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Research Article

Non-linear displacement and deformation damage limits of reinforced concrete circular columns by analytical observations according to TBSC 2018

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ABSTRACT

In the study, based on the non-linear calculation methods used to determine the seismic performance of structures in TBSC 2018, the stress-strain, moment-curvature, displacement capacity, plastic rotation limits, and deformation-based damage limit values of the reinforced concrete circular cross-section columns were calculated and compared according to different design parameters. The studied effects of the design parameters on the non-linear relation of reinforced concrete columns were also evaluated in terms of strength, curvature, and displacement ductility of the sections. All design parameters affecting the non-linear behavior and deformation limits of the reinforced concrete circular cross-section columns were taken into account. Deformation demands for reinforced concrete structural members are essential for detecting element damage. Based on TBSC (2018), non-linear relationships of reinforced concrete columns were obtained in order to calculate plastic hinge properties and deformation limits. For the Limited Damage, Controlled Damage, and Collapse Prevention performance levels defined for the structural elements in TBSC 2018, plastic rotation and deformation limit values were obtained according to the characteristic values calculated from the non-linear analyzes of reinforced concrete circular columns. For column models, damage limits and damage zones calculated based on TBSC 2018 were shown on the visually obtained moment-curvature relationships. Depending on the upper deformation limit values derived, cross-sectional deformation damage levels were determined and evaluated using the moment-curvature relationships. The variation of the non-linear behavior of column models by design parameters and deformation-based damage limits were examined both analytically and visually. The deformation limits remain in a safer direction as a result of increasing longitudinal and spiral reinforcement ratios for the reinforced concrete circular columns.

1. Introduction

In determining the earthquake safety of existing building systems, using methods that predict performance analysis is considered more appropriate. By using these methods based on the non-linear theory, the behavior of building systems under external loads and earthquake effects can be predicted, and earthquake performances due to displacements and deformations can be determined more realistically [1-2]. The performance-based design of reinforced concrete (RC) structures involves the designing of structures by calculating specific structural performance or damage limits using deformation-based methods under the influence of earthquakes. The deformation-based design method takes into account the non-linear behavior of the materials that make up the RC structural members [3]. This method is very important in terms of providing the desired life safety performance target and criteria without a decrease in load carrying capacity under the effect of earthquake loads applied to RC structural elements [4]. Ductility of carrier elements is an important parameter in terms of structural safety. The ductility of the carrier elements that make up RC structures is the property that allows the structures to dissipate energy in the seismic region [5-6]. To be able to understand and realize the ductile seismic design of RC structures better, it is necessary to estimate the deformation capacity of structural bearing elements under effective earthquakes [7]. Many of the building collapses that have occurred in the past have been caused by insufficient column behavior. The main causes of column failures in buildings are shear failure and insufficient ductility capacity. In the performance assessment methods of existing structures, seismic codes generally determine the performance of

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structural elements on their plastic rotational capacities [8-10]. In the regulations, the damage limits that determine the performance are determined by taking into account the plastic rotations calculated by considering the material deformation limits [11].

Whereas strength-based seismic design focuses on the estimation of internal forces, performance-based design focuses on the estimation of deformations [12]. The deformation-based design and assessment method is more advantageous than the strength-based design method because it allows taking into account the non-linear behavior of the material. The purpose of the deformation-based design and assessment methods to be used to determine the structural performance of RC structures under earthquakes is to calculate the internal force demands for brittle behavior and the deformation demands for ductile behavior [1, 3, 13-14]. It is very important to know the behavior of RC columns under earthquake effects and to calculate the column damage limits for this behavior. The damage limits used in determining the performance can be calculated based on the amount of plastic rotation in the sections. Plastic rotation amounts are determined according to the deformation limits of the materials that make up the structure [15-21].

Guidelines and codes have been prepared recently to provide procedures and acceptance criteria for the seismic design and assessment of RC buildings. The Turkish Building Seismic Code (TBSC) [11] is among the most recent ones containing sections on the seismic assessment of existing and newly constructed RC buildings. In the TBSC code, assessment and acceptance criteria are given on the basis of the elements that make up the structural system. The performance level evaluations of load-bearing elements are generally made according to the performance-based displacement capacities determined for the members. These deformation limits depend on the dominant behavior mode of the members. In the existing codes issued for the seismic evaluation of RC buildings, plastic rotation is adopted as the amount of deformation, and chord rotation is adopted as the measure of deformation. Unlike others, TBSC gives deformation limits in terms of strains [22].

Accurate analysis of the non-linear behavior of RC structural members has always been an important subject of study because it provides a reliable estimate of the capacity and performance of buildings under seismic and vertical load effects. According to TBSC [11], non-linear behaviors such as material strengths, reinforcement configuration in the section, stress-strain, moment-curvature relations, and plastic hinge properties are taken into account in the calculation of the deformation-based damage limits for different performance levels in RC structural elements. In addition, in TBSC, deformation-based damage limits and damage zones are calculated according to different performance levels for RC structural members [11].

In the study, non-linear inelastic calculation methods used to determine the earthquake performance of existing or newly built structures according to TBSC [11] were examined and stress-strain, moment-curvature, plastic rotation, and deformation-based damage limits of the designed RC circular column model were calculated. In order to obtain a more accurate simulation of the real structural behavior, non-linear moment-curvature relationships and stress-strain relationships of structural members should be investigated [23]. Based on TBSC [11], non-linear stress-strain, moment-curvature, and displacement relationships of the column sections to be considered in the analyses were first obtained in order to calculate the plastic rotation and deformation limit values. In previous studies, it has been observed that the moment-curvature, lateral force-peak displacement, curvature ductility, and displacement ductility behaviors of RC structural members are significantly affected by changes in the axial load, longitudinal and transverse reinforcement ratios [24-26]. It is known that the non-linear behavior of reinforced concrete structural members depends on many parameters such as axial load, concrete grade, displacement ductility, transverse and longitudinal reinforcement ratio, seismic performance level, and applied force-displacement history [27]. In the analyses, all the design parameters affecting the non-linear behavior such as axial load level, spiral reinforcement ratio, and concrete grade in RC circular columns were taken into account.

The basic philosophy in the design according to the deformation approach is based on the determination of the strength capacities of the elements that make up the structural system by non-linear analysis. The non-linear behavior of the designed RC column members was examined regarding the stress-strain obtained based on the real material behavior of concrete and reinforcing steel, and the moment-curvature relations according to different design parameters. Confined concrete strengths were calculated based on the Mander model [28] and the obtained stress-strain results were compared. Moment-curvature relations of RC columns were obtained with the SAP2000 [29] software by considering the non-linear behavior of concrete and reinforcing steel and presented graphically. Based on the characteristic values obtained from the non-linear analysis, damage limit values were calculated for the circular columns section. The plastic rotation and deformation limit values were calculated for the Limited Damage (SH), Controlled Damage (KH), and Collapse Prevention (GÖ) performance levels as defined in TBSC [11]. Based on the TBSC [11], deformation damage limits and damage regions were visually processed on the moment-curvature relations obtained for

RC columns. Thus, it was ensured that the deformation limits and regions to be monitored visually on the moment-curvature relations could be easily interpreted by the performance evaluation of the columns.

