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Research Article

Analysis of Bending Moment-Curvature and the Damage Limits of Reinforced Concrete Circular Columns

S. Bahadır Yüksel[1*], Saeid Foroughi[2]

[1] Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Konya / Turkey (ORCID: 0000-0002-4175-1156)
[2] Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Konya / Turkey (ORCID: 0000-0002-7556-2118)

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Abstract

In this study; the effect of axial load levels, longitudinal reinforcement ratio, transverse reinforcement diameter and transverse reinforcement spacing were investigated on the moment curvature relationships of reinforced concrete columns. For this purpose, circular reinforced concrete columns having different parameters were designed considering the regulations of the Turkish Building Earthquake Code (2018). The behavior of the columns were investigated from the moment-curvature relation, by considering the nonlinear behavior of the materials taken into account. The moment-curvature relationships of the reinforced concrete column cross-sections having different axial load levels have been obtained by considering Mander model, which considers the lateral, confined concrete strength. Moment-curvature relationships were obtained by SAP2000 Software, which takes the nonlinear behavior of materials into consideration. The designed reinforced concrete cross section models are considered to be composed of three components; cover concrete, confined concrete and reinforcement steel. The examined behavioral effects of the parameters were evaluated by the curvature and moment carrying capacity of the cross-sections. From the obtained moment-curvature relationship, cracking and destruction in cover and core concrete, yield and hardening conditions in reinforcement steel were calculated and the results were presented in charts and graphs. The confining effect in the core concrete is taken into account in the calculations. The behavior of the circular column sections and the types of refraction were interpreted according to the results obtained from the moment-curvature relationship of the sections. It is observed that the variation of the axial load, longitudinal reinforcement ratio, transverse reinforcement diameter and transverse reinforcement spacing have an important effect on the moment-curvature behavior of the reinforced concrete columns. The load bearing capacity of reinforced concrete column sections ends by destruction of the core concrete. Reinforced concrete column sections damaged by reinforcement yield before crushing of cover concrete exhibit more ductile behavior.

Keywords: Transverse reinforcement, nonlinear behavior, confined concrete strength, axial load, moment-curvature,

Betonarme Dairesel Kolonların Eğilme Momenti-Eğrilik ve Hasar Sınırlarının Analizi

Öz

Bu çalışmada; eksenel yük seviyesi, boyuna donatı oranı, sargı donatı çapı ve sargı donatı aralığının değişiminin betonarme kolonların moment-eğrilik ilişkisine olan etkisi incelenmiştir. Bu amaçla, farklı parametrelere sahip betonarme dairesel kolon modelleri Türkiye Bina Deprem Yönetmeliği (2018) hükümlerine uyularak tasarlanmıştır. Betonarme kolonların davranışı, malzemelerin doğrusal olmayan davranışları göz önüne alınarak moment-eğrilik ilişkisi üzerinden elde edilmiştir. Betonarme kolon kesitlerinin moment-eğrilik ilişkileri farklı eksenel yük seviyeleri için yanal sargı basıncını göz önüne alan Mander modeli ile elde edilmiştir. Moment-eğrilik ilişkileri, malzemelerin doğrusal olmayan davranışlarını dikkate alan SAP2000 programı ile elde edilmiştir. Tasarlanan betonarme kesit modellerinin kabuk betonu, sargılı beton ve donatı çeliği olarak üç farklı unsurdan oluştuğu düşünülmüştür. Parametrelerin incelenen davranışsal etkileri, kesitlerin eğrilik ve moment taşıma kapasitesi kullanılarak değerlendirilmiştir. Elde edilen Moment-eğrilik ilişkilerinden, kabuk ve çekirdek betonunda çatlama ve kırılma, donatı çeliğinde akma ve pekleşme durumları hesaplanarak sonuçlar çizelgeler ve grafikler halinde sunulmuştur. Çekirdek betonundaki sargı etkisi hesaplarda gözönüne alınmıştır. Dairesel kesitli

[*] Sorumlu Yazar: Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Konya / Turkey, ORCID: 0000-0002-4175-1156, sbyuksel@ktun.edu.tr

kolonlarının davranışı ve kırılma tipleri, kesitlerin moment-eğrilik ilişkisinden elde edilen sonuçlara göre yorumlanmıştır. Eksenel yükün, boyuna donatı oranının, sargı donatı çapının ve sargı donatı aralığının değişiminin betonarme kolonların moment-eğrilik davranışı üzerinde önemli bir etkiye sahip olduğu gözlemlenmiştir. Betonarme kolon kesitlerinin yük taşıma kapasitesi, çekirdek betonun ezilerek kırılması ile sona ermektedir. Kabuk betonun ezilmesinden önce donatı akması ile hasar gören betonarme kolon kesitleri daha fazla sünek davranış göstermektedir.

Anahtar Kelimeler: Sargı donatısı, doğrusal olmayan davranış, sargılı beton dayanımı, eksenel yük, moment-eğrilik.

1. Introduction

In reinforced concrete structures, reinforced concrete columns are one of the most crucial elements under earthquake loads. Column mechanisms are very critical to prevent total collapse in earthquakes. The objective performance levels of reinforced concrete structures could not be ensured due to the failure of some critical reinforced concrete columns. Because of this, determining the behavior of the structures should be known well to design earthquake-resisting structures (Dok et al., 2017). In seismic zones, it is important to design structures, with power ranging deformation beyond the elastic deformations without losing its ability to stay in service, in other words designing structures with ductile behavior. The current philosophy used in the seismic design of reinforced concrete frames auto-stable is based on the hypothesis of the formation of plastic hinges at critical sections, the ability of the latter to resist several cycles of inelastic deformations without significant loss in bearing capacity is evaluated in terms of available ductility (Youcef and Chemrouk, 2012).

The behavior of reinforced concrete elements are determined by the cross-sectional behavior of elements. Cross-sectional behavior depends on the materials designed of the cross-section and the loading on that particular cross-section. The behavior of a reinforced concrete cross-section under bending moment or bending moment plus axial force can be monitored from moment-curvature relationship (Xie et al., 1994).

The bending moment-curvature curve can be widely applied in cross-section seismic analysis of reinforced concrete as the seismic performance that evaluates the cross-section. The bending moment-curvature curve is obtained by section size and reinforcement. The method of using this curve to evaluate the cross-section seismic performance is simple and able to save the analysis time (Jun and Hui, 2015).

Bedirhanoglu and Ilki (2004) obtained the analytical moment-curvature relationships for reinforced concrete cross-sections by using three different models for confined concrete. The theoretical moment-curvature relationships were then compared with experimental data reported in the literature. The results showed that the theoretical moment-curvature relationships obtained by all of these three models were in quite good agreement with experimental data. In the second part, a parametric investigation was carried out for examining the effects of various variables on the moment-curvature relationships, such as quality of concrete, level of axial load, amount and arrangement of transverse reinforcement.

Foroughi and Yuksel (2020) investigated the effect of the material model, axial load, longitudinal reinforcement ratio, transverse reinforcement ratio and transverse reinforcement spacing on the behavior of square reinforced concrete cross-sections. The effect of axial load, transverse reinforcement diameter and transverse reinforcement spacing on the behavior of reinforced concrete column models have been analytically investigated. The moment-curvature relationships for different axial load levels, transverse reinforcement diameter and transverse reinforcement spacing of the reinforced concrete column cross-sections were obtained considering the Mander confined model (Mander et. al, 1988). It was examined behavioral effects of the parameters were evaluated by comparing the curvature ductility and the cross-section strength. It has been found that transverse reinforcement diameters and transverse reinforcement spacing are effective parameters on the ductility capacities of the column sections. Axial load is a very important parameter affecting the ductility of the section. It has been observed that the cross-sectional ductility of the column sections increases with the decrease in axial load.

