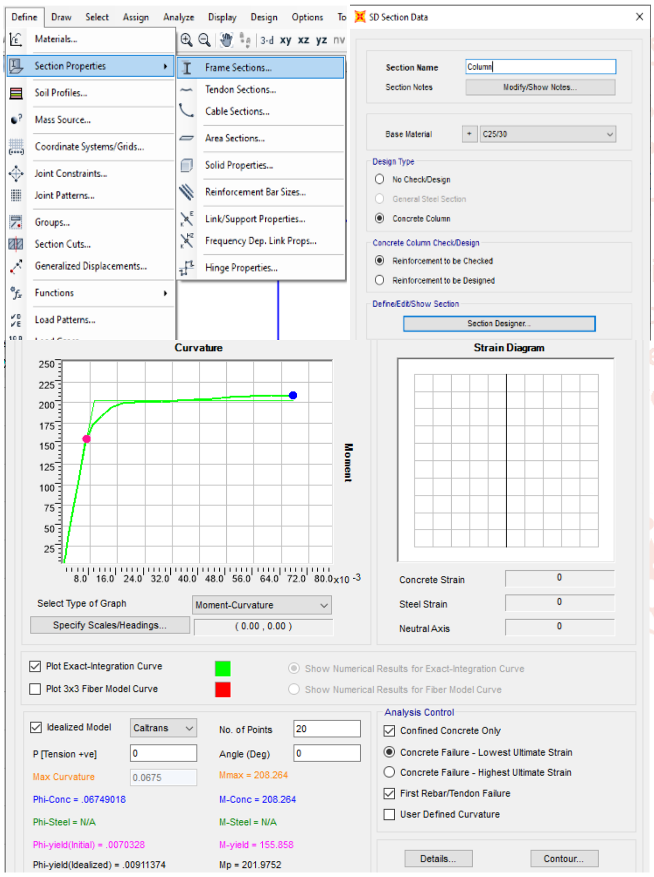


Figure 5-4: The values of Moment-Curvature at column

The values obtained by the analysis are (Figure 5-3)
$\Phi_u = 0.0675 \; \Phi_y = 0.0070$

Here Φ_u is max curvature, Φ_y is yield curvature show the total curvature before the collapse, taking into account the unit deformations of concrete and reinforcing steel and also the axial force acting on the section [11].

The length (Lp) of the plastic deformation zone, called the plastic hinge length shall be taken equal to half of the sectional dimension (h = 0.5 m) in the direction [11].
Lp = 0.5/ 2 = 0.25

Ls-is the shear length (ratio of moment / shear force in the section). Approximately half of the span can be taken in columns and beams [11].

For the columns
Ls = 3.25 / 2 = 1.6;

The d_b value a represents the pullout of the reinforcement for the yielding state and shows the average diameter of the reinforcing steels attached to the support (at node or on foundation).
$d_b = 0.016$

In TBEC-2019 (Section 5.8) a η = 1 in beams and columns and η= 0,5 in shear wall [11].

f_{ye} *and* f_{cc} show the average (expected) compressive strength of concrete and the average yield strength of the reinforcement (Table 5-1) [17].

In accordance with the equations in TBEC-2019 Section 5.8, by using the Φ_u *and* Φ_y values, plastic hinge length(L_p) ,shear span (L_s), pull-out reinforcement (d_b) the permitted plastic rotation limits and yield rotation according to various cross-section damage limits are calculated as follows in the reinforced concrete column elements where plastic deformations occur [11].

➢ **Plastic Rotation Limit**

The allowable plastic rotation limit for the Collapse Prevention (CP) Performance Level was calculated in accordance with the equations specified in TBEC-2019 (Section 5.8).

$$\theta_P^{(CP)} = \frac{2}{3}\left[(\Phi_u + \Phi_y)L_p\left(1 - 0.5\frac{L_p}{L_s}\right) + 4.5\Phi_u d_b\right]$$
$$= \frac{2}{3}\left[(0.0675 + 0.0070)0.2\left(1 - 0.5\frac{0.2}{1.6}\right) + 4.5 \cdot 0.0675 \cdot 0.016\right] = 0.0127$$

The permitted plastic rotation limit for the Life Safety (LS) Performance Level has been calculated based on the values defined in the İmmediate Occupancy (IO) performance level [11].

$$\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0095$$
$$\theta_P^{(IO)} = 0$$