2. Permitted Deformation Limits According to TBSC

The damage limits calculated for different performance levels of RC structural members and the evaluation of damage status are very important in the performance-based seismic design of earthquake-resistant RC structures [30]. To be able to apply the life safety-oriented performance-based seismic design method of RC structures, it is necessary to quantify the seismic performance indexes for structural members [31]. In the performance assessment to be made in TBSC [11], SH, KH, and GÖ performance levels and damage limit values were defined for structural RC load-bearing elements. Regarding RC members, SH defines a limited amount of performance level, KH's strength can be achieved safely, and GÖ defines advanced non-linear behavior. For different performance levels, the limit values for reinforcing steel and concrete unit deformation according to the distributed plastic behavior model are given in Table 1. Plastic rotation limit values according to the lumped plastic behavior model for performance levels are given in Table 2. Plastic rotation values can be calculated based on the moment-curvature relations by taking into account the axial load level and material models in the load-bearing elements. The mechanical reinforcement ratio of the effective confining reinforcement (ω_{we}) is calculated as in Equation (1).

$$\omega_{we} = \alpha_{se}\rho_{sh,min}\frac{f_{ywe}}{f_{ce}}\,;\, f_{ywe}=1.2f_{yk}\,,\, f_{ce}=1.3f_{ck} \qquad (1)$$

where α_{se} is confinement effectiveness coefficient, $\rho_{sh,min}$ is volumetric spiral reinforcement ratio, f_{ywe} and f_{ce} are expected yield strength of reinforcement and expected compressive strength of concrete, f_{ck} is the compressive strength of unconfined concrete, and (f_{ck}=30-50MPa) and f_{yk} are yield strength of transverse reinforcement (f_{yk}=420MPa).

The confinement effectiveness coefficient of the circular confining reinforcement in circular cross-section elements is given in Equation (2) and the volumetric ratio of the spiral confining reinforcement is given in Equation (3). In these equations, s and A_{os} are spacing and area of spiral reinforcement, and D is the concrete core dimension to center line of perimeter spiral reinforcement. n=1 for spiral reinforcement.

$$\alpha_{se} = \left(1 - \frac{s}{2D}\right)^{n} \qquad (2)$$

$$\rho_{sh} = \frac{2A_{os}}{Ds} \qquad (3)$$

3. Non-linear Behavior of Reinforced Concrete Columns

According to TBSC [11], in the calculation of deformation and internal forces for different performance levels of RC structural elements, non-linear behavior such as material strengths, reinforcement configuration in cross-section, stress-strain, moment-curvature, displacement relationships, and plastic hinge properties are taken into account. Stress-strain relations proposed by Mander et al. [28] were used for unconfined and confined concrete models in the performance evaluation according to deformation with non-linear methods.

Table 1. Total unit deformations of concrete and reinforcing steel according to different performance levels [11]

Deformation Limits	Concrete	Reinforcement
GÖ	a) $\varepsilon_c^{(GÖ)} = 0.0035 + 0.04\sqrt{\omega_{we}} \le 0.018$ b) $\varepsilon_c^{(GÖ)} = 0.0035 + 0.07\sqrt{\omega_{we}} \le 0.018$	$\varepsilon_s^{(GÖ)} = 0.40\varepsilon_{su}$
KH	$\varepsilon_c^{(KH)} = 0.75\varepsilon_c^{(GÖ)}$	$\varepsilon_s^{(KH)} = 0.75\varepsilon_s^{(GÖ)}$
SH	$\varepsilon_c^{(SH)}$=0.0025	$\varepsilon_s^{(SH)}$=0.0075
a) rectangular columns, beams, and shear walls, b) Columns with circular cross-sections		

Table 2. Plastic rotations for different performance levels [11]

Deformation Limits	Plastic Rotations
GÖ	$\theta_p^{(GÖ)} = \frac{2}{3}\left[(\emptyset_u - \emptyset_y)L_p\left(1 - 0.5\frac{L_p}{L_s}\right) + 4.5\emptyset_u d_b\right]$
KH	$\theta_p^{(KH)} = 0.75\theta_p^{(GÖ)}$
SH	$\theta_p^{(SH)} = 0$
$\emptyset_u$; Maximum curvature, $\emptyset_y$; Yied curvature, L_p; Plastic hinge length, L_s; Shear span, d_b; longitudinal reinforcement diameters.	

The moment-curvature relations are required for the non-linear analysis of RC structures to predict section strength, stiffness, and ductility. For RC columns, the theoretical moment-curvature analysis can be done if the stress-strain relationships of both concrete and reinforcing steel are known. Accurate determination of the moment-curvature relationship of RC load-bearing elements is a reliable indicator of the load capacity of structures subjected to seismic loads [32].

In order to perform structural design under the influence of earthquakes and to examine the seismic behavior of the structure, first of all, the behavior of the materials and elements that make up the structure should be known. The behavior of the carrier element under the effect of simple flexural and normal force or only simple flexural can be examined by obtaining the moment-curvature relation, and the changes in ductility level and stiffness can be observed by looking at its behavior. The moment-curvature relations were calculated by considering the Mander unconfined and confined concrete model [28] and the material properties given for the reinforcing steel in Figure 2. The concrete model developed by Mander et al. [28] was used for unconfined and confined concrete models in the analysis of RC column models. According to the Mander model [28]; confinement effectiveness coefficient (k_e), Effective lateral confining stresses applied to core concrete in x and y directions (f'_{lx} and f'_{ly}), confined concrete compressive strength (f'_{cc}), and the corresponding strain at maximum concrete stress (ε_{cc}) can be calculated by Equations (4-7), respectively. The maximum compressive strain in the confined concrete (ε_{cu}) can be found by Equation (8). In the equation, ρ_s is the volumetric ratio of the total transverse reinforcement [33].

$$k_e = \left(1 - \sum_i^n \frac{(w'_i)^2}{6}\right)\left(1 - \frac{S'}{2b_c}\right)\left(1 - \frac{S'}{2d_c}\right) \Big/ (1 - \rho_{cc}) \quad (4)$$

$$f'_{lx} = k_e \frac{A_{sx}}{s.d_c} f_{yh} = k_e.f_{lx}$$
$$f'_{ly} = k_e \frac{A_{sy}}{s.b_c} f_{yh} = k_e.f_{ly} \quad (5)$$

$$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right) \quad (6)$$

$$\varepsilon_{cc} = \varepsilon_{co}\left[1 + 5\left(\frac{f'_{cc}}{f'_{co}} - 1\right)\right] \quad (7)$$

$$\varepsilon_{cu} = 0.004 + \frac{1.4\rho_s f_{yw}\varepsilon_{su}}{f'_{cc}} \quad (8)$$

For a comprehensive performance-based seismic assessment of existing or newly constructed RC framed structures, estimating the displacement capacity of the columns and their deformation relationships is crucial [34]. The displacement and deformation capacity of reinforced concrete columns are formed by sectional damage under seismic loads [35]. The displacement ductility of RC load-bearing members is an important parameter characterizing the seismic response of RC structures. Additionally, displacement ductility can be used to determine whether a structural design based on earthquake codes will achieve the main goal of seismic design [36].