In this study, reinforced concrete circular columns were designed and the effects of the longitudinal reinforcement ratio, axial load levels, transverse reinforcement diameter and transverse reinforcement spacing on the behavior of these models were investigated. The behavior of the reinforced concrete column models was investigated through the relation of moment-curvature. Forty-eight circular reinforced concrete columns having different longitudinal and transverse reinforcements were analyzed. Moment-curvature relations were obtained and presented in graphical form using SAP2000 Software (CSI, V.20.1.0) which takes nonlinear behavior of materials into consideration. The designed reinforced concrete cross section models are considered to be composed of three components; cover concrete, confined concrete and reinforcement steel. The SAP2000 Software material models are defined considering the Mander unconfined concrete model for cover concrete, and the Mander confined concrete model for core concrete. A concrete model proposed by Mander et al. (1988) which is widely used, universally accepted and mandated in Turkish Building Earthquake Code (TBEC, 2018) has been used to determine the moment-curvature relationships of reinforced concrete members. For reinforcement modeling stress-strain relationship given in TBEC (2018) was used. The examined behavioral effects of the parameters were evaluated by the curvature and moment carrying capacity of the cross-section. From the moment-curvature relationships obtained, the limits of damage zones were calculated in circular column sections. From the moment-curvature relationships, the limits of the damage zone were calculated based on limit states of strain in concrete and reinforcement bars in the section. From the obtained moment-curvature relationship, cracking and destruction in cover and core concrete, yield and hardening conditions in reinforcement steel were calculated and the results were presented in charts and graphs. The confining effect in the core concrete is taken into account in the calculations. The behavior of the circular section columns and the types of refraction were interpreted according to the results obtained from the moment-curvature relationship of the section.

2. Material and Method

The aim of this paper is to examine the influence of four parameters on the moment-curvature and the limits of the damage zone of reinforced concrete columns. SAP2000 software was used to predict the moment-curvature of reinforced concrete columns having different axial load levels (N/N_{max}). In order to investigate the effect of longitudinal reinforcement ratio, transverse reinforcement diameter, transverse reinforcement spacing and axial load levels, forty-eight reinforced concrete circular column models having dimensions 450mm diameter circular cross-sections were designed (Table 1). The parameters investigated in the moment-curvature relations of the reinforced concrete circular column models are the longitudinal reinforcement ratio, transverse reinforcement diameter, transverse reinforcement spacing and axial load levels. By using the Mander model (Mander et. al, 1988), the moment-curvature relationships of the reinforced concrete circular columns are obtained by using the SAP2000 software, which performs non-linear analysis for different models designed. For all RC column models, C30 was chosen as concrete grade and B420C was selected as reinforcement for the reinforcement behavior model. The stress-strain relationship for materials given in TBEC (2018) were used (Table 2 and Figure 1).

Different transverse reinforcement diameters; Φ8mm and Φ10mm and the transverse reinforcement spacing; 50mm were selected in order to investigate the effect of the transverse reinforcement on the cross-section behavior. In the column models the longitudinal column reinforcement was Φ20, Φ22, Φ24, Φ24, Φ26, Φ28 and Φ30 selected. Six different longitudinal reinforcement diameters and two different transverse reinforcement diameters are used for each reinforced concrete circular column models. In order to examine the effect of longitudinal reinforcement diameter on cross-sectional behavior, six different longitudinal reinforcement diameters (Φ20 mm, Φ22 mm, Φ24 mm, Φ26 mm, Φ28 mm ve Φ30 mm) were selected.

The combined effect of vertical and seismic loads (N_{dm}), gross section area of column shall satisfy the condition $A_c \geq N_{dmax}/0.40f_{ck}$ (TBEC, 2018). In this section, the moment-curvature relationships of the column sections were investigated for the values of N/N_{max} ratios of 0.10, 0.20, 0.30 and 0.40. To investigate the effect of axial force on the cross-section behavior the circular columns models were investigated under four different axial loads (480 kN, 960 kN, 1440 kN and 1920 kN). The aim of this paper is to examine the influence of different axial load levels, transverse reinforcement diameter and transverse reinforcement spacing on the moment-curvature and the limits of the damage zone for the designed column cross-sections are presented. The results obtained from the analyzes for reinforced concrete columns with different parameters were compared and interpreted.

Table 1. Details for the designed column model cross-sections

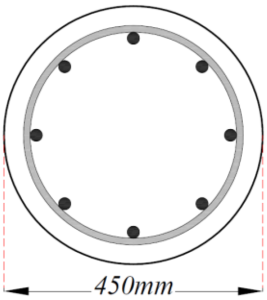
No	Cross-sectional dimensions	Longitudinal reinforcement	Transverse reinforcement	Axial Load (N/N_{max})
A		8Φ20 mm	Φ8/50 mm	0.10 0.20 0.30 0.40
B		8Φ22 mm		
C		8Φ24 mm		
D		8Φ26 mm		
E		8Φ28 mm		
F		8Φ30 mm		
J		8Φ20 mm	Φ10/50 mm	0.10 0.20 0.30 0.40
H		8Φ22 mm		
I		8Φ24 mm		
G		8Φ26 mm		
K		8Φ28 mm		
L		8Φ30 mm		

Table 2. Material parameters for concrete and reinforcement (TBEC, 2018)

Standard Strength	Parameters	Values
Concrete: C30	Strain at maximum stress of unconfined concrete (ε_{co})	0.002
	Ultimate compression strain of concrete (ε_{cu})	0.0035
	Characteristic standard value of concrete compressive strength (f_{ck})	30 MPa
Reinforcement: B420C	Yield strain of reinforcement (ε_{sy})	0.0021
	Spalling strain in reinforcing steel (ε_{sp})	0.008
	Strain in reinforcing steel at ultimate strength (ε_{su})	0.080
	Characteristic yield strength of reinforcement (f_{yk})	420 MPa
	Ultimate strength of reinforcement (f_{su})	550 MPa

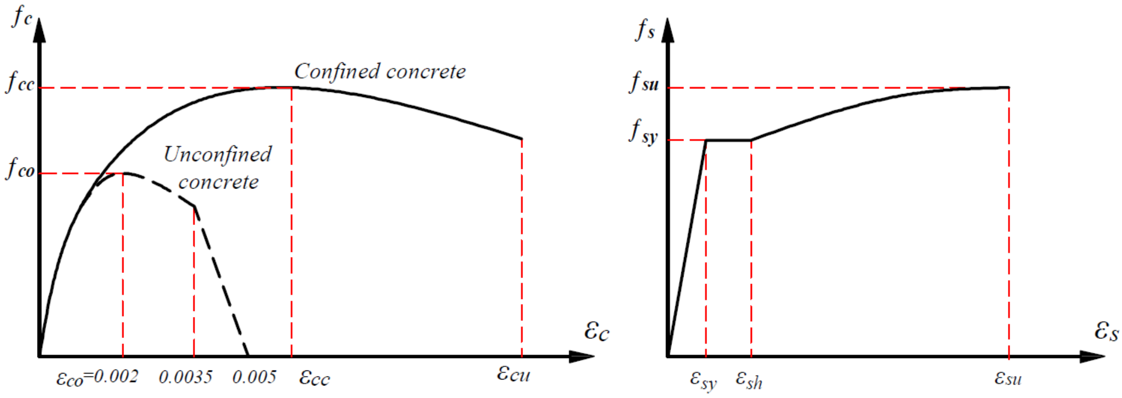
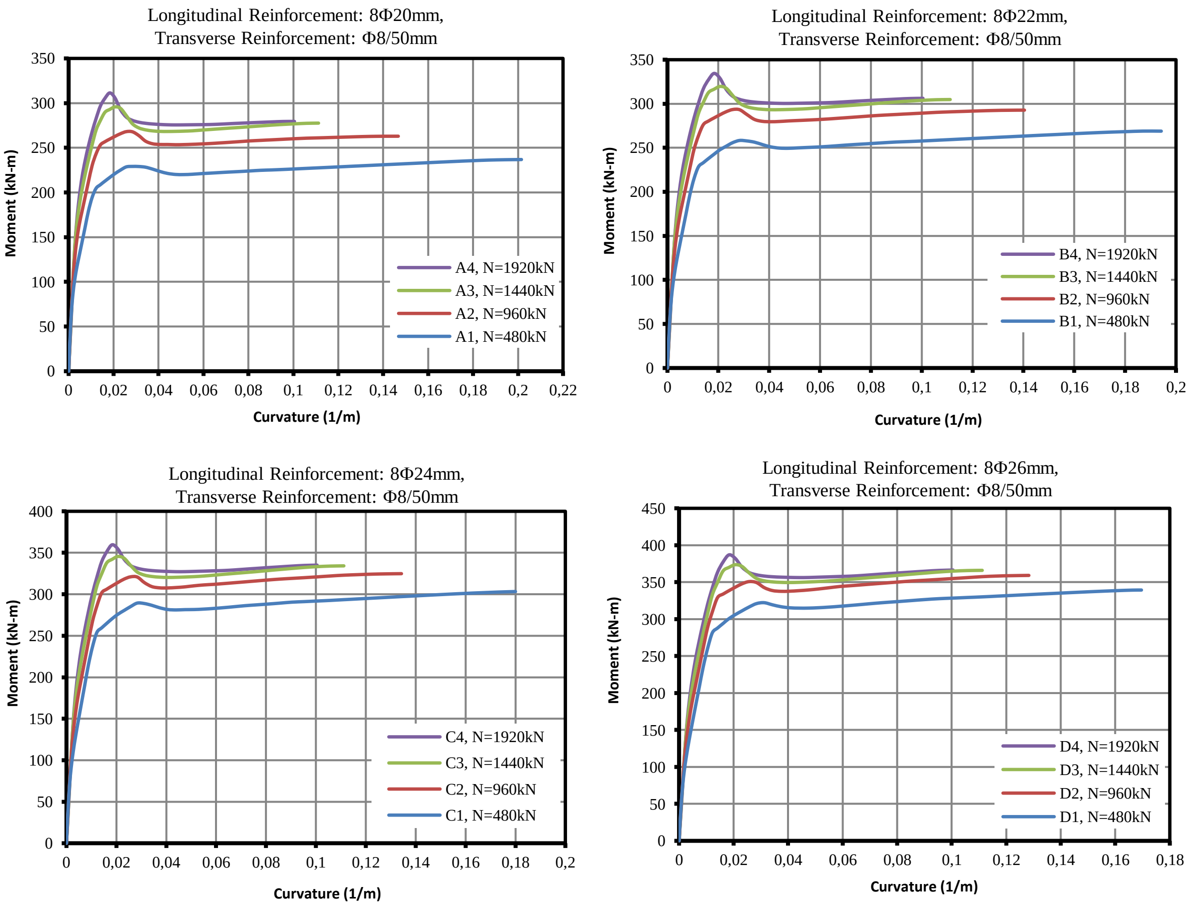


