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Investigation of Nonlinear Displacement and Deformation Damage Limits of Reinforced Concrete Square Columns According to ASCESEI 41-17

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ABSTRACT

The deformation-based damage limits and plastic rotation properties of reinforced concrete square column models according to ASCE/SEI 41-17 and nonlinear displacement capacities according to displacement-based seismic performance evaluation procedures were analytically investigated. Reinforced concrete square column models were designed to analytically investigate the effects of various design parameters such as concrete grade, transverse reinforcement ratio and axial load levels on the nonlinear displacement and deformation damage limits. According to the results obtained from the nonlinear behaviour relations, the deformation damage limits and plastic rotation properties for the IO, LS and CP performance levels and the force-deformation relations of the designed column models according to different parameters according to ASCE/SEI 41-17 were obtained and compared. The results obtained from the analysis for each section of the whole study were interpreted by comparing them. In the performance evaluation of reinforced concrete structures, the deformation demands, that are taken into consideration as a basis are very important in order to determine the damages of the carrier elements. It has been concluded that the transverse reinforcement ratio and axial load levels have significant effects on the nonlinear behaviour of the reinforced concrete column models, section damage limits and plastic hinge properties, displacement capacities and force-strain relationships.

Betonarme Kare Kolonların Doğrusal Olmayan Yer değiştirme ve Deformasyon Hasar Sınırlarının ASCESEI 41-17'ye göre İncelenmesi

ÖZ

ASCE/SEI 41-17'ye göre betonarme kare kolon modellerinin deformasyona dayalı hasar limitleri, plastik dönme özellikleri ile yer değiştirmeye dayalı sismik performans değerlendirme prosedürlerine göre doğrusal olmayan yer değiştirme kapasiteleri analitik olarak incelenmiştir. Beton sınıfı, enine donatı oranı ve eksenel yük seviyeleri gibi çeşitli tasarım parametrelerinin doğrusal olmayan yer değiştirme ve deformasyon hasar limitleri üzerindeki etkilerini analitik olarak araştırmak için betonarme kare en-kesitli kolon modelleri tasarlanmıştır. Doğrusal olmayan davranış ilişkilerinden elde edilen sonuçlara göre, Farklı parametrelerde tasarlanan kolon modellerinin ASCE/SEI 41-17'ye göre IO, LS ve CP performans seviyeleri için deformasyon hasar limitleri, plastik dönme özellikleri ve kuvvet-deformasyon ilişkileri elde edilerek karşılaştırılmıştır. Tüm çalışmanın her bölümü için yapılan analizlerden elde edilen sonuçlar karşılaştırılarak yorumlanmıştır. Betonarme yapıların performans değerlendirmesinde, esas alınan deformasyon talepleri, taşıyıcı elemanlardaki hasarların belirlenmesi açısından oldukça önemlidir. Enine donatı oranı ve eksenel yük seviyelerinin betonarme kolon modellerinin doğrusal olmayan davranışı, kesit hasar limitleri ve plastik mafsal özellikleri, yer değiştirme kapasiteleri ve kuvvet-şekil değiştirme ilişkileri üzerinde önemli etkileri olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Sismik yük, performans seviyesi, hasar sınırı, deformasyon sınırı

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1. Introduction

The ability of reinforced concrete (RC) structural elements to remain under seismic effects without a reduction in load carrying capacity is of vital importance for ensuring life safety performance targets and criteria [1]. RC columns are the main load-bearing members that determine the seismic behavior and performance of framed structures. Performance-based evaluations of RC columns are based on comparison with the displacement capacity and deformation-based damage limits obtained from the nonlinear structural analysis [2]. Due to the damages in the columns after earthquakes in RC structures, objective performance levels of the structures cannot be achieved. Therefore, the behavior of structural elements should be well known for earthquake-resistant building design [3]. RC columns that do not conform with the seismic design and detailing requirements given in current standards and codes carry the risk of non-ductile collapse, which can lead to catastrophic damage and collapse of the structure [4]. The seismic performance of RC structures is of great importance for structures in severe earthquake zones [5]. The seismic performance of RC bearing members greatly affects the total performance of RC structures under seismic effects [6].

Performance is related to the extent to which the capacity of a structure can meet seismic demands [7]. Performance-based design is the design of a structure under the influence of a design earthquake, by predicting a certain structural performance or damage, using deformation-based methods. deformation-based design methods; It takes into account the nonlinear behaviour of the material [8]. One of the most important stages of performance-based methods is to determine the damage levels in structural elements. For this reason, methods based on deformations that are directly related to damage give much more reliable results than those based on force. However, the deformation parameter used to determine the damage is also of great importance [9]. Performance-based earthquake codes express the bending performance of columns with the total rotational capacity of the plastic hinge regions or the plastic rotational capacity [10].

The displacements and deformations in RC columns consist of section damages caused by earthquake effect [11]. Predicting the displacement and deformation capacity of RC columns is very important for a comprehensive performance-based seismic evaluation of new or existing buildings [12]. In order to achieve a more accurate simulation of the real structural behaviour, designers need the accurate nonlinear behaviour of materials (reinforcement and concrete) and moment-curvature relationship for RC members [13].

The purpose of the nonlinear analysis methods to be used to determine the seismic performance of RC buildings under earthquake effects is to calculate the plastic rotation and plastic deformation capacities for ductile behaviour and internal force demands for brittle behaviour of structural elements for a given earthquake. Then, these demand sizes are compared with the deformation and internal force capacities and structural performance evaluation is made at the section and building level. The damage levels of the sections are determined by comparing the deformations calculated with nonlinear calculation methods with the numerical values defined in seismic codes to correspond to the section damage limits. In many seismic codes, some methods have been proposed to determine the earthquake safety of existing buildings [14-15].