The ductile deformation capacity of RC columns as resistant to the effects of lateral loads is an important factor for achieving a better seismic performance in structures. Reinforced concrete columns designed with sufficient ductility typically prevent brittle fracture of structures. Ductility is an important property in terms of the determination of whether the seismic response of structures is suitable for the initial targets for which they were designed. The seismic design and evaluation of structural members should not only focus on strength but should also take into account the ductility of the members. In order to better understand and evaluate the ductile seismic design, the deformation capacity of the structural elements under the effect of severe seismic loads should be calculated [24]. The performance evaluation methods taken into account in obtaining the non-linear displacement capacity of the structural elements can be calculated by considering the plastic hinge and the displacement-controlled seismic design method [25]. The catastrophic deterioration of the mechanical strength of columns at final displacements is an important factor in terms of the seismic collapse of RC structures. Accurately calculating the deterioration of the mechanical strength is critical for evaluating the seismic collapse capacity of structures [37]. Reinforced concrete columns are exposed to lateral displacements under gravity loads and severe earthquake effects, and major damages occur in the plastic hinge regions where non-linear deformations occur. Deformations occur in the plastic hinge regions of the structural elements. To calculate large lateral displacement capacities, the structural members must have a large curvature capacity in the plastic hinge region.

The plastic hinge method is used in the seismic design and performance evaluation of RC columns according to displacement-based. In RC structural members, the lumped plastic rotation values (θ_p) along the length of the plastic hinge (L_p) are calculated as shown in Equation (8). The bending displacement capacity (Δ_u) of RC columns is obtained as the sum of yield (Δ_y) and plastic displacements (Δ_p) (Equation 9). The term $(\emptyset_u - \emptyset_y)L_p$ in the equation refers to the plastic rotation based on the assumption of plastic curvature, where the plastic hinge region is stacked at its center. In RC columns, the plastic hinge length (L_p) shall be taken as half of the section height in the active direction ($L_p = 0{,}50h$). $\emptyset_y$ and $\emptyset_u$ are yield and ultimate curvature values, respectively (Figure 1).

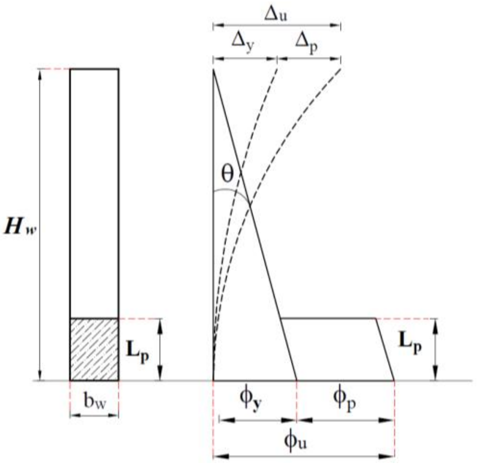

Figure 1. Theoretical model of elastic and plastic displacements in cantilever column

$$\theta_p = \varphi_p L_p = (\varphi_u - \varphi_y) L_p \tag{9}$$

$$\Delta_u = \frac{\varphi_y \times H_w^2}{3} + (\varphi_u - \varphi_y) L_p (H_w - 0.50 L_p) \tag{10}$$

4. Materials and Method

In this study, depending on the non-linear behavior and calculation methods, the seismic performance of RC column models was analytically investigated by considering the displacement capacity and the deformation-based damage limits. The displacement capacities are taken into account in the theoretical model of elastic and plastic displacements for the cantilever column. Deformation values for RC column models are calculated for SH, KH, and GÖ performance levels defined in TBSC [11]. Total unit deformation limits of concrete were calculated based on spiral ratios and plastic rotation limit values at axial loads, and they were examined for different performance levels. The unit deformations of reinforcing steel is calculated by multiplying the strain in reinforcement at ultimate strength with constant coefficients for different damage levels.

Circular cross-section columns are popular for column design of RC structures since their strength characteristics under seismic effects are similar in all directions. Therefore, circular column models with diameters of D=565mm and with the different concrete grades, spiral reinforcement diameters, spiral reinforcement spacing, and different axial loads were designed (Table 3 and Figure 2). How different design parameters such as material properties, axial load levels, rebar diameter, and spacing affected the non-linear behavior of the bearing elements and ductility criteria were calculated. Non-linear stress-strain, moment-curvature, and displacement capacity of RC columns were first obtained in order to calculate deformation limits and plastic hinge properties according to TBSC [11].

In RC column models, the total displacement values were obtained according to the yield, and plastic displacement values were calculated by taking into account the axial load levels acting on the section according to the plastic hinge length. For the calculation of the total peak displacement values of the RC columns, characteristic yield and ultimate curvature (pre-failure curvature) values were obtained from the section properties, plastic hinge length, and non-linear analysis. The results are presented and interpreted in tables and graphs. For RC circular cross-section columns, the deformation damage limits and damage regions obtained based on the TBSC [11] regulation are given visually on the moment-curvature relations. Thus, the deformation damage limits and regions to be monitored visually on the moment-curvature relations will be easily interpreted by the performance evaluation of the bearing elements. Elastic and plastic displacements of RC circular column models were analytically calculated based on the cantilever column model. Accordingly, deformation limits calculated according to TBSC [11] are valid for circular cantilever columns (column height, h=3500mm).