Figure 1. Stress-strain relationship for concrete and reinforcement (TBEC, 2018)

3. Numerical Study

In this study, the design parameters of reinforced concrete members are investigated to determine the behavior of reinforced concrete circular columns. Theoretical moment-curvature analysis for reinforced concrete circular columns indicating the available bending moment and curvature can be constructed providing that the stress-strain relations for both concrete and steel are known. The objective of this study is to analyze the moment-curvature and the limits of the damage zone of forty-eight reinforced concrete circular columns with different parameters. Moment-curvature relationships were obtained by SAP2000 Software which takes the nonlinear behavior of materials into consideration. In this part of the study, the moment-curvature relations are obtained by changing the longitudinal reinforcement ratio, transverse reinforcement diameter, transverse reinforcement spacing and axial load levels. The numerical model was employed to calculate the moment and curvature values at the limit of the damage zone of reinforced concrete circular columns with different parameters. The moment-curvature relationships of reinforced concrete circular columns were determined and the results were prepared are given in Figure 2. In Figure 2, moment-curvature relationships are presented comparatively for different axial load levels. For different axial load levels, critical points in moment-curvature relations of circular cross-section column models are determined and presented in tables.



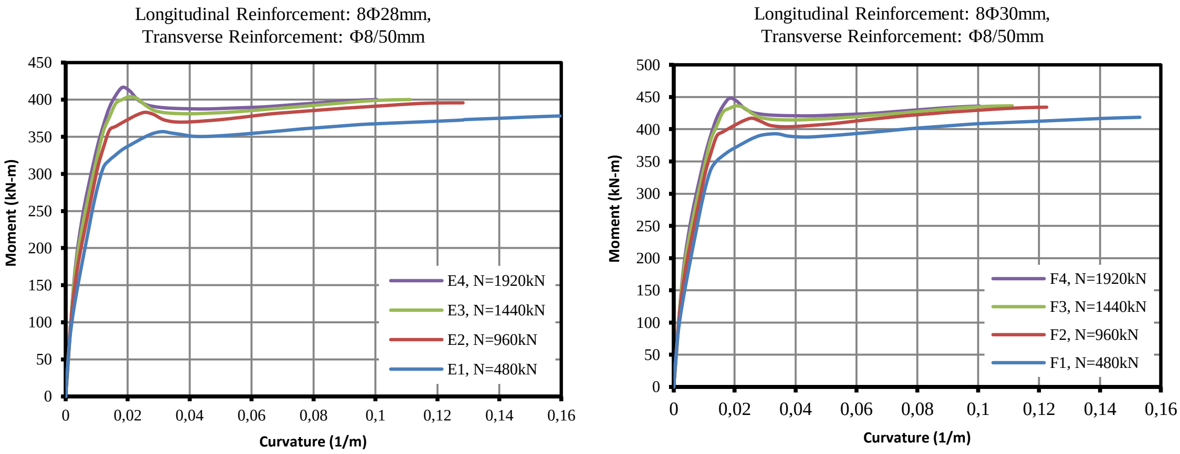


Figure 2. Moment-curvature relationships for different axial load levels (transverse reinforcement Φ8/50 mm)

From the moment-curvature relationships of reinforced concrete circular column sections, the limits of the damage zone were calculated. Three material models are defined as cover concrete, reinforcing steel and core concrete for each section. From the obtained moment-curvature relationship, cracking and destruction in cover and core concrete, yield and hardening conditions in reinforcement steel were calculated and the results were presented in charts and graphs. The behavior of the circular section columns and the types of destruction were interpreted according to the results obtained from the moment-curvature relationship of the section. The values obtained according to different parameters for each material model in circular column sections are given in Tables 3 to 8 and 10 to 15, respectively. The units for the moment (M) is kN.m and the units for the curvature (C) is rad/m in all Tables. The circular reinforced concrete column sections given in the tables are prepared for four different axial loads, six different longitudinal rebar diameters and two different transverse reinforcement diameters and spacings. Using the values obtained from the moment-curvature relationships given in the tables, the fracture types and behaviors of the column sections were examined.

Table 3. Critical moment and curvature values calculated for (A) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
A1	0.1	183.1	0.0092	229.1	0.0312	216.9	0.0183	220.1	0.0494	236.9	0.2015
A2	0.2	230.8	0.0105	254.5	0.0342	248.2	0.0132	257.4	0.0374	262.9	0.1467
A3	0.3	267.3	0.0120	268.3	0.0406	253.4	0.0105	274.6	0.0298	277.6	0.1112
A4	0.4	293.1	0.0136	275.6	0.0475	252.2	0.0088	284.3	0.0257	279.5	0.1005

Table 4. Critical moment and curvature values calculated for (B) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
B1	0.1	202.8	0.0093	257.8	0.0312	240.3	0.0172	249.4	0.0475	268.9	0.1870
B2	0.2	249.6	0.0106	280.1	0.0374	263.9	0.0122	281.1	0.0357	292.8	0.1404
B3	0.3	286.3	0.0120	293.3	0.0406	269.7	0.0105	298.7	0.0298	304.8	0.1112
B4	0.4	312.2	0.0136	300.4	0.0475	265.2	0.0088	308.5	0.0257	306.2	0.1005

Table 5. Critical moment and curvature values calculated for (C) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
C1	0.1	224.1	0.0095	287.8	0.0327	265.0	0.0162	281.3	0.0458	303.3	0.1800
C2	0.2	267.6	0.0105	307.7	0.0374	286.1	0.0122	309.3	0.0342	324.8	0.1343
C3	0.3	307.1	0.0120	320.3	0.0410	287.6	0.0105	324.9	0.0298	334.2	0.1112
C4	0.4	333.1	0.0135	327.3	0.0475	279.3	0.0088	334.7	0.0257	335.1	0.1005

Table 6. Critical moment and curvature values calculated for (D) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
D1	0.1	247.3	0.0096	320.9	0.0327	291.1	0.0151	315.2	0.0423	339.4	0.1696
D2	0.2	292.3	0.0108	337.6	0.0374	310.1	0.0122	338.7	0.0342	359.2	0.1283
D3	0.3	329.8	0.0120	349.7	0.0423	307.1	0.0105	355.1	0.0284	366.1	0.1112
D4	0.4	355.8	0.0134	356.4	0.0475	294.8	0.0088	363.1	0.0257	366.5	0.1005

Table 7. Critical moment and curvature values calculated for (E) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
E1	0.1	272.3	0.0097	354.9	0.0342	297.1	0.0113	341.3	0.0219	378.1	0.1596
E2	0.2	316.3	0.0108	369.7	0.0374	310.8	0.0105	380.1	0.0284	395.8	0.1253
E3	0.3	354.3	0.0120	381.2	0.0423	328.0	0.0105	385.7	0.0284	400.1	0.1112
E4	0.4	380.3	0.0134	387.7	0.0475	341.6	0.0088	393.8	0.0257	400.1	0.1005

Table 8. Critical moment and curvature values calculated for (F) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
F1	0.1	299.1	0.0099	392.8	0.0342	350.9	0.0141	389.6	0.0374	418.6	0.1531
F2	0.2	341.9	0.0109	403.8	0.0374	363.2	0.0122	405.4	0.0327	434.3	0.1225
F3	0.3	380.5	0.0120	414.7	0.0423	350.4	0.0105	418.4	0.0284	436.4	0.1112
F4	0.4	406.4	0.0133	421.1	0.0475	329.5	0.0088	429.6	0.0244	436.1	0.1005

The effect of longitudinal reinforcement ratio on the moment-curvature relationship in reinforced concrete column sections is given in Figures 3 and 5 comparatively. In Figure 3, the effect of the change of longitudinal reinforcement ratio under constant axial load for Φ8/50 mm transverse reinforcement on moment-curvature relationship is summarized. In Figure 5, the effect of the change of longitudinal reinforcement ratio under constant axial load for Φ10/50 mm transverse reinforcement on moment-curvature relationship is summarized.