The reliability-based analysis and assessment can be performed for different components and elements of RC structures such as beams, columns, and other elements that involve shear stress, etc. [16]. Design codes for RC structures provide minimum criteria and requirements for the design of structures in accordance with the code to ensure the safety of life and property [17]. As the main lateral force and moment resisting members, the ductile displacement and deformation capacity of RC columns is an important parameter for obtaining better seismic performance of structures [18]. Displacement capacity and ductility are parameters that characterize the seismic response of RC structures [19]. Load-bearing elements of structural systems resistant to lateral force and moment should be designed with sufficient strength and ductility [20].

Some research and studies have been carried out to determine the nonlinear displacement and deformation damage limits of RC structural members. Özdemir and Kazaz [1], investigated the deformation limits according to different codes by using the nonlinear finite element method of experimentally tested RC columns. Foroughi and Yüksel [13], investigated the effect of the material model, axial load, longitudinal reinforcement ratio, transverse reinforcement ratio and transverse reinforcement spacing on the behaviour of RC cross-sections. Foroughi and Yüksel [3], parametric studies were conducted for RC columns and the adequacy of the deformation and damage limit levels given in seismic codes were investigated. Foroughi et al. [14], in order to determine the earthquake performance of structural elements, the deformation-based damage limits for RC elements in codes were analysed analytically. Aydemir et al. [8], a procedure to obtain total limit curvature of RC columns is explained and interaction of the flexural damage limit curvature with various design parameters especially axial load level- are investigated.

In order to determine the seismic performance of the designed square cross-section column models in this study, the deformation-based damage limits and damage regions defined in Seismic Evaluation and Retrofit of Existing Buildings (ASCE/SEI 41) [21] were analysed analytically. In addition to the deformation-based damage limits, modelling parameters and numerical acceptance criteria for nonlinear procedures are also calculated for the RC square column models. According to the modelling parameters and numerical acceptance criteria for the RC square column models calculated according to ASCE/SEI 41 [21], generalized force-deformation relation obtained for the column models. For a better understanding and realization of ductile seismic design, it is necessary to estimate the structural deformation capacity under severe earthquakes. In plastic hinge analysis, the total top (peak) displacement of a cantilever column models is obtained as the sum of yield displacement and plastic displacement component. Depending on the curvature values which were obtained from the nonlinear curvature-moment analysis, the peak displacement in the case of yield and pre-collapse and the peak displacement ductility values were obtained of the column models. In the performance evaluation of the RC column models designed within the scope of the study; the performance levels of the column sections were investigated by calculating the plastic rotation properties of the deformation limit values for the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) structural performance levels. The nonlinear behaviour of RC column models were investigated using the stress-strain and moment-curvature relationships obtained based on real material behaviours. Mander concrete model [22] is taken into account in nonlinear moment-curvature analyses of RC column models according to different design parameters. As design parameters in all analyses of RC square cross-section column models; concrete compressive strength, axial load level, transverse reinforcement diameter and transverse reinforcement spacing are taken into account.

2. Structural Performance Levels

Buildings show nonlinear behavior during earthquakes. In order to evaluate this nonlinear behavior, the concept of structural evaluation and design based on the performance criteria related to deformation and displacement has emerged. The ASCE/SEI 41 [21], for seismic evaluation and retrofit of buildings defines target performance levels for different seismic hazard levels, together with modeling procedures and acceptance criteria to assess structural members. Three main performance levels are considered for structural members, namely, Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) structural performance levels. IO, is defined as the postearthquake damage state in which a structure remains safe to occupy and essentially retains its preearthquake strength and stiffness. LS, is defined as the post-earthquake damage state in which a structure has damaged components but retains a margin of safety against the onset of partial or total collapse. CP, is defined as the post-earthquake damage state in which a structure has damaged components and continues to support gravity loads but retains no margin against collapse [21].

In ASCE/SEI 41 [21] regulations, acceptance criteria are given according to shear force ratio, axial load ratio, concrete compressive strength, yield strength of confining reinforcement and longitudinal reinforcement ratio. In ASCE/SEI 41 [21], acceptance criteria for RC columns are divided into two according to the splicing condition of the longitudinal reinforcement of the columns. Performance levels due to plastic rotation are given depending on the design parameters a and b values. The deformation, plastic rotation angels and strength ratio parameters in Table 1 are used to establish the significant points in the idealized shear force-chord rotation relation shown in Figure 1. The nonlinear analysis procedures proposed in ASCE/SEI 41 [21] represent the response of RC members classified as deformation-controlled through idealized load-deformation relations. According to ASCE/SEI 41 [21], the governing failure modes of columns strongly affect the force-deformation relation [23]. The generalized force-deformation relation shown in Figure 1 shall be described by the linear response from A (unloaded component) to an effective yield B, then a linear response at reduced stiffness from point B to C, then the sudden reduction in seismic force resistance to point D, then response at reduced resistance to E, and final loss of resistance thereafter [21].

To determine the deformation capacity of a RC column, ASCE/SEI 41 [21] classifies columns in three different failure modes depending on the plastic shear demand ratio of shear strength at low ductility demand. The shear strength of the RC column (V_{Col}) in ASCE/SEI 41 [21] is defined by the Equation (1). In Table 1 and Equation (1), V_{Col} is the shear strength, k_{nl}; a ductility factor. In which $k_{nl}=1$ for $\mu_\Delta \leq 2$ and $k_{nl}=0.7$ for $\mu_\Delta > 6$. $\lambda = 1$ for normal-weight aggregate concrete. $\alpha_{Col}=1$ for $s/d \leq 0.75$, $\alpha_{Col}=0$ for $s/d \geq 1$. A_v is the area of transverse reinforcement, $f'_{cL/E}$ and $f_{ytL/E}$ expected concrete strength and yield strength of transverse reinforcement (f'_{CE} =1.5f'_C, f_{ytE}=1.25f_{yt}), d is the effective depth of a columns, s is the transverse reinforcement spacing, ρ_t is the ratio of transverse reinforcement and A_g is the area of the column cross-section. $\lambda=1$ for normal-weight aggregate concrete. N_{UG} axial force and M_{UD} moment of the column [21].