Table 3. Designed column section details

Material (MPa)	Spiral Reinforcement		Axial Load (N/N_{max})
	Diameters	spacing	
C30 C35 C40 C45 C50	Φ8mm Φ10mm Φ12mm	50mm 55mm 60mm 65mm 70mm 75mm 80mm	0.10 0.20 0.30 0.40

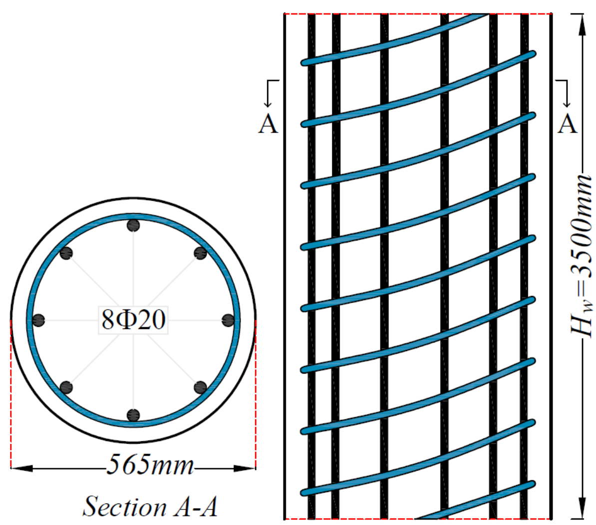

Figure 2. Sectional geometry and reinforcement layout view of the designed RC circular columns

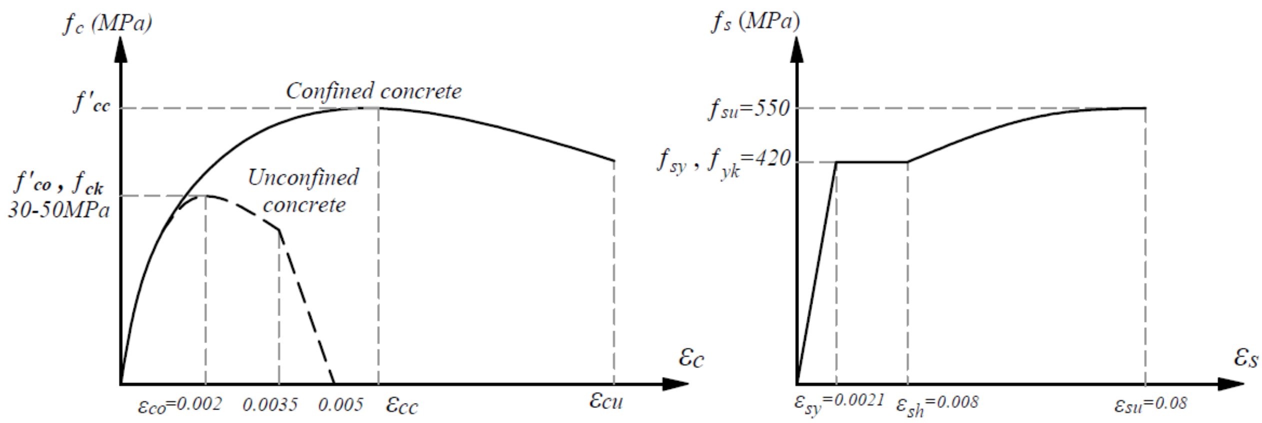

Figure 3 Stress-strain relationship for materials [11]

In the non-linear analysis of RC column models, the material models for concrete and reinforcing steel are given in Figure 3. The combined effect of seismic and vertical loads (N_{dm}), cross-section area of RC column shall satisfy the condition $A_c \geq N_{dm}/0.40f_{ck}$ [11]. In this study, N/N_{max} ratios of 0.10, 0.20, 0.30, and 0.40 were taken into account to investigate the effect of axial load levels on the non-linear analysis of RC circular columns.

In the designed circular column models, the minimum ratio of the spiral reinforcement and the volumetric ratio of the spiral reinforcement are taken into account based on the conditions given in TBSC [11] and ACI318 [39] regulations. TBSC [11] and ACI318 [39] state that the ratio of spiral reinforcement shall not be less than Equations (10) and (11). A_c and A_{ck} are gross section area and core concrete area of column, respectively.

5. Numerical Study

5.1 Stress–Strain Relation of Circular Columns

In the designed RC circular column models, the stress-strain relations for the confined concrete were obtained according to different spiral reinforcement ratios and concrete grade. The compressive stresses as a function of the compressive strain of the confined concrete were presented comparatively. The effect of the design parameters in the column sections on the stress-strain relationship of the confined concrete was calculated and compared (Figure 4). Although the yield strength of the spiral reinforcement used in the models was constant, it was concluded that the use of spiral reinforcement in different diameters and spacing values affects the lateral compressive strength of the designed reinforced concrete column sections. Increasing the spiral reinforcement ratio should be expected to have the same effect; therefore, it is normal for the section bearing capacity to increase when the spiral reinforcement is increased. As the spiral reinforcement spacing is reduced and the spiral reinforcement diameter increases, the ductility increases due to the confining effect. For the constant spiral reinforcement spacing in circular cross-section column models, it was concluded that the compressive strength of the confined concrete, calculated with the increase of the spiral reinforcement diameter, increases. For constant concrete grade, ε_{cc} and ε_{cu} values increase as spiral reinforcement diameter increases (confined concrete has more ductile behavior). For the constant spiral reinforcement ratio, as the concrete grade increases, the f_{cc} also increases, but the confined concrete exhibits a brittle behavior ($\varepsilon_{cc}$and ε_{cu} values decrease). According to the constant spiral reinforcement diameter, $\varepsilon_{cc}$and ε_{cu} values decrease as spiral spacing and concrete grade increase. Since the longitudinal reinforcement ratio in the confined concrete models does not have a significant effect on the f_{cc} , ε_{cc} , ε_{cu} values and the ductility of the column sections, it was considered constant in this study.

$$\rho_s = 0.45\left(\frac{A_c}{A_{ck}} - 1\right)\frac{f_{ck}}{f_{yk}} \tag{11}$$

$$\rho_{sh} \geq 0.12\left(\frac{f_{ck}}{f_{yk}}\right) \tag{12}$$

5.2 Moment-Curvature Relationships of Circular Columns

The moment-curvature analysis is required to calculate the non-linear behavior, strength, stiffness, and ductility of structural members. Moment-curvature relations are obtained according to different design parameters for circular column models. Moment-curvature relations of the designed RC circular section column models were obtained by making necessary analyses according to different design parameters, and investigations were made. The ductility of the RC column section can be expressed as the ratio of the maximum curvature to the yield curvature $\mu_{\emptyset} = \emptyset_u/\emptyset_y$. In the RC circular columns, the influence of different design parameters on the M-$\emptyset$ and $\mu_{\emptyset}$ are shown in Figures 5-6, respectively.