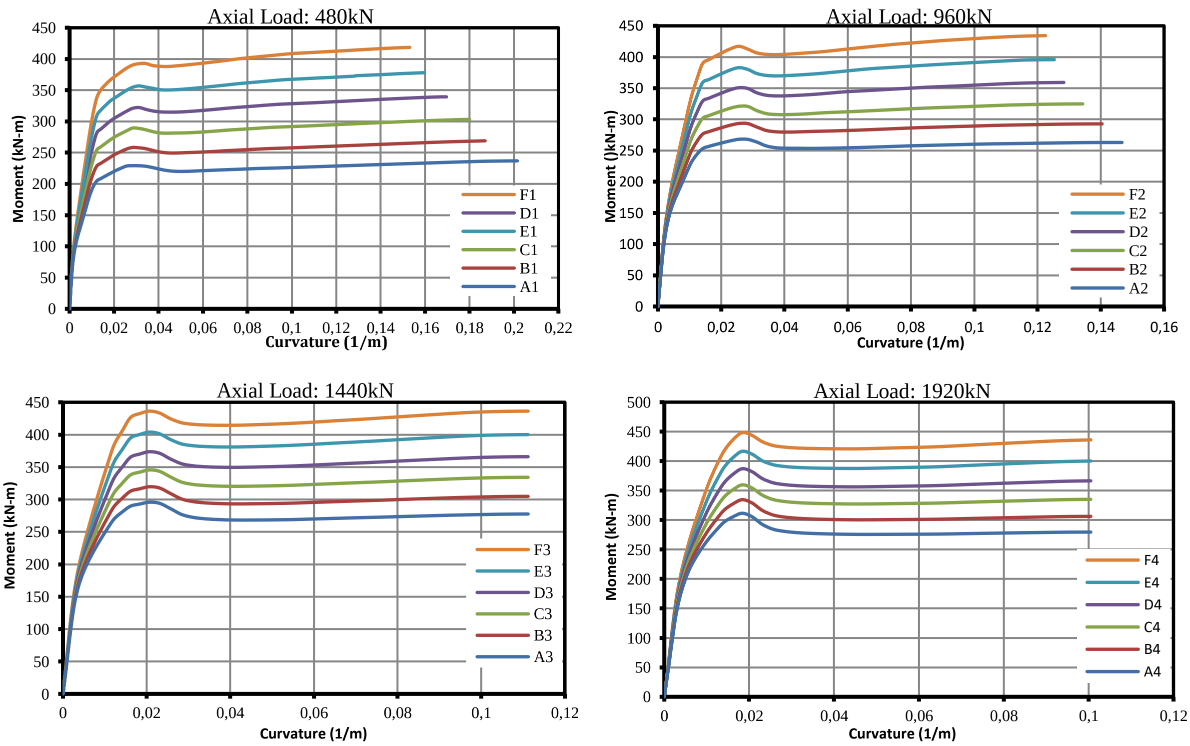


Figure 3. Moment-curvature relationships for different longitudinal reinforcement ratio (transversae Reinforcement Φ8/50 mm)

Table 9 was prepared to compare the effects of longitudinal reinforcement ratio and axial load levels on moment-curvature behavior of circular sections for constant transverse reinforcement spacing (Φ8/50 mm). In Table 9, by using the moment-curvature relationships given in Figure 3, maximum moment (M_u) and maximum curvature values (C_u) are summarized.

Table 9. Maximum moment (M_u) and maximum curvature (C_u) values at the moment of destruction in circular column sections (transverse reinforcement: Φ8/50mm)

No	N/N_{max}	Destruction		No	N/N_{max}	Destruction		No	N/N_{max}	Destruction		No	N/N_{max}	Destruction	
		M_u	C_u			M_u	C_u			M_u	C_u			M_u	C_u
A1	0.10	236.9	0.2015	A2	0.20	263.0	0.1467	A3	0.30	277.6	0.1112	A4	0.40	279.5	0.1005
B1		269.0	0.1870	B2		292.8	0.1404	B3		304.8	0.1112	B4		306.2	0.1005
C1		303.3	0.1800	C2		324.8	0.1343	C3		334.2	0.1112	C4		335.1	0.1005
D1		339.4	0.1696	D2		359.2	0.1283	D3		366.1	0.1112	D4		366.5	0.1005
E1		378.0	0.1596	E2		395.8	0.1253	E3		400.1	0.1112	E4		400.1	0.1005
F1		418.6	0.1531	F2		434.3	0.1225	F3		436.4	0.1112	F4		436.0	0.1005

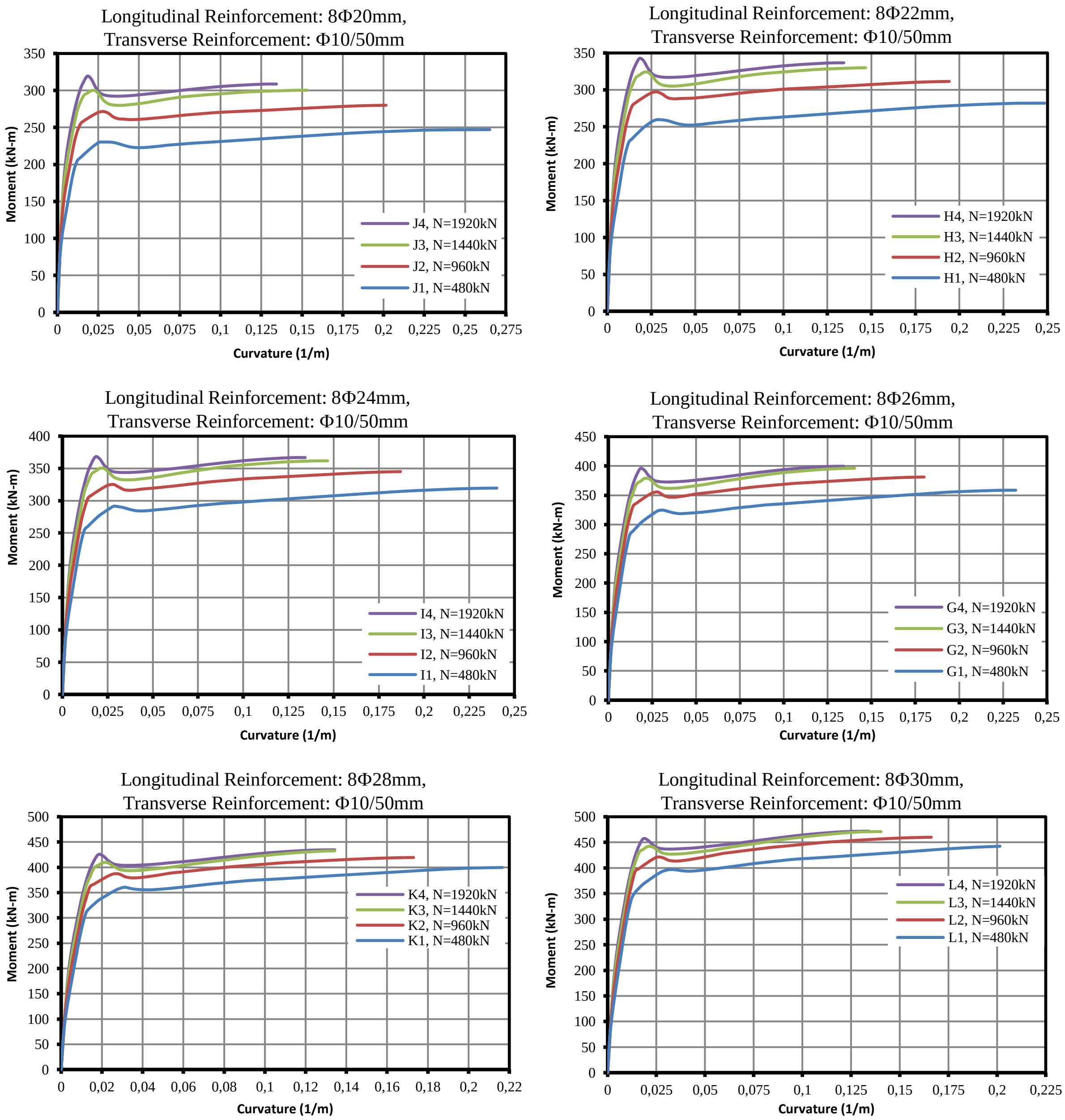


Figure 4. Moment-curvature relationships for different axial load levels (transverse reinforcement: Φ10/50 mm)