$$V_{Col} = k_{nl}V_{Col0} = k_{nl}\left[\alpha_{Col}\left(\frac{A_v F_{ytL/E}\, d}{s}\right) + \lambda\left(\frac{0.5\sqrt{f'_{cL/E}}}{M_{UD}/V_{UD}\, d}\sqrt{1+\frac{N_{UG}}{0.5A_g\sqrt{f'_{cL/E}}}}\right)0.8A_g\right](MPa) \qquad (1)$$

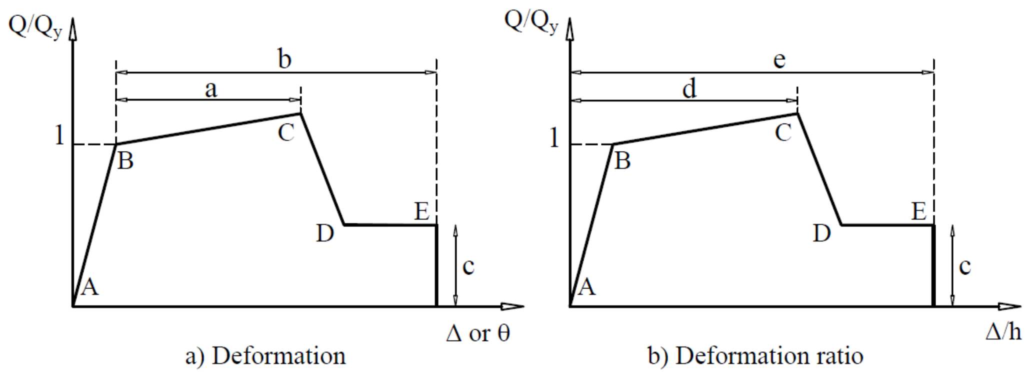

Figure 1. Generalized force–deformation relation for concrete elements or components [21].

Table 1. Modeling parameters and numerical acceptance criteria of RC columns for nonlinear procedures [21]

Modeling Parameters	Acceptance Criteria		
Plastic Rotation Angles, a and b (rad) Residual Strength Ratio, c	Plastic rotation Angle (Rad) Performance Level		
	IO	LS	CP
Columns not controlled by inadequate development or splicing along the clear height			
$a=\left(0.042-0.043\frac{N_{UD}}{A_g f'_{CE}}+0.63\rho_t-0.023\frac{V_{yE}}{V_{ColOE}}\right)\geq 0$			
$for\ \frac{N_{UD}}{A_g f'_{CE}}\leq 0.5 \left\{ b=\frac{0.5}{5+\frac{N_{UD}}{0.8A_g f'_{CE}}\frac{1}{\rho_t}\frac{f'_{CE}}{f_{ytE}}}-0.01\geq a \right.$	$0.15a \leq 0.005$	$0.5b$	$0.7b$
$c=0.24-0.4\frac{N_{UD}}{A_g f'_{CE}}\geq 0$			

3. Nonlinear Displacement in Reinforced Concrete Columns

In order to perform the ductile seismic design of RC structures under strong earthquakes, the structural deformation capacity should be estimated [24]. Performance assessment methods used in the calculation of nonlinear displacement capacity can be calculated using displacement controlled seismic design and plastic hinge method. Extreme loads are used to predict the behavior of plastic hinges subjected to nonlinear deformations. These loads, earthquakes, etc. are important in calculating the maximum displacement capacity of RC structures [25]. The RC columns are exposed to large lateral displacements under high seismic loads in addition to gravity loads, and major damage occurs in the regions where nonlinear deformations occur. Since nonlinear deformations in RC structural members usually occur in the plastic hinge regions, the members must have a major curvature capacity in these regions in order to obtain large lateral displacement capacities. With the development of performance/displacement based seismic design and assessment of RC structures, the deformation capacity of structural members has received great attention.

Plastic hinge method and analysis to determine the seismic behavior of RC columns are still used in displacement-based seismic design and performance evaluation procedures to calculate nonlinear displacement capacities. The lumped plastic rotation (θ_p), along the plastic hinge length (l_p) is then computed as Equation (2). Where $\emptyset_u$; is the maximum curvature and $\emptyset_y$; is the yield curvature, as shown in Figure 2. In the plastic hinge analysis, the total peak displacement (Δ_u) of a cantilever column model is obtained as the sum of its yield displacement (Δ_y) and plastic displacement (Δ_p) component (Equation 3). H_w; is the height of the column section, Δ_y; yield displacement, Δ_p; plastic displacement and Δ_u; total peak displacement. After the calculation of the total peak and yield displacement are calculated, displacement ductility is determined to $\mu_\Delta = \Delta_u/\Delta_y$.

$$\theta_p = \emptyset_p L_p = \left(\emptyset_u - \emptyset_y\right) L_p \quad (2)$$

$$\Delta_u = \Delta_y + \Delta_p = \frac{\emptyset_y H^2}{3} + \theta_p\left(H - 0.5L_p\right) \quad (3)$$

In this study, the yield curvature ($\emptyset_y$) and ultimate curvature ($\emptyset_u$) in Equation (3) are computed through a moment-curvature analysis using the Mender confined and unconfined concrete model [22]. The ultimate concrete compressive strain (ε_{cu}), corresponds to the value at the moment of first fracture in the transverse reinforcement. The maximum compressive strain in the confined concrete can be calculated from the Equation (4) [26].

$$\varepsilon_{cu} = 0.004 + \frac{1.4.\rho_s.f_{yw}.\varepsilon_{su}}{f'_{cc}} \quad (4)$$

ρ_s; ratio of transverse confining steel, ε_{su}; strain in reinforcement at maximum strength and f_{yw}; yield strength of transverse reinforcement. f'_{cc}; denotes the compressive strength of confined concrete calculated by Equation (5). In Equation (5), f'_{co} is the unconfined concrete strength and f'_l is the effective lateral confining pressure [22].