➢ **Yield Rotation**

Plastic hinge yield rotation is calculated below according to the equation in TBEC-2019 Section 5.4 [11].

$$\theta_y = \frac{\Phi_y L_s}{3} + 0.0015\eta\left(1 + 1.5\frac{h}{L_s}\right) + \frac{\Phi_y d_b f_{ye}}{8\sqrt{fcc}}$$
$$= \frac{0.0070 \cdot 2}{3} + 0.0015 \cdot 1\left(1 + 1.5\frac{0.4}{1.6}\right) + \frac{0.0070 \cdot 0.016 \cdot 32.5}{8\sqrt{504}} = 0.0067$$

As seen in Figure 5-2, it is possible to express the behavior of an element by determining the coordinates of some points on the curve (such as B, C, D and E). Then, the moment-rotation angle relation of the cross-section known as the stress-strain relationship can be obtained. This curve is idealized in the Figure shown in Figure 5-2 by accepting the amount of reinforcement in the section and certain deformation values for the reinforcement as limit values [18].

➢ **Moment-Rotation relations**

Based on the Moment-rotation relations (Figure 5-3), according to the value of My = 155.858 kNm (My = Myield), the yielding moment (Mb, Mc, Md, Me) in accordance with the performance levels in the above graphical relationship values are calculated as follows:

$M_y = 155.858\ kNm$
$M_B = 155.858\ kNm$
$M_C = 155.858 + 0.1 \cdot 155.858 = 171.44\ kNm$
$M_D = 0.2 \cdot 155.858 = 31.17\ kNm$
$M_E = M_D = 0.2 \cdot 155.858 = 31.17\ kNm$

In accordance with the equations $\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0076$ and $\theta_P^{(LS)} = 0.75\theta_P^{(CP)} = 0.0076$ specified in TBEC-2019 (Section 5.8), the angle of rotation ($\varphi_B, \varphi_C, \varphi_D, \varphi_E$)for the points B, C, D, E suitable for the yield moment values (M_B, M_C, M_D, M_E)according to performance levels in the graphical relationship in Figure 5-2 are calculated below.

$\varphi_y = \Phi_y \cdot L_p = 0.0070 \cdot 0.2 = 0.0014\ \varphi_B = \varphi_y = 0.0014 \varphi_C = \varphi_B + \theta_P^{(LS)} = 0.0109 \varphi_D = \varphi_C = 0.0109$
$\varphi_E = \varphi_B + \theta_P^{(CP)} = 0.0141$
to the reviews above

Moment/SF
$B = M_B/M_y = 155.858/155.858 = 1$
$C = M_C/M_y = 171.44/155.858 = 1.1$
$D = M_D/M_y = 31.17/155.858 = 0.2$
$E = M_E/M_y = 31.17/155.858 = 0.2$

Rotation /SF
$B = \varphi_B/\varphi_Y = 0.0014/0.0014 = 1$
$C = \varphi_C/\varphi_Y = 0.0125/0.0014 = 7.7911$
$D = \varphi_D/\varphi_Y = 0.0125/0.0014 = 7.7911$
$E = \varphi_E/\varphi_Y = 0.0162/0.0014 = 10.0548$

For the points B, C, D, E values, the hinge properties calculated as the multiples of the moment of yield rotation and the moment of yielding are calculated in multiples of the "Frame Hinge Property data for beam" tab in Sap 2000 software (Figure 5-4) entered

The columns are under axial force, they are defined as P-M2-M3 joints (Figure 5-4).

Moment and curvature values are converted to “Moment/Yield Moment” and “Rotation/SF” coefficient values, which will be proportional to the curvature values corresponding to the yield moment.

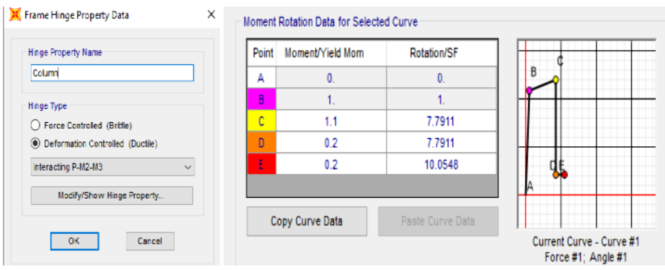


Figure 5-4: Visual illustration of frame hinge property Data for Column

Based on the above information, the Pushover analysis was carried out in comparison with the SAP2000 [16] and AASEM [14] software on the basis of the finite element method to achieve the Life Safety-LS performance target. The column, beam classification of the structure frame finite elements and the plastic hinge properties at the ends were entered as shown in Figure 5-2 and Figure 5-4 in the SAP2000 software based on the information in sections a and b.