Table 10. Critical moment and curvature values calculated for (J) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
J1	0.1	183.5	0.0092	230.3	0.0312	215.6	0.0172	222.7	0.0512	247.0	0.2651
J2	0.2	231.9	0.0105	263.1	0.0358	249.9	0.0132	261.8	0.0374	279.9	0.2015
J3	0.3	269.9	0.0119	280.1	0.0406	256.4	0.0105	281.9	0.0312	300.4	0.1531
J4	0.4	297.5	0.0134	293.2	0.0458	256.6	0.0088	297.3	0.0257	308.7	0.1343

Table 11. Critical moment and curvature values calculated for (H) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
H1	0.1	203.2	0.0093	259.3	0.0312	238.8	0.0162	252.2	0.0475	281.9	0.2484
H2	0.2	250.8	0.0106	288.7	0.0358	265.7	0.0122	288.7	0.0358	311.4	0.1942
H3	0.3	289.1	0.0119	305.4	0.0406	272.8	0.0105	306.3	0.0312	329.9	0.1467
H4	0.4	316.6	0.0134	318.2	0.0458	269.4	0.0088	321.5	0.0257	336.6	0.1343

Table 12. Critical moment and curvature values calculated for (I) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
I1	0.1	224.7	0.0095	289.9	0.0327	266.1	0.0162	284.4	0.0458	319.6	0.2403
I2	0.2	271.4	0.0107	316.6	0.0358	288.2	0.0122	316.6	0.0358	345.1	0.1870
I3	0.3	309.8	0.0119	332.9	0.0406	290.8	0.0105	335.1	0.0298	361.8	0.1467
I4	0.4	337.5	0.0133	344.8	0.0440	283.5	0.0088	347.7	0.0257	366.8	0.1343

Table 13. Critical moment and curvature values calculated for (G) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
G1	0.1	247.9	0.0096	323.3	0.0327	292.3	0.0151	318.9	0.0440	358.6	0.2322
G2	0.2	293.8	0.0108	346.6	0.0374	312.4	0.0122	346.9	0.0342	381.2	0.1800
G3	0.3	332.5	0.0119	362.7	0.0406	310.3	0.0105	363.9	0.0298	396.1	0.1404
G4	0.4	360.1	0.0133	374.1	0.0440	298.9	0.0088	376.1	0.0257	399.5	0.1343

Table 14. Critical moment and curvature values calculated for (K) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
K1	0.1	273.1	0.0097	358.1	0.0342	319.7	0.0141	355.6	0.0406	399.6	0.2166
K2	0.2	317.9	0.0108	379.3	0.0374	338.3	0.0122	379.2	0.0342	419.5	0.1730
K3	0.3	357.0	0.0119	394.6	0.0406	331.4	0.0105	394.9	0.0298	432.6	0.1404
K4	0.4	384.6	0.0132	405.5	0.0440	315.7	0.0088	406.8	0.0257	434.6	0.1343

Table 15. Critical moment and curvature values calculated for (L) columns

No	N/N_{max}	Reinforcement Steel				Cover Concrete				Core Concrete	
		Yield		Hardening		Cracking		Destruction		Destruction	
		M	C	M	C	M	C	M	C	M	C
L1	0.1	299.9	0.0099	396.7	0.0342	352.3	0.0141	394.4	0.0390	442.4	0.2015
L2	0.2	343.7	0.0109	413.9	0.0374	351.2	0.0113	414.3	0.0327	460.1	0.1662
L3	0.3	383.2	0.0119	428.5	0.0406	353.9	0.0105	428.9	0.0284	470.9	0.1404
L4	0.4	410.7	0.0132	439.1	0.0440	333.6	0.0088	439.4	0.0257	471.9	0.1343

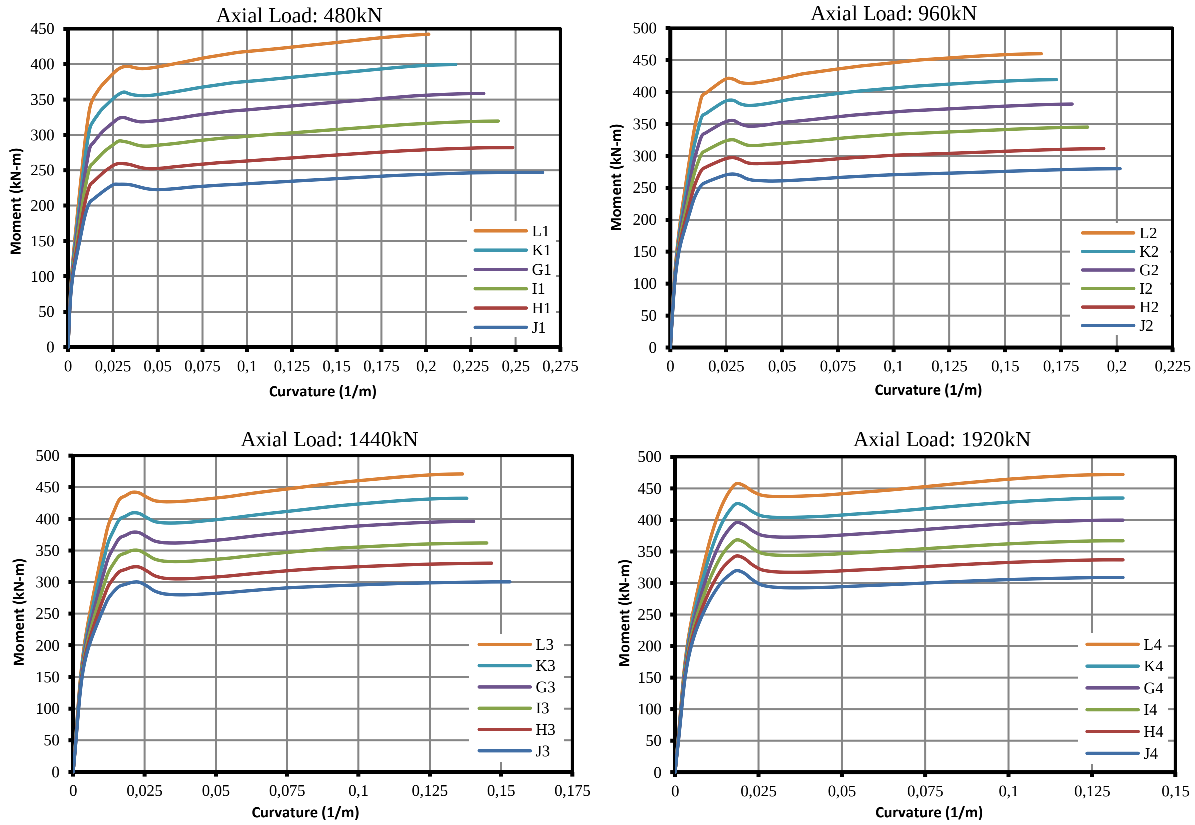


Figure 5. Moment-curvature relationships for different longitudinal reinforcement ratio (transverse reinforcement Φ10/50 mm)

Table 16 was prepared to compare the effects of longitudinal reinforcement ratio and axial load levels on moment-curvature behavior of circular sections for constant transverse reinforcement spacing (Φ10/50 mm). In Table 16, by using the moment-curvature relationships given in Figure 5, maximum moment (M_u) and maximum curvature values (C_u) are summarized.