$$f'_{cc} = f'_{co}\left(-1.254 + 2.254\sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}}\right) \quad (5)$$

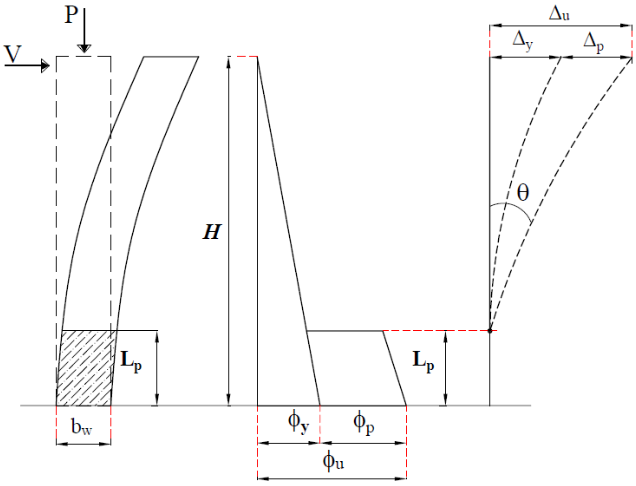

Figure 2. Theoretical model of elastic and plastic displacements in cantilever column

4. Materials and Methods

The deformation-based damage limits of RC square column models according to ASCE/SEI 41 [21] and nonlinear displacement capacities were analytical calculated according to displacement-based seismic design and performance evaluation procedures. For this purpose, square column models with different design parameters were designed. Turkish Building Earthquake Code (TBEC) [27] and Building Code Requirements for Structural Concrete (ACI318) [28] codes were taken into account in the design of square cross-section RC columns. Since this condition is required by the regulations in order to ensure ductile behaviour in RC columns, the limit values given in the regulations were taken into account in this study.

A total of 96 models were designed for different concrete grade, axial loads, transverse reinforcement diameters and spacing of each model. The cross-sectional properties of column models with square cross-section dimensions of 500mm×500mm are given in Figure 3 and Table 2. In order to investigate the effect of transverse reinforcement on the section behaviour of RC square cross-section column models, two different transverse reinforcement diameters (8, 10) and four different transverse reinforcement spacings (50mm, 60mm, 70mm and 80mm) were taken into account. Longitudinal reinforcement is taken as 8Φ20 in column models. For all RC column models, C30, C40 and C50 were chosen as the concrete class and B420C as the reinforcing steel. In the analytical study, the material properties given for concrete and reinforcement in TBDY [27] were used (Figure 4). In Figure 4, f_{co} and f_{cc} unconfined and confined concrete compressive strength, ε_{co} is the strain at maximum stress of unconfined concrete, ε_{cc} is the corresponding strain at maximum concrete stress, ε_{cu} ultimate compression strain of concrete, f_{sy} is the characteristic yield strength of reinforcement, f_{su} is the ultimate strength of reinforcement, ε_{sy} is the yield strain of reinforcement, ε_{sh} is the strain hardening value of reinforcing steel and ε_{su} is the strain in reinforcing steel at ultimate strength.

The minimum total area of transverse reinforcement to be calculated to satisfy the more unfavourable of the requirements are given in Equation (6). A_{sh} and s total area and spacing of transverse reinforcement, b_k cross section dimension of concrete core of column, A_c gross section area of column, A_{ck} concrete core area within outer edges of confinement reinforcement, f_{ck} characteristic standard value of unconfined concrete compressive strength, f_{ywk} characteristic yield strength of transverse reinforcement.

$$\frac{A_{sh}}{sb_k} \geq 0.30\left[\frac{A_c}{A_{ck}} - 1\right]\frac{f_{ck}}{f_{ywk}}$$
$$\frac{A_{sh}}{sb_k} \geq 0.30\left[\frac{A_c}{A_{ck}} - 1\right]\frac{f_{ck}}{f_{ywk}} \quad (6)$$

Moment-curvature relations of a RC section under normal force and flexural moment depend on axial load levels. Moment-curvature relations for different design parameters were obtained with the SAP2000 [29] program by considering the nonlinear behaviour of the RC columns and the nonlinear behaviour of the materials. The moment-curvature relationships for different axial load levels of the column cross-sections were obtained considering mender concrete model [22]. The combined effect of vertical and earthquake loads (N_{dm}), gross section area of RC column shall satisfy the condition $A_c \geq N_{dmax}/0.40f_{ck}$ [27]. To investigate the effect of axial load on the nonlinear behaviour of the RC column, models were investigated under four different axial forces (N_1=480kN, N_2=960kN, N_3=1440kN and N_4=1920kN).

According to the plastic hinge length, the yield displacement (Δ_y) and plastic displacement (Δ_p) values of the RC columns were calculated and the total peak displacement (Δ_u) values of the RC columns were obtained. Displacement ductility (μ_Δ) is related to a structural system or member configuration and its section ductility and is based on the load-displacement curve.

Several key factors that are considered in ASCE/SEI 41 [21] to affect the nonlinear force-deformation behaviour of RC columns are examined, which include the governing failure mode, axial load levels, concrete compressive strength, transverse reinforcement diameter and spacing. Also, the ASCE/SEI 41 [21] procedures to determine the force-deformation relations of RC column models are reviewed. Modelling parameters and numerical acceptance criteria given in ASCE/SEI 41 [21] were taken into consideration in order to investigate the effect of the force-deformation relations in the designed RC column models.