6. PUSHOVER ANALYSIS MADE ACCORDING TO THE PBD INPUT INFORMATION IN THE CURRENT REGULATION TBEC-2019 IN LINE WITH THE PERFORMANCE CRITERIA

According to the results of the analysis, plastic joints formed in the structure are shown in Figure 6.1.

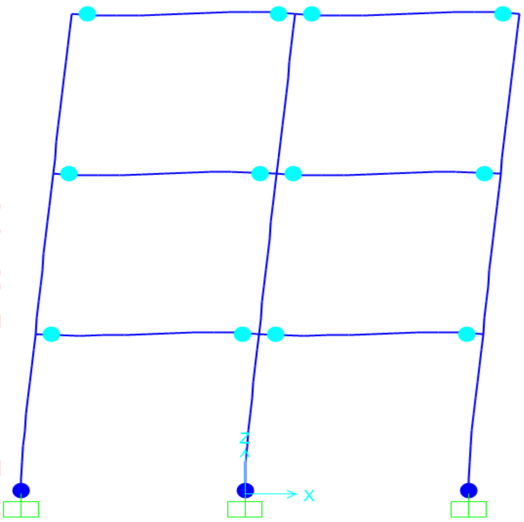


Figure 6-1: Location of plastic hinges formed in the sample building and their corresponding performance levels. (IO – dark blue; LS -blue)

Table 6-1: Performance levels equivalent to beam and column plastic hinges

Performance Level					Total plastic hinges number
B	IO (Dark Blue)	LS (Blue)	CP	C	
0	3	12	0	0	15

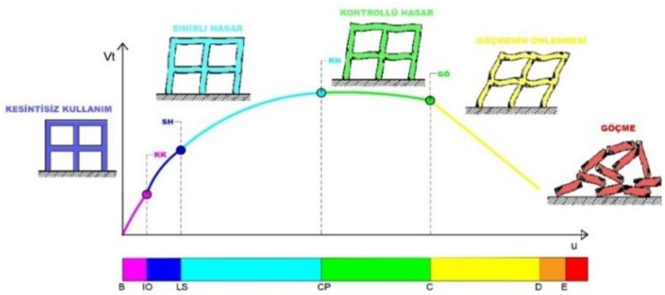
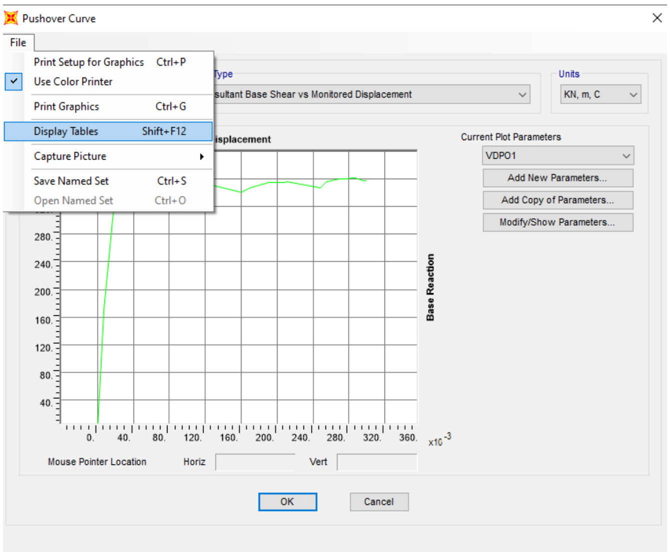


Figure 6-2: Display of calculated performance levels of the sample building (Operational -B, İmmediate-Occupancy- IO, Life-Safety- LS, Collapse-Prevention-CP, Collapse-C) depending on displacement (u) and base shear force (Vt)

in Figure 6-3 the maximum bearing force capacity Vt = 229.057 kN in accordance with the performance condition shown in Figure 6-1 is presented



Pushover Capacity Curve

File View Edit Format-Filter-Sort Select Options

Units: As Noted

Filter:

LoadCase Text	Step Unitless	Displacement	BaseForce KN	AtoB Unitless
Pushover	0	-2.9E-05	0	
Pushover	1	0.001723	34.895	
Pushover	2	0.003569	62.755	
Pushover	3	0.015411	174.717	
Pushover	4	0.019694	197.231	
Pushover	5	0.029833	222.216	
Pushover	6	0.040477	230.434	
Pushover	7	0.045119	232.544	
Pushover	8	0.119015	227.444	
Pushover	9	0.192004	229.057	
Pushover	10	0.265902	233.101	
Pushover	11	0.302663	237.043	
Pushover	12	0.376974	236.969	
Pushover	13	0.414361	240.19	
Pushover	14	0.423619	240.589	

Figure 6-3: Values obtained in Sap2000 software

As it is seen, the bearing capacity of the building has been obtained as 229.057 kN as a result of examining the building with PBD method in accordance with the relevant regulation, and the target performance has been formed at the level of LS.

7. CONTROL OF RELATIVE FLOOR DISPLACEMENT ACCORDING TO TBEC-2019 REGULATION

A. Calculation of empirical main natural vibration period and elastic design spectral acceleration

In structures with DTS = 1, 1a, 2, 2a and BYS ≥ 6, the empirical main natural vibration period is calculated according to TBEC-2019 Chapter 4 as below.

Buildings whose load bearing structural system consists of only reinforced concrete frames $C_1 = 0.1$

$$T_{pA} = C_1 H_N^{3/4} = 0.1 \cdot 9.75^{3/4} = 0.5517\ sec\ (T_B \le T \le T_L)$$

Calculation of elastic design spectral acceleration for DD2-Earthquake ground motion level

$$S_{ae}^{DD2}(T) = \frac{S_{D1}}{T} = \frac{0.269}{0.5517} = 0.4875$$

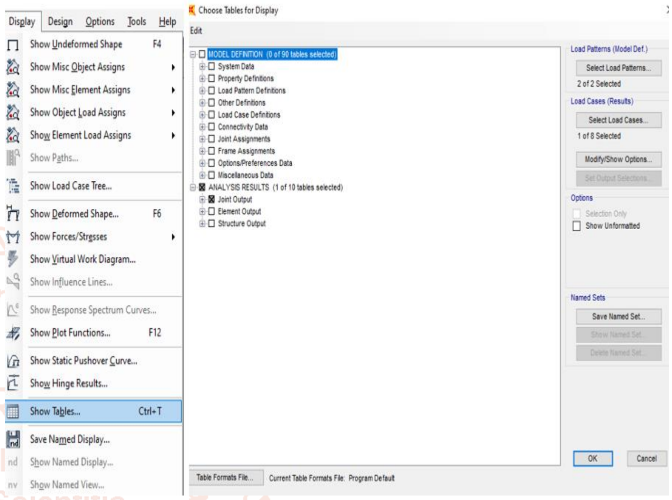
Calculation of elastic design spectral acceleration for DD3-Earthquake ground motion level

$$S_{ae}^{DD3}(T) = \frac{S_{D1}}{T} = \frac{0.111}{0.5517} = 0.2012$$

B. Control of relative floor displacement

As a result of the analysis made in Sap2000, according to the article 4.9.1 of the TBEC-2019, the reduced relative floor displacement for the typical (X) earthquake direction, which represents the displacement difference between the two floors, is shown as below

(In Sap2000 software, after selecting the end points of the columns for each floor, the Display-Show Tables-Choose Tables for Display tab is used.)



(The highest displacement (U max) for each floor is chosen in mm.)

Joint Displacements

File View Edit Format-Filter-Sort Select Options

Units: As Noted Joint Displacements

Filter:

Joint Text	OutputCase	CaseType Text	U1 m
8	Yatay	LinStatic	0.001164
5	Yatay	LinStatic	0.001169
2	Yatay	LinStatic	0.001172

$$\Delta_1^{(X)} = 1.164$$

Joint Displacements

File View Edit Format-Filter-Sort Select Options

Units: As Noted

Filter:

Joint Text	OutputCase	CaseType Text	U1 m
3	Yatay	LinStatic	0.002455
6	Yatay	LinStatic	0.002443
9	Yatay	LinStatic	0.002439

$$\Delta_2^{(X)} = 2.445$$

Joint Displacements

File View Edit Format-Filter-Sort Select Options

Units: As Noted

Filter:

Joint Text	OutputCase	CaseType Text	U1 m
10	Yatay	LinStatic	0.003268
11	Yatay	LinStatic	0.00325
12	Yatay	LinStatic	0.003244

$$\Delta_3^{(X)} = 3.268$$

Earthquake load reduction coefficient will be R = 4, Structure significance coefficient I = 1 according to TBEC-2019 Table 4.1.