Table 16. Maximum moment (M_u) and maximum curvature (C_u) values at the moment of destruction in circular column sections (transverse reinforcement: Φ10/50mm)

No	N/N_{max}	Destruction		No	N/N_{max}	Destruction		No	N/N_{max}	Destruction		No	N/N_{max}	Destruction	
		M_u	C_u			M_u	C_u			M_u	C_u			M_u	C_u
J1	0.10	247.0	0.2651	J2	0.20	279.9	0.2015	J3	0.30	300.4	0.1531	J4	0.40	308.7	0.1343
H1		281.9	0.2484	H2		311.4	0.1942	H3		329.9	0.1467	H4		336.6	0.1343
I1		319.6	0.2403	I2		345.1	0.1870	I3		361.8	0.1467	I4		366.8	0.1343
G1		358.6	0.2322	G2		381.2	0.1800	G3		396.1	0.1404	G4		399.5	0.1343
K1		399.6	0.2166	K2		419.5	0.1730	K3		432.6	0.1404	K4		434.6	0.1343
L1		442.4	0.2015	L2		460.1	0.1662	L3		470.9	0.1404	L4		471.9	0.1343

4. Research Results and Discussion

The examined behavioral effects of the parameters were evaluated by the curvature and moment carrying capacity of the cross-section. Moment and curvature values in case of destruction according to different parameters of reinforced concrete circular column sections are summarized in Table 17 comparatively. The behavior of the circular column sections and the types of refraction were interpreted according to the results obtained from the moment-curvature relationship of the section. The influence of different parameters on the moment bearing capacity and curvature of the reinforced concrete circular columns are given Figures 6 to 11 comparatively.

Table 17. Moment and curvature values in case of destruction according to different parameters

No	N/N_{max}	Longitudinal Reinforcement	Transverse Reinforcement	Destruction		No	Transverse Reinforcement	Destruction	
				M_u	C_u			M_u	C_u
A1	0.10	8Φ20 mm	Φ8/50 mm	236.9	0.2015	J1	Φ10/50 mm	246.9	0.2651
A2	0.20			262.9	0.1467	J2		279.9	0.2015
A3	0.30			277.6	0.1112	J3		300.4	0.1531
A4	0.40			279.5	0.1005	J4		308.7	0.1343
B1	0.10	8Φ22 mm	Φ8/50 mm	268.9	0.1870	H1	Φ10/50 mm	281.9	0.2484
B2	0.20			292.8	0.1404	H2		311.4	0.1942
B3	0.30			304.8	0.1112	H3		329.9	0.1467
B4	0.40			306.2	0.1005	H4		336.6	0.1343
C1	0.10	8Φ24 mm	Φ8/50 mm	303.3	0.1800	I1	Φ10/50 mm	319.6	0.2403
C2	0.20			324.8	0.1343	I2		345.1	0.1870
C3	0.30			334.2	0.1112	I3		361.8	0.1467
C4	0.40			335.1	0.1005	I4		366.8	0.1343
D1	0.10	8Φ26 mm	Φ8/50 mm	339.4	0.1696	G1	Φ10/50 mm	358.6	0.2322
D2	0.20			359.2	0.1283	G2		381.2	0.1800
D3	0.30			366.1	0.1112	G3		396.1	0.1404
D4	0.40			366.5	0.1005	G4		399.5	0.1343
E1	0.10	8Φ28 mm	Φ8/50 mm	378.1	0.1596	K1	Φ10/50 mm	399.6	0.2166
E2	0.20			395.8	0.1253	K2		419.5	0.1730
E3	0.30			400.1	0.1112	K3		432.6	0.1404
E4	0.40			400.1	0.1005	K4		434.6	0.1343
F1	0.10	8Φ30 mm	Φ8/50 mm	418.6	0.1531	L1	Φ10/50 mm	442.4	0.2015
F2	0.20			434.3	0.1225	L2		460.1	0.1662
F3	0.30			436.4	0.1112	L3		470.9	0.1404
F4	0.40			436.1	0.1005	L4		471.9	0.1343

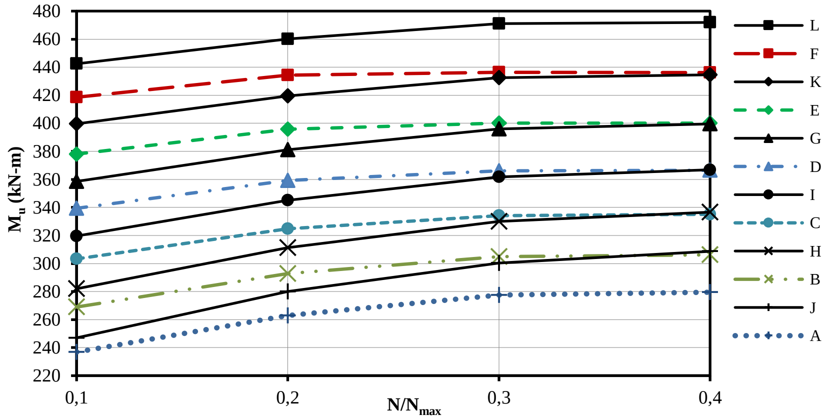


Figure 6. Influence of different parameters on the moment bearing capacity of the reinforced concrete circular columns

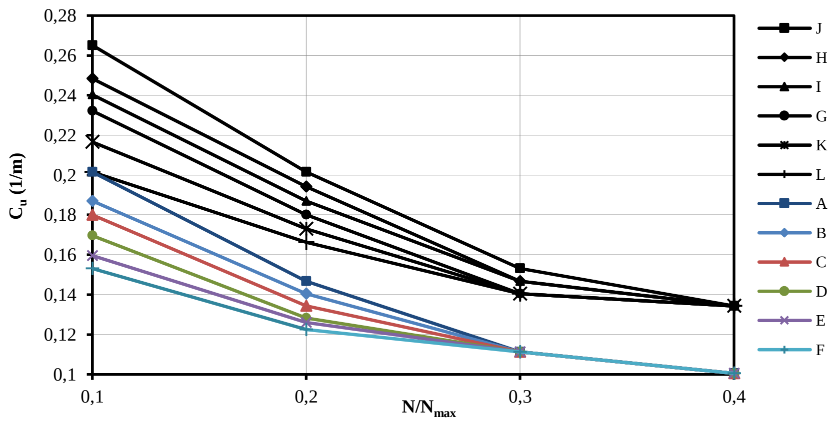


Figure 7. Influence of different parameters on the curvature of the reinforced concrete circular columns (ductility)

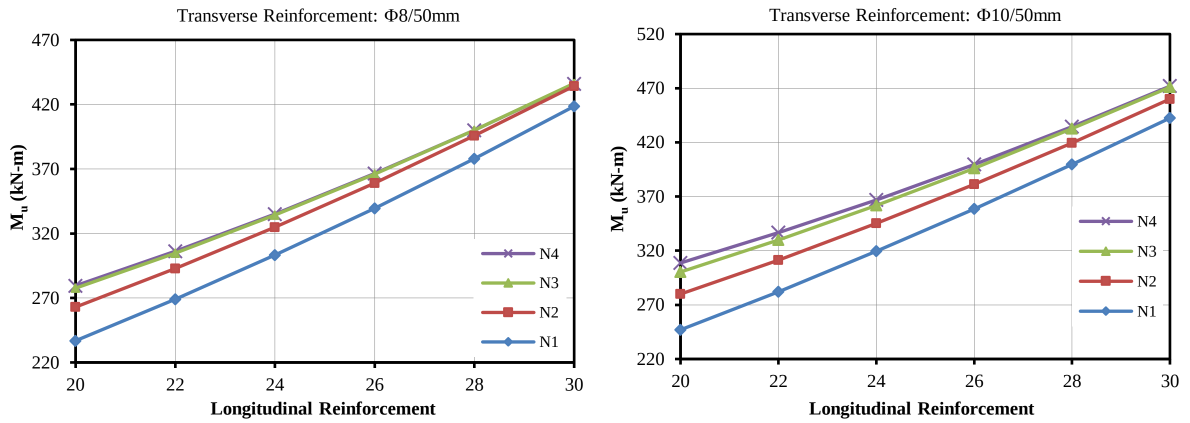


Figure 8. Influence of different longitudinal reinforcement ratios on the moment bearing capacity of the reinforced concrete circular columns