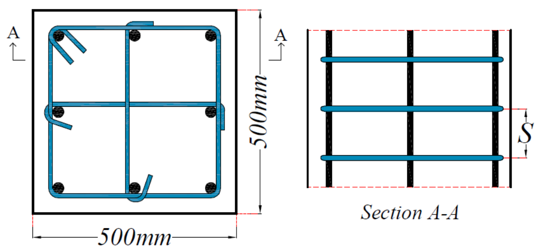

Figure 3. Cross-section of RC column models

Table 2. Designed column section details

Longitudinal reinforcement	Material (MPa)	Transverse reinforcement	Axial Load
8Φ20 mm	C30 C40 C50	Φ10/50 mm Φ10/60 mm Φ10/70 mm Φ10/80 mm Φ12/50 mm Φ12/60 mm Φ12/70 mm Φ12/80 mm	0.10 0.20 0.30 0.40

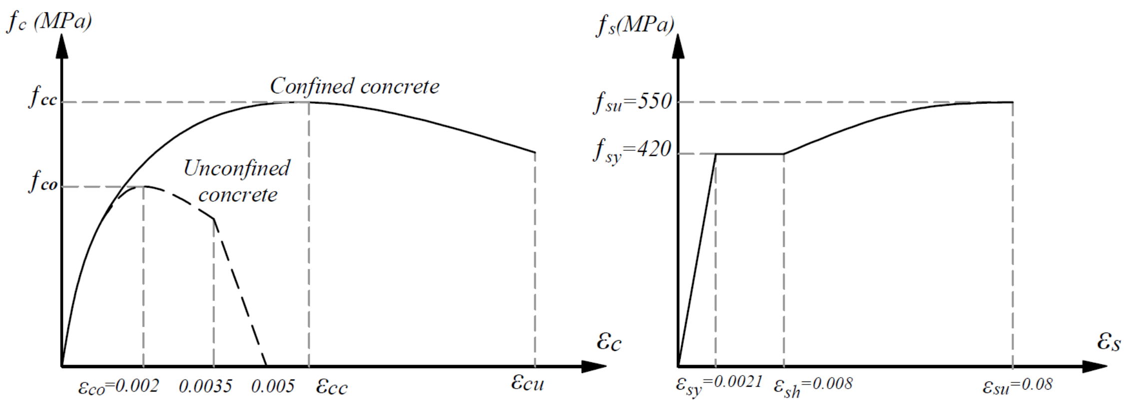

Figure 4. Stress-strain relationship for materials [27]

5. Research Findings and Discussion

RC columns are the most important structural members that determine the ductility of the structures. The main design parameters affecting the behavior of RC column models are axial load level, concrete compressive strength, and transverse reinforcement ratios. The tip displacement of a cantilever columns is obtained as the sum of its Δ_y and Δ_p. Δ_y, Δ_p, Δ_u and μ_Δ values of the elements were calculated for different axial load levels according to the calculated by plastic hinge length in RC column sections (Table 3-4). The results of the calculations are summarized in Figure 5 respectively according to different parameters. In calculating the total displacement of the RC columns, the yield and maximum curvature values were obtained from the moment-curvature relationships which take into account the section height, plastic hinge length and nonlinear behavior are taken into consideration. The plastic hinge length (L_p) shall be taken as half of the section length in the active direction ($L_p = 0{,}50h$).

The load-deformation relations of the designed column models according to different parameters were obtained according to the modeling parameters given in the ASCE/SEI 41 [21] standard. Performance level values of non-linear procedures of RC square columns according to different transverse reinforcement diameters, transverse reinforcement spacing and concrete compressive strength were calculated. The calculated performance level values are given in Tables 5, 6 and 7, respectively, according to different design parameters. Plastic rotation values calculated for different performance levels according to different design parameters are given Figure 6. For the nonlinear procedure defined in ASCE/SEI 41 [21], the load-deformation relationships of RC square columns or the curves describing the behavior under the effect of monotonically increasing deformation are given in Figure 7, respectively, according to different design parameters. As shown in Figure 7, the modeling parameter provides the plastic rotation at significant loss of lateral force capacity.

Table 3. Δ_y, Δ_p, Δ_u and μ_Δ values calculated according to different concrete grade

N/N_{max}	Transverse Reinforcement	ρ_s	Material	Δ_y (mm)	Δ_p (mm)	Δ_u (mm)	μ_Δ
0.1	Φ12/50mm	0.031	30	30.2	240.8	271	8.97
			40	30.2	195.4	225.6	7.47
			50	30.2	170	200.2	6.63
0.2			30	35.1	173.2	208.3	5.93
			40	35.1	133.7	168.8	4.81
			50	35.5	111.9	147.4	4.15
0.3			30	40.0	123.7	163.7	4.09
			40	41.2	99.4	140.6	3.41
			50	42.1	83.3	125.4	2.98
0.4			30	45.5	101.9	147.4	3.24
			40	47.1	75.3	122.4	2.60
			50	48.15	61.65	109.8	2.28

Table 4. Δ_y, Δ_p, Δ_u and μ_Δ values calculated according to different transverse reinforcement ratio

Material	Transverse Reinforcement	ρ_s	N/N_{max}	Δ_y (mm)	Δ_p (mm)	Δ_u (mm)	μ_Δ
C30	Φ10/50mm	0.0214	0.1	30.2	221.4	251.6	8.33
			0.2	35.4	163.7	199.1	5.62
			0.3	40.6	137.8	178.4	4.39
			0.4	47.5	119.8	167.3	3.52
	Φ12/50mm	0.031	0.1	30.2	241.3	271.5	8.99
			0.2	35.1	188.5	223.6	6.37
			0.3	40.0	180.0	220.0	5.50
			0.4	46.0	170.1	216.1	4.70
	Φ12/60mm	0.0258	0.1	30.2	232.5	262.7	8.70
			0.2	35.2	181.8	217.0	6.16
			0.3	40.2	167.9	208.1	5.18
			0.4	46.5	153.6	200.1	4.30
	Φ12/70mm	0.0221	0.1	30.2	227.4	257.6	8.53
			0.2	35.3	173.2	208.5	5.91
			0.3	40.4	153.5	193.9	4.80
			0.4	47.0	132.4	179.4	3.82
	Φ12/80mm	0.0194	0.1	30.2	215.9	246.1	8.15
			0.2	35.6	154.3	189.9	5.33
			0.3	40.8	123.9	164.7	4.04
			0.4	48.0	103.7	151.7	3.16