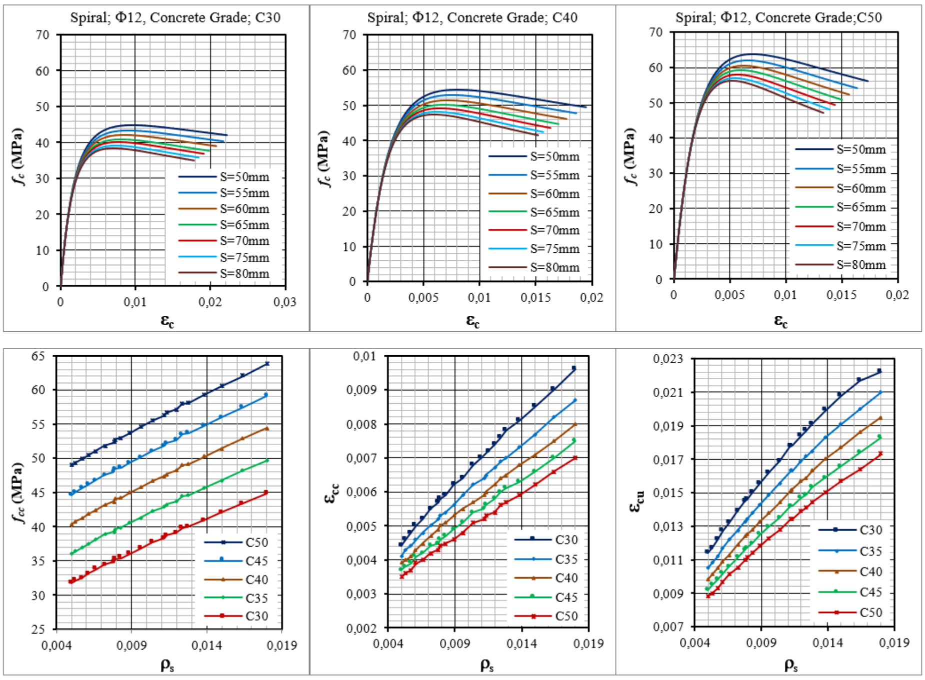

Figure 4. Stress-strain relationships of the RC circular columns according to Mander model

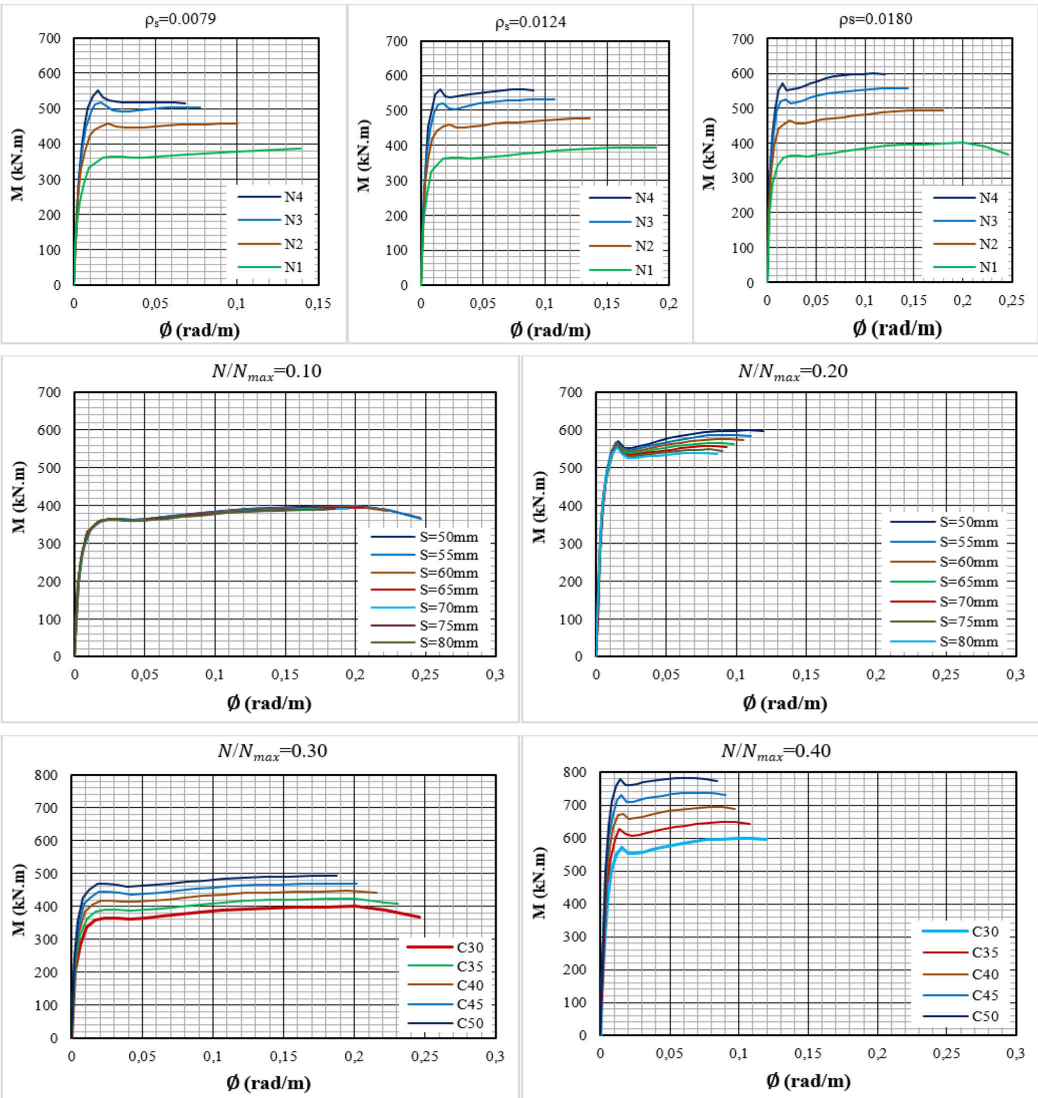

Figure 5. Moment-curvature relations for RC circular columns according to different design parameters