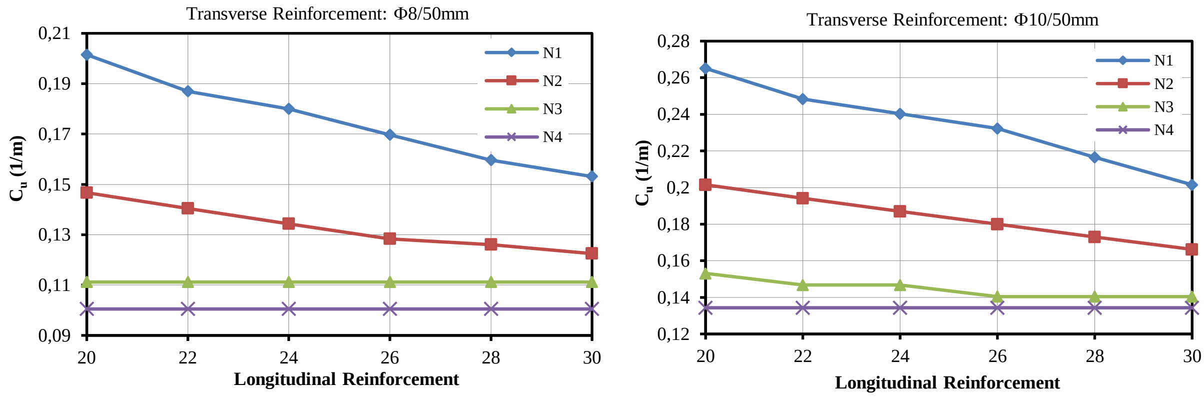


Figure 9. Influence of different longitudinal reinforcement ratios on the curvature of the reinforced concrete circular columns

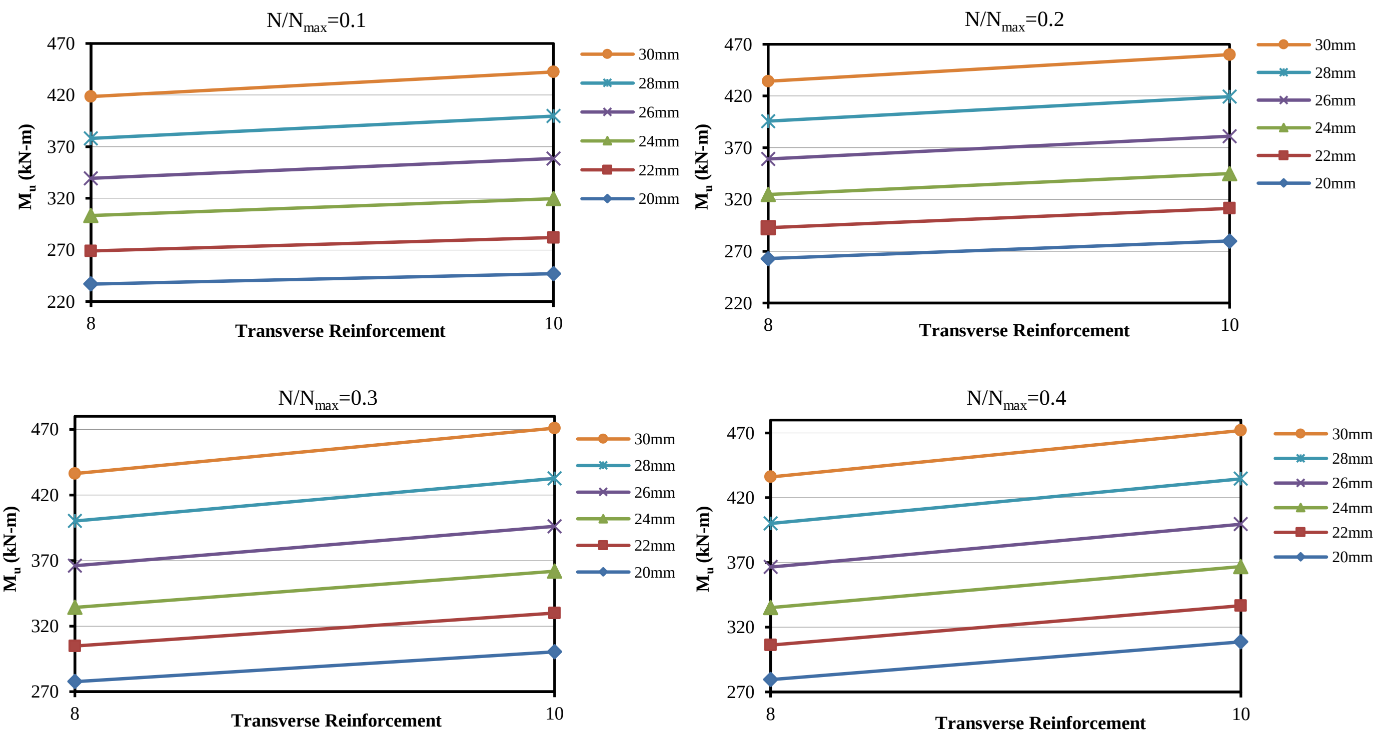


Figure 10. Influence of different transverse reinforcement ratios on the moment bearing capacity of the reinforced concrete circular columns

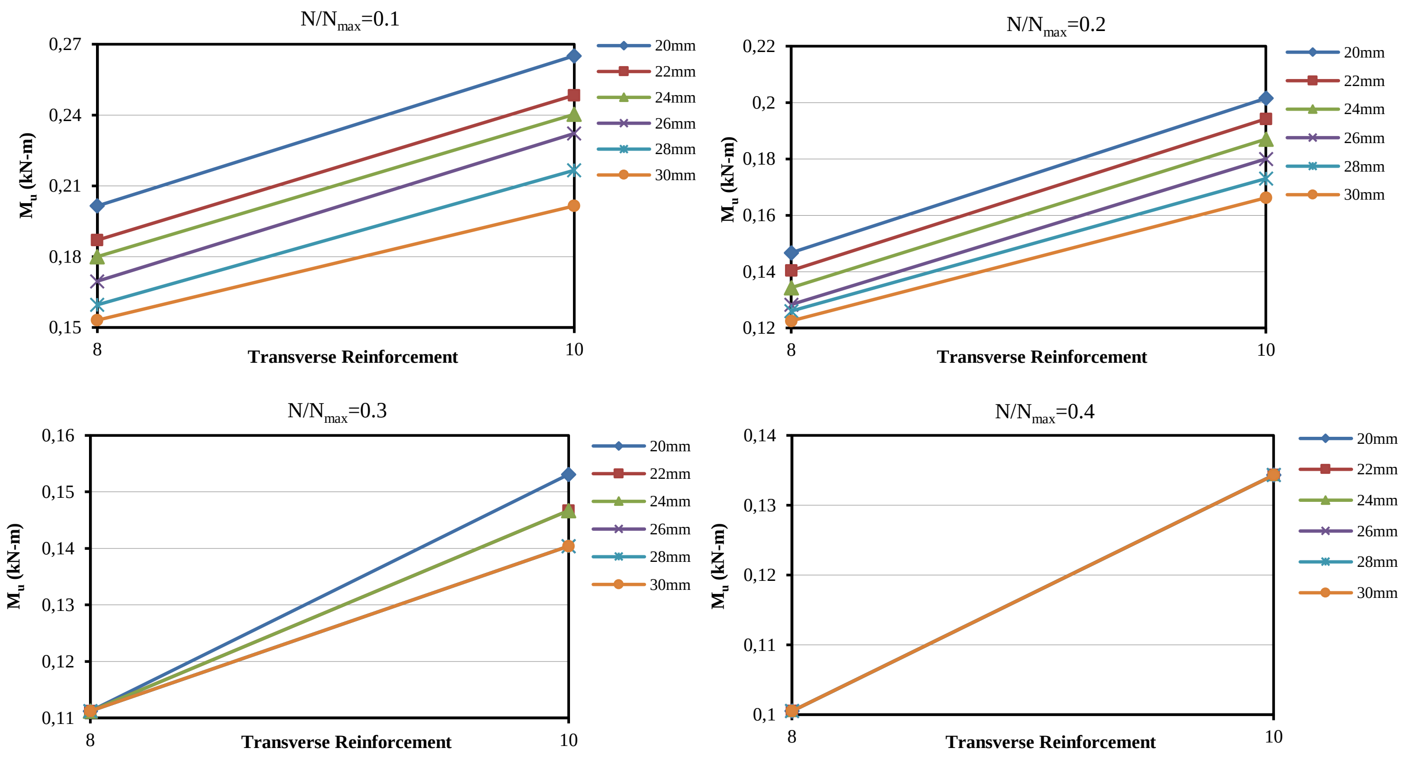


Figure 11. Influence of different transverse reinforcement ratios on the curvature of the reinforced concrete circular columns