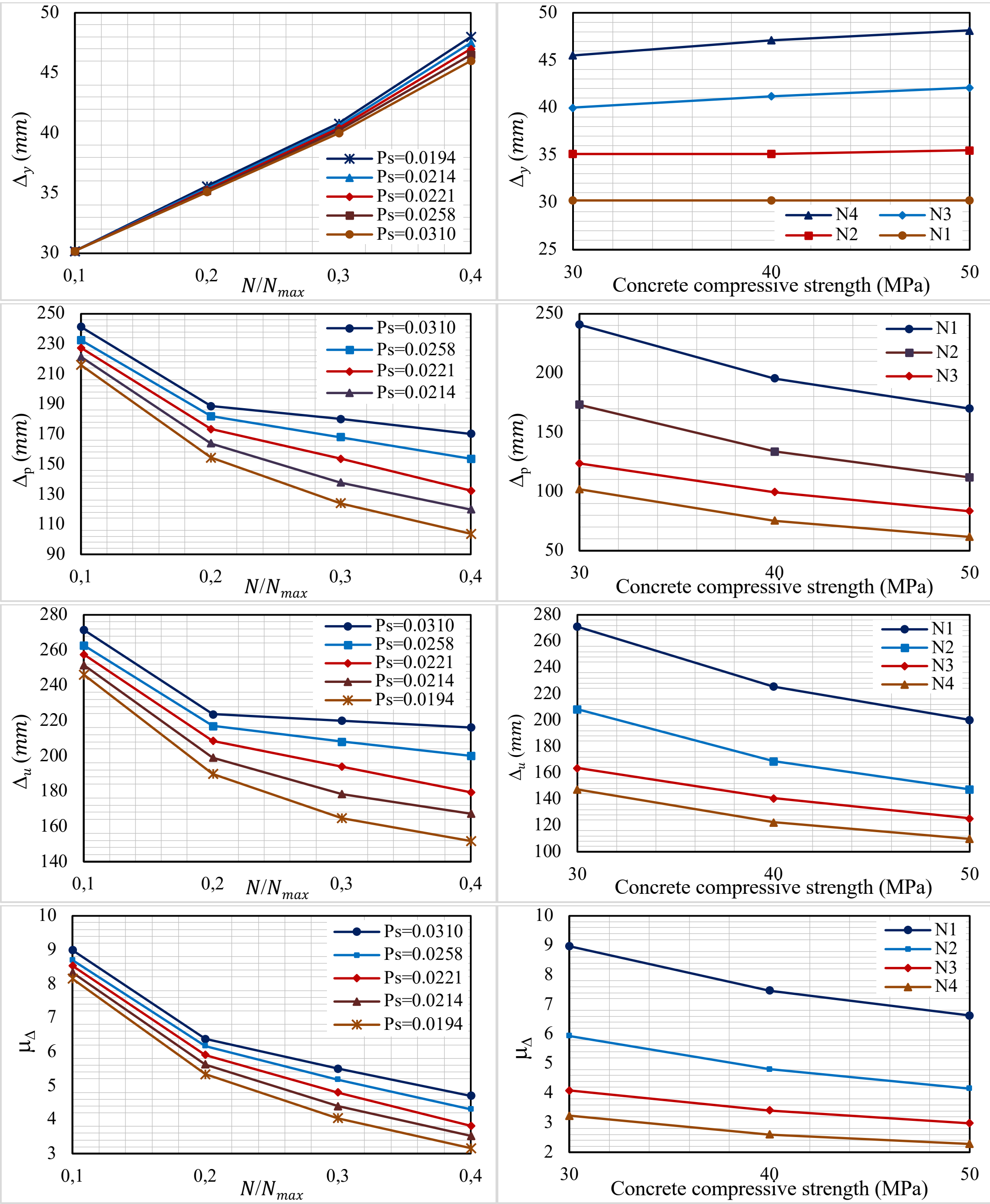

Figure 5. Influence of different parameters on the total peak displacement and displacement ductility

Table 5. Performance level values of RC square columns for different transverse reinforcement diameters

Material	Transverse Reinforcement	ρ_s	N/N_{max}	Modeling Parameters			Acceptance Criteria		
				Plastic rotation Angle (Radians)					
				a	b	c	Performance Level: IO	LS	CP
C30	Φ10/50mm	0.0214	0.10	0.042	0.078	0.213	0.0062	0.0391	0.0548
			0.20	0.037	0.069	0.187	0.0056	0.0345	0.0482
			0.30	0.034	0.061	0.160	0.0051	0.0307	0.0430
			0.40	0.031	0.055	0.133	0.0047	0.0276	0.0386
	Φ12/50mm	0.0310	0.10	0.046	0.082	0.213	0.0069	0.0408	0.0571
			0.20	0.042	0.074	0.187	0.0063	0.0372	0.0521
			0.30	0.038	0.068	0.160	0.0057	0.0342	0.0478
			0.40	0.035	0.063	0.133	0.0053	0.0315	0.0441

Table 6. Performance level values of RC square columns for different transverse reinforcement spacings