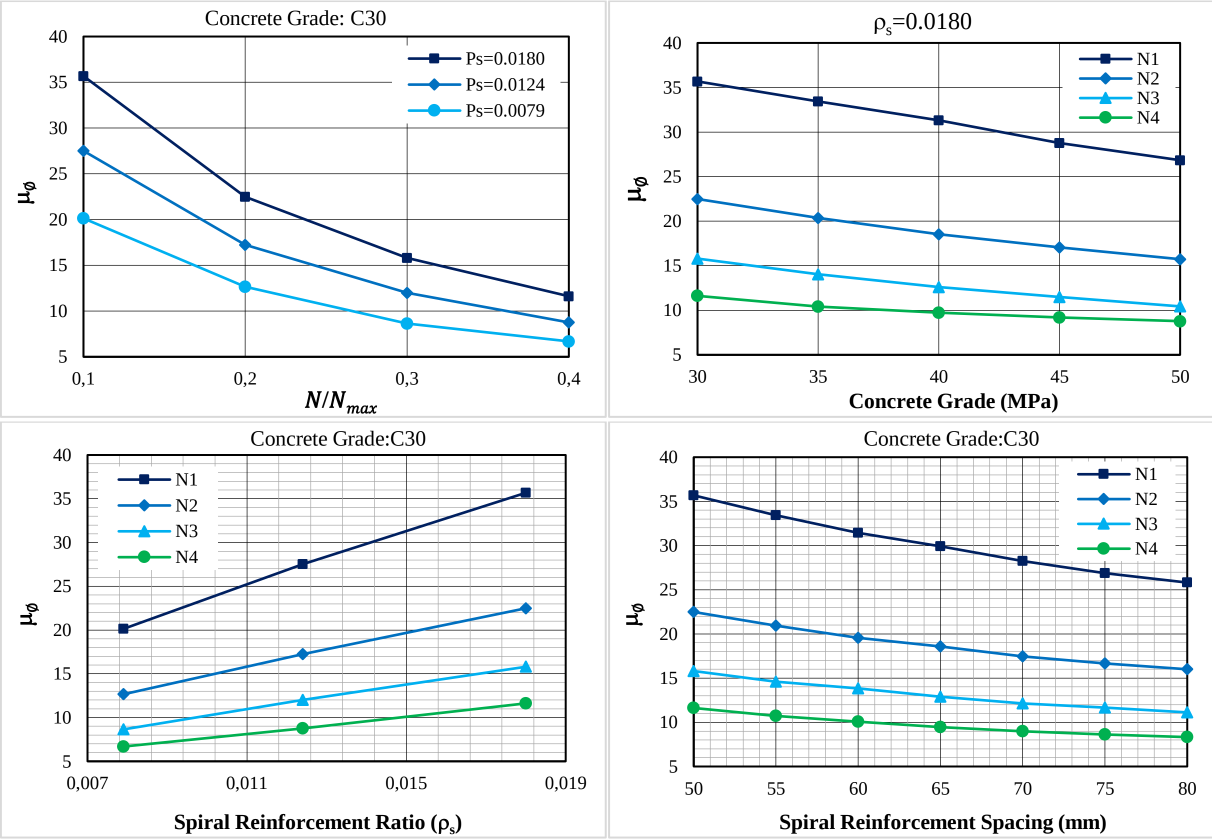

Figure 6. Influence of different parameters on the curvature ductility

When the moment-curvature analysis results of the RC circular column models are examined, it is seen that the variation of the axial load and spiral reinforcement has a significant effect on the non-linear behavior of the sections. For the constant spiral reinforcement and concrete grade, ductility values of column sections decrease as the axial load level increases. As a result of the increase in the spiral ratio, the moment capacity values of the column increase. As the moment bearing capacity increases with the increase in the spiral reinforcement ratio, the section ductility also increases. The spiral ratio is important for the ductility behavior of the columns and the curvature values increase significantly.

5.3 Non-linear Displacement of Circular Columns

In order to calculate the displacement capacity and ductility demands of RC circular cross-section columns, the Δ_y and Δ_p values according to the $\emptyset_y$ and the length of the plastic hinge of the sections were calculated, and the Δ_u value was obtained. The displacement ductility (μ_Δ) values were calculated based on the calculated Δ_y and Δ_u values. The Δ_u and μ_Δ values were calculated based on axial loads and plastic hinge analysis in circular columns. Δ_y and Δ_p were taken into account in the calculation of Δ_u values of columns. In the RC circular columns, the influence of different design parameters on the Δ_u and μ_Δ are shown in Figures 7 and 8 respectively.

There are differences in $\emptyset_{\boldsymbol{y}}$, $\emptyset_{\boldsymbol{u}}$, $\Delta_{\boldsymbol{y}}$, $\Delta_{\boldsymbol{p}}$, $\Delta_{\boldsymbol{u}}$and μ_Δ values calculated for the axial load levels. As the axial load levels increase, the $\Delta_{\boldsymbol{p}}$, $\Delta_{\boldsymbol{u}}$and μ_Δ values decrease. As the spiral reinforcement ratio increases, the $\Delta_{\boldsymbol{u}}$and μ_Δ values increase. As the spiral spacing increases, the $\Delta_{\boldsymbol{u}}$ and μ_Δ values decrease. The μ_Δ value decreases with increasing $\Delta_{\boldsymbol{y}}$ values and decreasing $\Delta_{\boldsymbol{u}}$ values.

5.4 Deformation Limits for Different Performance Levels

According to the non-linear calculation method, one of the most important steps in performance evaluation is to determine the damage limits for different performance levels in the structural elements. Deformation demands, which are taken as a basis for the evaluation, are also of great importance in order to determine the damage that will occur to the structural elements. In the calculation of deformation limits and plastic hinge properties, three different deformation limits (GÖ, KH, and SH performance levels) defined in TBSC [11] were used. In TBSC [11], the deformation limits given for reinforcing steel at different performance levels are obtained by multiplying the unit deformation values corresponding to the tensile strength of reinforcing steel by constant coefficients. The deformation limits for the As constant values, GÖ, KH, and SH performance levels are given as $\varepsilon_s^{(GÖ)} = 0.0320$, $\varepsilon_s^{(SH)} = 0.0075$, and $\varepsilon_s^{(KH)} = 0.0240$, respectively. ε_c limit values were calculated for different spiral and longitudinal reinforcement ratios by taking into account the different performance levels. Plastic rotation limit values (θ_p) are functions of $\emptyset_y$, $\emptyset_u$, L_P, L_S, and d_b. Therefore, parameters affecting $\emptyset_y$ and $\emptyset_u$ values, such as concrete grade, axial load level, spiral ratio, and configuration of spiral reinforcement, also affect the θ_p values. Deformation limits for different performance levels were calculated for the RC circular columns according to different parameters (Figure 9).