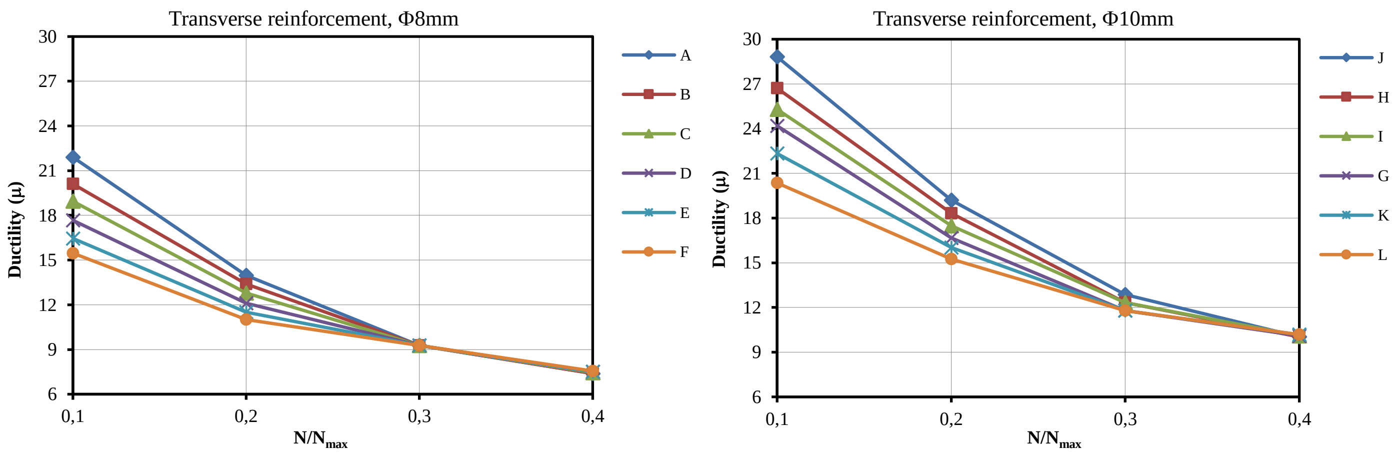


Figure 12. Influence of different transverse reinforcement ratios on the ductility of the reinforced concrete circular columns

As can be seen from Table 17, two different transverse reinforcement diameters (Φ8 mm and Φ10 mm) have been chosen for reinforced concrete circular column section models, with constant transverse reinforcement spacing. In terms of the ratio of transverse reinforcement, by examining the bearing capacity and curvature of the reinforced concrete column section; the increase in the ratio of transverse reinforcement was found to be effective in terms of bearing capacity and the curvature (ductility) of the section. Increased axial load level for reinforced concrete circular column sections, fixed longitudinal reinforcement, transverse reinforcement diameter and spacing has been found to be effective in moment and curvature. Increasing the axial load value in reinforced concrete column sections increases the moment bearing capacity of the section and decreases its ductility (curvature value decreases). It was observed that the axial load level was the effective parameter for the moment bearing capacity and the moment-curvature relation of the reinforced circular columns (Figure 4 and Table 17). With the increase of the longitudinal reinforcement ratio, the bearing capacity of reinforced concrete column sections increases, but the section ductility decreases. Increasing the ratio of transverse reinforcement increases both bearing capacity and ductility of reinforced concrete column sections and affects the moment-curvature relationships of the sections significantly.

5. Conclusion

The following results were obtained from the moment curvature analyses of the circular columns:
When the analysis results are examined, it is observed that the variation of the axial load, longitudinal reinforcement diameter, transverse reinforcement diameter and transverse reinforcement spacing have an important effect on the moment-curvature behavior of the reinforced concrete circular columns. Axial load, transverse reinforcement diameter and spacing are very important parameters affecting the ductility of the cross-section. With increasing axial load values yield curvature, yield moment and ultimate moment values increase, however, the ultimate curvature and curvature ductility values decrease. As can be seen from the moment-curvature relationships, the axial load is a very important parameter affecting the ductility of the cross-section of the columns. Significant reductions in ductility capacities of the column sections under increasing axial force have been observed.

It is observed that the variation of the axial load, longitudinal reinforcement diameter, transverse reinforcement diameter and transverse reinforcement spacing have an important effect on the moment-curvature behavior of the reinforced concrete circular columns. The cross-section ductility decreases when the transverse reinforcement spacing is increased under constant axial load. As can be seen from the moment-curvature relationships, it is observed that the cross-section ductility and the curvature increase significantly with the reduction of the transverse reinforcement spacing. The ratio of transverse reinforcement is effective in cross-section behavior of reinforced concrete cross-section. The increase in transverse reinforcement diameter increases the ductility of the cross-section and the maximum moment bearing capacity. The increase in the transverse reinforcement diameter increases the ultimate moment, ultimate curvature and curvature ductility values, but yield moment and yield curvature values remain almost constant (transverse reinforcement spacing and axial load levels are the constant). Yield moment, yield curvature, ultimate moment and ultimate curvature values increases however, curvature ductility values decreases as the longitudinal reinforcement diameter increases while other parameters kept constant. Moreover, with the increase of the transverse reinforcement ratio, the more ductile behavior is achieved due to the increment of curvature ductility on reinforced concrete columns. In order to see the real behavior of a reinforced concrete cross-section, a concrete model that takes the transverse reinforcement ratio into consideration should be used.

As can be seen from the comparison of the limit values of the damage zones calculated from the moment-curvature relations of the reinforced concrete circular columns according to different parameters: the first damage occurs by craking the cover concrete or yielding of the reinforcement. In cases where the axial load value applied to reinforced concrete column sections is small (N/N_{max} = 0.1 and 0.2), the first damage occurs with the yielding of the reinforcement. In case of increased axial load value (N/N_{max}= 0.3 and 0.4), first damages occur by cracking the cover concrete outside the core concrete of reinforced concrete columns. Under increasing deformations after the reinforcement yield, the cover concrete is cracked and the reinforced concrete column section is damaged. After cover concrete is cracked hardening in reinforcement occurs and moment bearing capacity is also increasing. The moment and curvature values increase up to the maximum axial load level that the reinforced concrete columns can bear. The load-bearing capacity of reinforced concrete column sections ends with the destruction of the core concrete. Reinforced concrete column sections damaged by reinforcement yield before crushing of cover concrete exhibit more ductile behavior.

References

Bedirhanoglu, I., & Ilki, A. (2004). Theoretical Moment-Curvature Relationships for Reinforced Concrete Members and Comparison with Experimental Data, *Sixth International Congress on Advances in Civil Engineering*, 6-8 October 2004 Bogazici University, Istanbul, Turkey, 231-240.

Dok, G., Ozturk, H., & Demir, A. (2017). Determining Moment-Curvature Relationship of Reinforced Concrete Columns, *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM)*, 1, 52-58.

Foroughi, S., & Yuksel, S. B. (2020). Investigation of the Moment-Curvature Relationship for Reinforced Concrete Square Columns, *Turkish Journal of Engineering (TUJE)*, 4(1), 36-46. doi:10.31127/tuje.571598.

Jun, J., & Hui, W., 2015. The Relationship Between Moment and Curvature and the Elastic-Plastic Seismic Response Analysis of High Pier Section, The Open Mechanical Engineering Journal, 9, 892-899.

Mander, J. B., Priestley, M. J. N., & Park, R. (1988). Theoretical stress-strain model for confined concrete, *Journal of Structural Engineering*, 114(8), 1804-1826. doi:10.1061/(ASCE)0733-9445(1988)114:8(1804).

SAP2000, Structural Software for Analysis and Design, *Computers and Structures, Inc*, USA.

TBEC, (2018). Turkish Building Earthquake Code: Specifications for Building Design under Earthquake Effects, *T.C. Bayındırlık ve İskan Bakanlığı*, Ankara.

Xie, Y., Ahmad, S., Yu, T., Hino, S., & Chung, W. (1994). Shear ductility of reinforced concrete beams of normal and high strength concrete, *ACI Structural Journal,* 91(2), 140-149.

Youcef, S. Y., & Chemrouk, M. (2012). Curvature Ductility Factor of Rectangular Sections Reinforced Concrete Beams, World Academy of Science, *International Journal of Civil and Environmental Engineering*, 6(11), 971-976.