Material	Transverse Reinforcement	ρ_s	N/N_{max}	Modeling Parameters			Acceptance Criteria		
				Plastic rotation Angle (Radians)					
				a	b	c	Performance Level		
							IO	LS	CP
C30	Φ12/60mm	0.0258	0.10	0.044	0.080	0.213	0.0065	0.0400	0.0560
			0.20	0.040	0.072	0.187	0.0059	0.0359	0.0503
			0.30	0.036	0.065	0.160	0.0054	0.0325	0.0455
			0.40	0.033	0.059	0.133	0.0050	0.0297	0.0415
	Φ12/70mm	0.0221	0.10	0.042	0.079	0.213	0.0063	0.0393	0.0550
			0.20	0.038	0.069	0.187	0.0057	0.0347	0.0486
			0.30	0.034	0.062	0.160	0.0051	0.0310	0.0435
			0.40	0.032	0.056	0.133	0.0047	0.0280	0.0392
	Φ12/80mm	0.0194	0.10	0.040	0.077	0.213	0.0061	0.0386	0.0540
			0.20	0.036	0.067	0.187	0.0054	0.0336	0.0470
			0.30	0.033	0.059	0.160	0.0050	0.0297	0.0415
			0.40	0.030	0.053	0.133	0.0046	0.0264	0.0370

Table 7. Performance level values of RC square columns for different concrete compressive strength

Material	Transverse Reinforcement	ρ_s	N/N_{max}	Modeling Parameters			Acceptance Criteria		
				Plastic rotation Angle (Radians)					
				a	b	c	Performance Level		
							IO	LS	CP
C40	Φ12/50mm	0.0310	0.10	0.046	0.079	0.213	0.0068	0.0395	0.0553
			0.20	0.042	0.070	0.187	0.0063	0.0351	0.0492
			0.30	0.038	0.063	0.160	0.0057	0.0315	0.0441
			0.40	0.035	0.057	0.133	0.0053	0.0285	0.0399
C50			0.10	0.046	0.077	0.213	0.0068	0.0383	0.0537
			0.20	0.042	0.066	0.187	0.0063	0.0332	0.0465
			0.30	0.039	0.058	0.160	0.0058	0.0292	0.0409
			0.40	0.036	0.052	0.133	0.0053	0.0260	0.0364

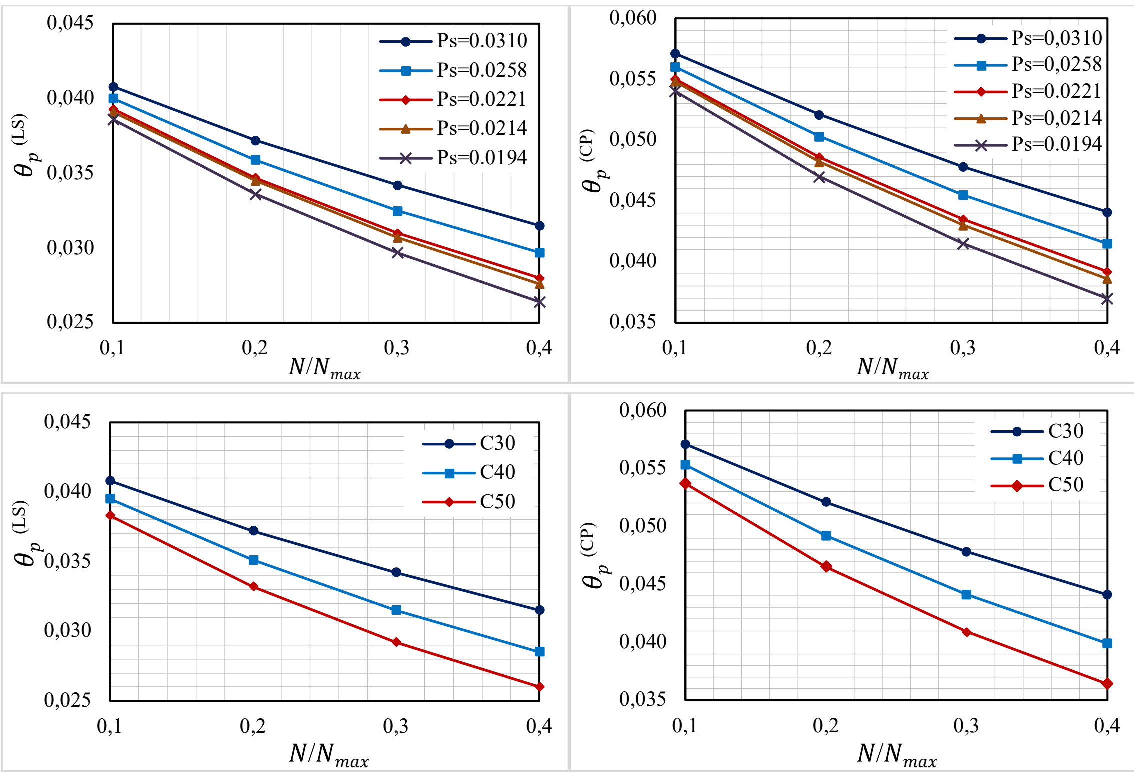

Figure 6. Plastic rotation values calculated for different performance levels according to different design parameters