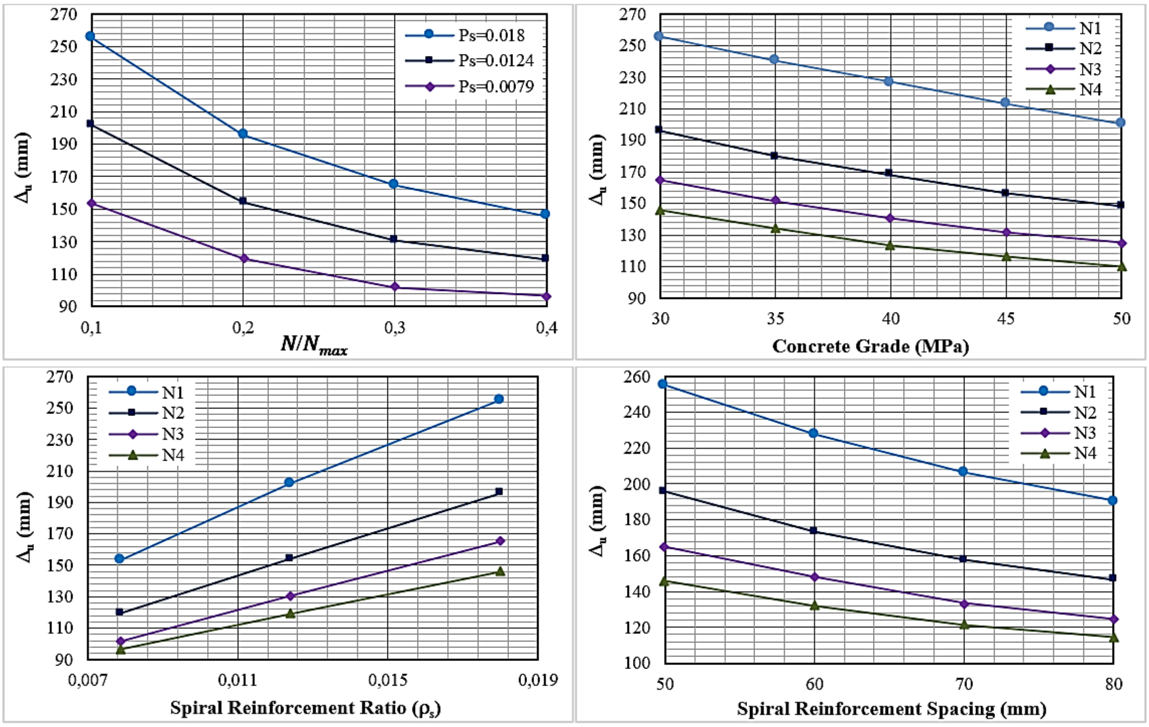

Figure 7. Influence of different design parameters on the ultimate displacement

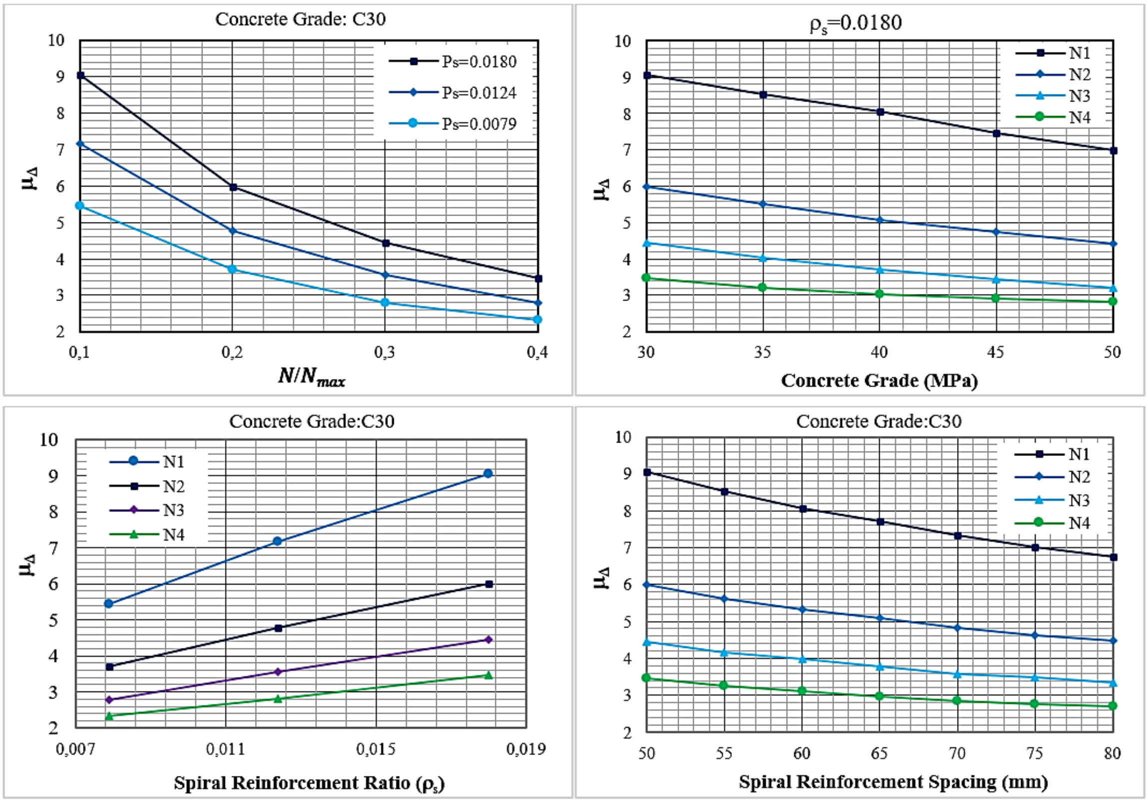

Figure 8. Influence of different design parameters on the displacement ductility

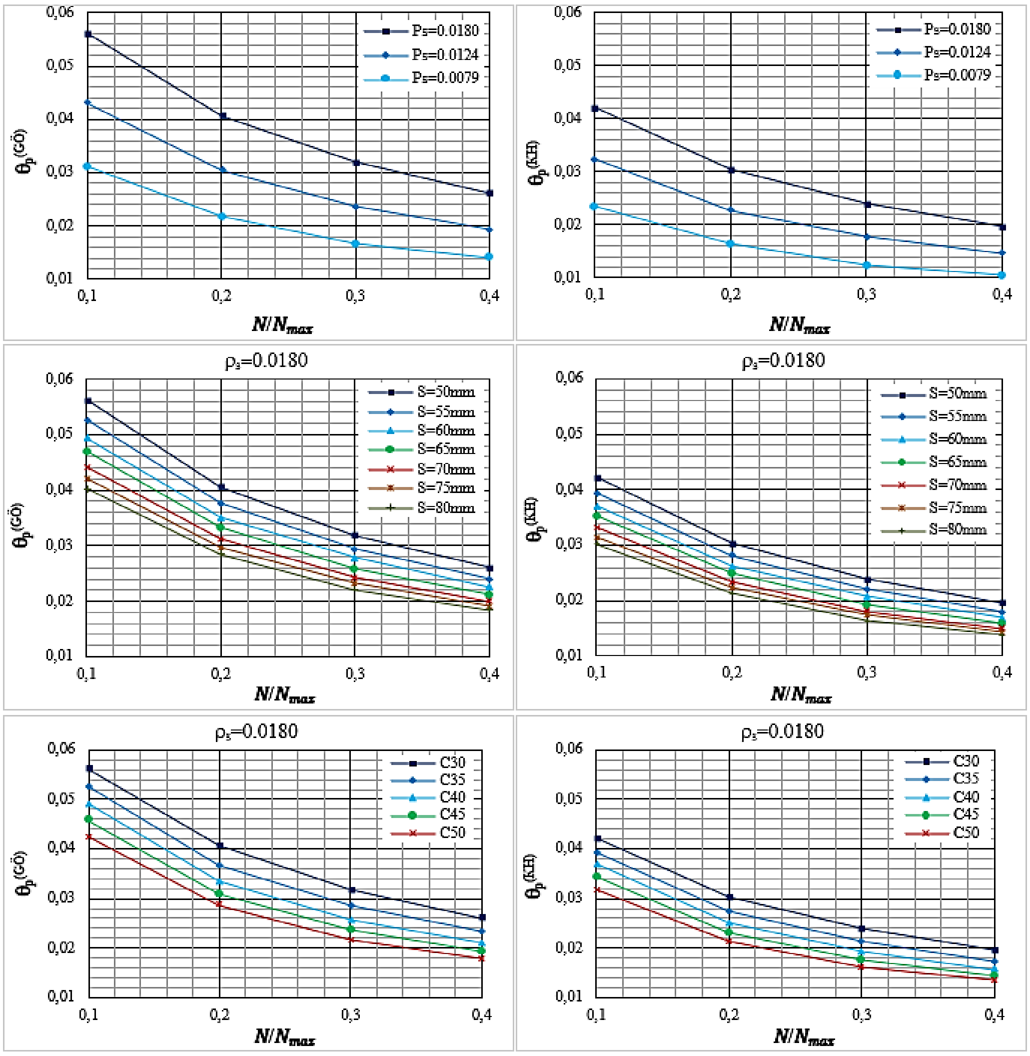

Figure 9. Deformation limits according to different parameters

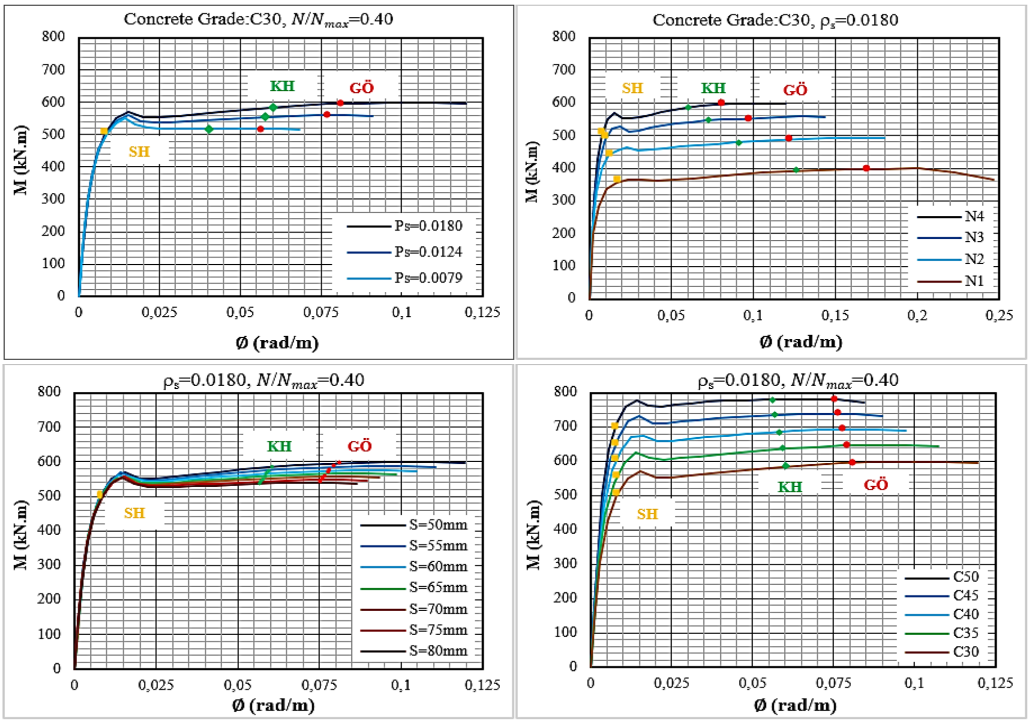

Figure 10. Moment-curvature relationship deformation limits distribution

The deformation limits for the concrete ($\varepsilon_c^{(GÖ)}$, $\varepsilon_c^{(KH)}$) are calculated based on the expected strength of reinforcement steel and concrete (f_{ye}, f_{ce}), reinforcement ratio of the confined reinforcement (ρ_{sh}) , and the configuration of the spiral reinforcement. Deformation limit for the SH performance level of the confined concrete is given as constant value ($\varepsilon_c^{(SH)} = 0.0025$). The $\varepsilon_c^{(GÖ)}$ and $\varepsilon_c^{(KH)}$ damage limits vary based on different spiral reinforcement diameters and spiral reinforcement spacing. Total unit deformation limit values corresponding to different performance levels of RC column models were obtained based on TBSC [11]. Depending on the deformation upper limit values obtained, cross-sectional deformation damage levels were determined by the excel software, and they are shown on the moment-curvature graphs (Figure 10).

6. Conclusions

The ratio of spiral reinforcement affects the non-linear behavior of RC columns and their deformation limits and plastic hinge properties. In this study, definitions of structural performance levels were presented, and for members, performance indicator limits, which are mainly based on definitions of material deformation limits for each structural performance level, were achieved. It was determined that $\varepsilon_c^{(GÖ)}$ve $\varepsilon_c^{(KH)}$ values decrease as spiral reinforcement spacing increases for the constant concrete grade and longitudinal and spiral reinforcement