For the typical (X) earthquake direction, the relative story displacement of the columns $\delta_i^{(X)}$was achieved according to TBEC-2019 Section 4.9.1.2 [11].

$$\delta_i^{(X)} = \frac{R}{I}\Delta_i^{(X)}$$
$$\delta_1^{(X)} = \frac{R}{I}\Delta_1^{(X)} = \frac{4}{1}1.164 = 4.656$$
$$\delta_2^{(X)} = \frac{R}{I}\Delta_2^{(X)} = \frac{4}{1}2.445 = 9.78$$
$$\delta_3^{(X)} = \frac{R}{I}\Delta_3^{(X)} = \frac{4}{1}3.268 = 13.072$$

λ-The coefficient is the ratio of the elastic design spectral acceleration of the DD-3 earthquake ground motion to the elastic design spectral acceleration of the DD-2 earthquake ground motion, defined for the prevailing vibration period in the direction of the earthquake in the structure [11].

$$\lambda = \frac{S_{ae}^{DD3}}{S_{ae}^{DD2}} = \frac{0.2012}{0.4875} = 0.417818$$

Relative floor offset control in the structure according to TBEC-2019 Section 4.9.1.3

k-coefficient will be taken as k = 1 in reinforced concrete buildings and k = 0.5 in steel buildings. h-3250 mm and indicates the height of the column [11].

$$\lambda\frac{\delta_i^{(X)}}{h} \leq 0.008k$$
$$\lambda\frac{\delta_1^{(X)}}{h} = 0.417818\frac{4.656}{3250} = 0.000591 \leq 0.008\,\surd$$
$$\lambda\frac{\delta_2^{(X)}}{h} = 0.417818\frac{9.78}{3250} = 0.001242 \leq 0.008\,\surd$$
$$\lambda\frac{\delta_3^{(X)}}{h} = 0.417818\frac{13.072}{3250} = 0.001660 \leq 0.008\,\surd$$

As can be seen, relative floor offset on all floors met the condition specified in the regulation.

8. PUSHOVER ANALYSIS ON THE BASIS OF THE NEW PERFORMANCE CRITERION AND PBD INFORMATION OF TBEC-2019

In addition to the existing design criteria in the presented study, “to increase the number of plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by regulation” new criteria addition results are shown below.

In short: 1) to increase the number of plastic hinges to be formed in the building in line with the target performance (LS) to the number of theoretical plastic hinges as much as possible; and 2) It will be provided that these plastic joints to be formed mainly coincide with the target performance LS status.

Since the rigidity decreases throughout the height of the structure structure, it is preferred to reduce the cross-section or reinforcement of beams along the height of the structure to achieve the stated goal in this study (different ways can be chosen in the relevant aim but this is also an other research topic).

According to this information, building beam sections are reduced as in Table 8-2.

Table 8-2: Related changes after pre-sizing of the structure

Element		Height (cm)	Width(cm)
Column		46	40
Beam	B1, B2	50	30
	B3, B4	40	30
	B5, B6	35	30

On base above input information, PBD analysis results are presented below

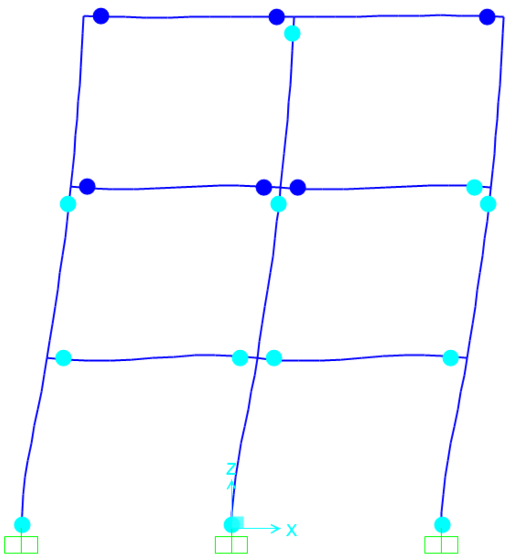


Figure 8-1: Plastic hinge in the structure as a result of pushover analysis.(IO – dark blue; LS -blue)