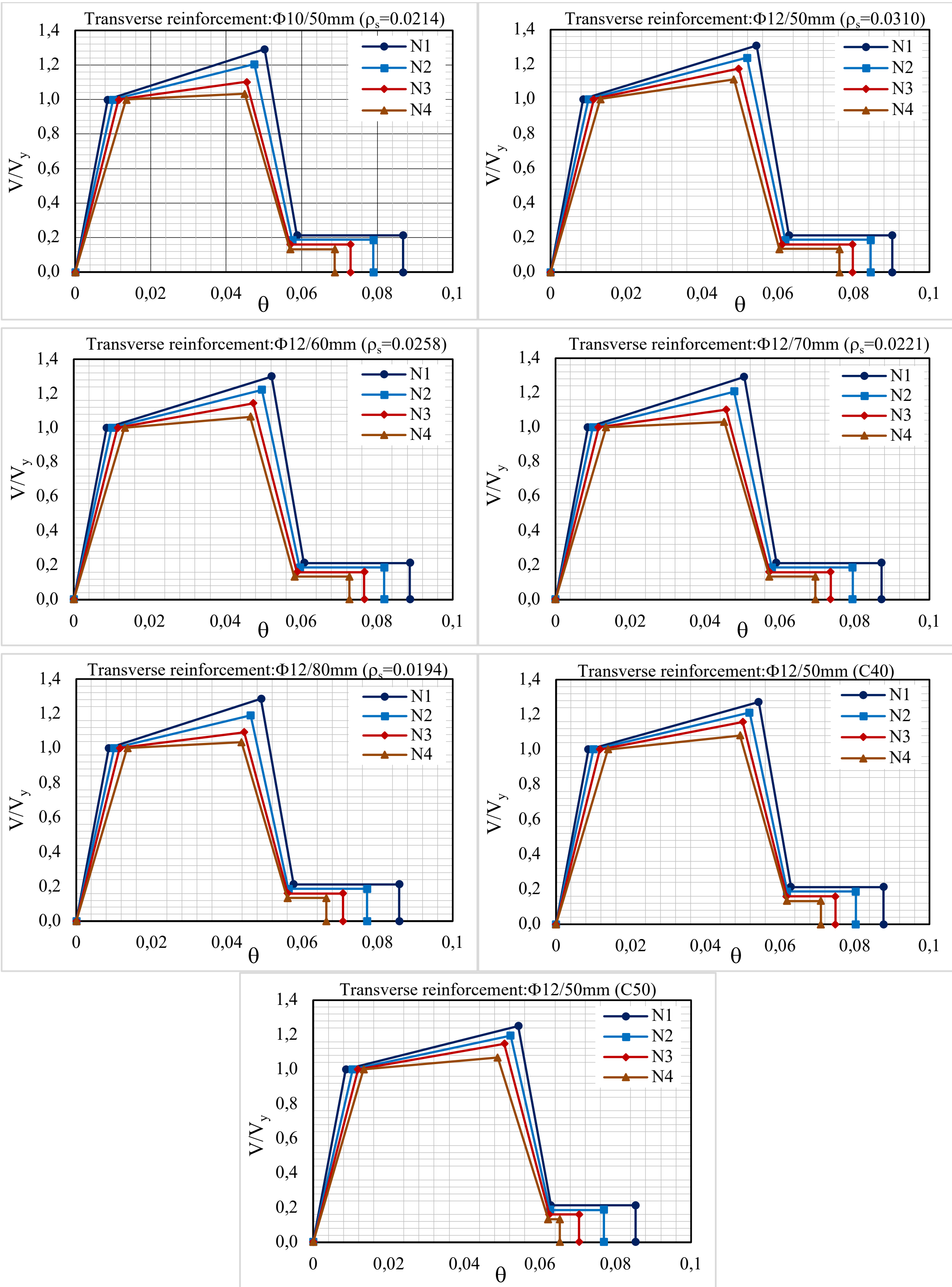

Figure 7. Force–deformation relation for RC square columns accordingt to different design parameters.

6. Conclusion

The ratio of transverse reinforcement is an effective parameter on the nonlinear behaviour of RC columns. The transverse reinforcement ratios have an important effect on the bearing capacity and ductility of the RC columns. In the displacement-controlled seismic design and plastic hinge analysis, the Δ_u of a cantilever column is obtained as the sum of its Δ_y and Δ_p component. There are differences in the values of $\emptyset_y$ and $\emptyset_u$ values in addition Δ_y, Δ_p, Δ_u and μ_Δ values calculated according to different axial load levels. Δ_y value increases, Δ_p, Δ_u and μ_Δ value decreases with increasing axial load level. The value of μ_Δ decreases with increasing Δ_y values and decreasing of Δ_u values. There are differences in the calculated Δ_y, Δ_p, Δ_u and μ_Δ values according to $\emptyset_y$, $\emptyset_u$ values and different axial load levels. According to different axial load levels, different Δ_u and μ_Δ values are natural result.

In the present study, the parameters affecting damage limits for RC square columns according to the deformation and rotation limits of the various codes were investigated. The following results were obtained from the code-based seismic performance assessment procedures in the square columns. One of the most important steps in the deformation-based seismic design and performance evaluation procedures according to the ASCE/SEI 41, 2017 is to determine the performance damage levels of CP, LS, and IO in the structural elements. From the load-deformation relations obtained for the column models; the V/V_y ratios increase with the increase of transverse reinforcement ratio (concrete compressive strength and axial load levels are constant). For the constant transverse reinforcement ratio and concrete compressive strength, V/V_y ratios decrease with increasing axial load levels. For the constant transverse reinforcement ratio and axial load levels, V/V_y ratios decrease with increasing compressive strength of concrete. The deformation ratio (θ) of the column models increases with the increase of transverse reinforcement ratio and concrete compressive strength.

Deformation ratio decreases with increasing axial load levels. IO values according to different parameters was obtained as a constant value of 0.005. LS and CP performance level damage values increase with increasing transverse reinforcement ratio and these performance damage values decrease with increasing axial load levels. The increase in concrete compressive strength remains constant with the modelling parameters calculated at the LS and CP performance levels in ASCE/SEI 41, 2017. However, the modelling parameters calculated for these performance levels decrease with increasing axial load level and transverse reinforcement spacing. Modelling parameters values increase with increasing transverse reinforcement diameter. It significantly reduces the damage limitations of the increase in the axial load levels. In the case of increasing axial load levels, plastic rotation values decrease for LS and CP performance levels. Plastic rotation values for LS and CP performance levels decrease when axial load levels increase for constant transverse reinforcement ratio and concrete compressive strength. With the increase of the transverse reinforcement ratio for the constant axial load level and the concrete compressive strength, the plastic rotation values for the LS (CD) and CP performance levels increase. As the axial load levels increase in RC column models, the damage limit values and plastic rotation values calculated for different performance levels decrease. At these axial load levels, it is seen from the analysis results that the transverse reinforcement ratio is more important in the performance levels of the sections and the modelling parameters and acceptance criteria stipulated in the regulation are quite effective.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest

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