diameter. $\varepsilon_c^{(GÖ)}$, $\varepsilon_c^{(KH)}$ values increase with the increase of the spiral reinforcement diameter for the constant concrete grade, longitudinal reinforcement diameter, and spiral reinforcement spacing. In addition, for the designed column sections, $\varepsilon_c^{(GÖ)}$ and $\varepsilon_c^{(KH)}$ values increase with increasing concrete grade for constant longitudinal and spiral reinforcement ratio.

$\theta_p^{(GÖ)}$ and $\theta_p^{(KH)}$ deformation damage limits vary based on the moment-curvature relationship and axial load levels. The values of $\theta_p^{(GÖ)}$ and $\theta_p^{(KH)}$ decrease with the increase of spiral reinforcement ratio for constant concrete grade and axial load levels. The values of $\theta_p^{(GÖ)}$ ve $\theta_p^{(KH)}$ increase with the increase of spiral reinforcement diameter for the constant concrete grade, axial load level, and spiral reinforcement spacing. As the concrete grade increases for the constant axial load level, spiral reinforcement diameter, and spacing, $\theta_p^{(GÖ)}$ and $\theta_p^{(KH)}$ values decrease by a little difference. $\theta_p^{(GÖ)}$ and $\theta_p^{(KH)}$ values decrease with increasing axial load level for constant concrete grade and spiral reinforcement ratio. One of the most important steps in the performance evaluation according to the non-linear calculation method is to determine the deformation damage limits and plastic rotation limits of GÖ, KH, and SH in the structural members. Because of increasing spiral reinforcement ratios, deformation damage limits of the RC columns remain in the safer direction.

Declaration

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The authors also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

The design of RC column models, analysis plan, statistical analysis, data collection, writing article, and evaluation of the results was shared by S. Foroughi and S.B. Yüksel.

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