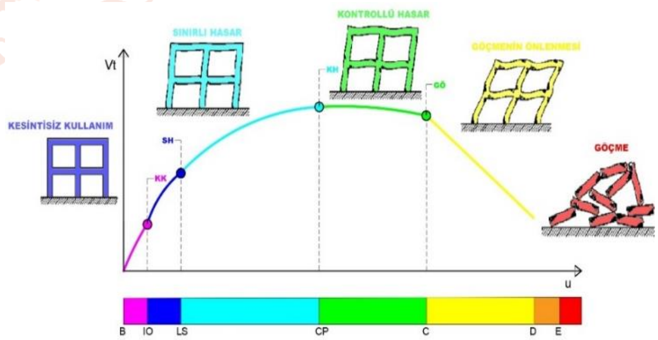


Figure 8-2: Display of calculated performance levels of the sample building (Operational -B, İmmediate-Occupancy- IO, Life-Safety- LS, Collapse-Prevention-CP, Collapse-C) depending on displacement (u) and base shear force (Vt)

Table 8-3: Performance levels equivalent to beam and column plastic hinges

Performance Level					Total plastic hinges number
B	IO (Dark Blue)	LS (Blue)	CP	C	
0	6	12	0	0	18

Keeping the structure below the previously targeted performance (the majority - at least more than 50% of the number of plastic hinges that will occur in the system coincides with the predetermined target performance), the pushover analysis results are presented in Figure 8.1, 8.3, and Table 8.3. Since it took place in the tenth step, the value corresponding to the tenth step (maximum bearing force capacity Vt = 343.621 kN, etc.) according to Sap 2000 software (Resultant Base shear vs Monitored Displacement) is shown in Figure 8-3.

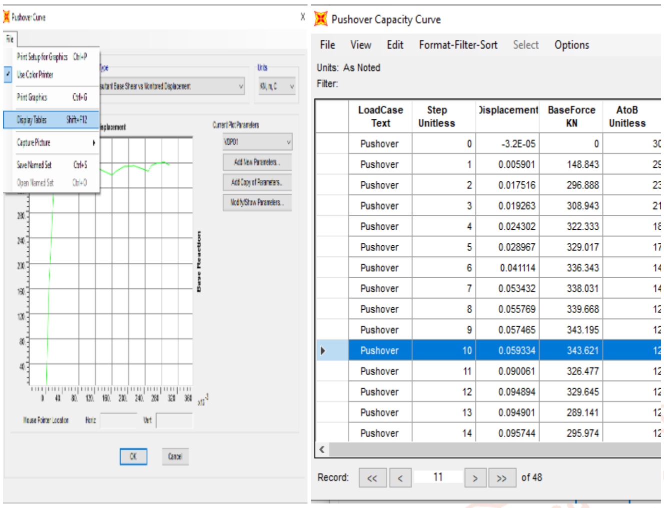


Figure 8-3: Values obtained in Sap2000 software

As can be seen, with the addition of the new design criteria of the structure as a result of the examination with PBD method in line with the regulation six plastic hinges (33% of total plastic hinges) formed at IO performance level, twelve plastic hinges (67% of total plastic hinges) formed at of performance LS level. Bearing capacity of the structure was obtained as Vt = 343.621kN.

With the addition of the new design criteria mentioned obtained by PBD method in structure example structure horizontal load carrying capacity (Vt = 343.621 kN) increased by 50% from the structure horizontal load carrying capacity (229.057 kN) obtained by PBD method with the current regulation. With the decrease in beam cross-section areas (and the amount of reinforcement proportional to this) by the height of the structure (on the 2nd floor, 20%, on the 3-floor 30%), the bearing system has become lighter and therefore more economical design has been achieved.

9. CONCLUSION

In addition to the existing design criteria in the presented study, "to increase the number of plastic hinges to be formed in the structure as much as possible and to keep the structure below its targeted performance by regulation" new criteria addition results are shown below:

- As a result of the analysis, with the addition of the new design criteria, the building horizontal load carrying capacity obtained by the PBD method has increased by 50% from the building horizontal load carrying capacity obtained by the PBD method in the current regulation.
- Parallel to this, with the decrease in beam section areas (and the amount of reinforcement proportional to this) by the height of the structure (2-floor, 20%, and 3-floor 30%), the bearing system has become lighter and therefore more economical design has been achieved.

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