EVALUATION OF PERFORMANCE BASED DISPLACEMENT LIMITS FOR REINFORCED CONCRETE COLUMNS UNDER FLEXURE

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ABSTRACT

EVALUATION OF PERFORMANCE BASED DISPLACEMENT LIMITS FOR REINFORCED CONCRETE COLUMNS UNDER FLEXURE

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Reinforced concrete frame buildings are the most common type of constructions in Turkey which are exposed to various types of forces during their lifetime. Seismic performance of reinforced concrete frame buildings is dominated by columns which can be classified as primary members of these structures. When current codes are considered, all of them contain several provisions in order to implement reliable seismic performances of reinforced concrete columns. In order to evaluate the accuracy of these provisions, analytical and parametric studies are carried out for flexure critical reinforced concrete columns. In these studies, total numbers of 30 flexure critical columns are extracted from PEER database (2005) and analytically investigated. Once the seismic responses obtained from analytical investigations are close enough to experimental seismic responses, performance based displacement limits are pointed out according to TEC (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009). In addition to this, total numbers of 144 flexure critical columns are generated in parametric studies to present the effects of various parameters such as column geometry, concrete strength, axial load ratio, transverse reinforcement ratio, and yielding strength of longitudinal reinforcement on performance based displacement limits. Performance based displacement limits proposed by TEC (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009) are found very conservative compared to limits obtained from both experimental and analytical behavior. On the other hand, performance based displacement limits given in Eurocode 8 (2003) and ASCE/SEI 41 Update (2009) predict the experimental behavior more accurate than TEC (2007) and FEMA 356 (2000). Improvements on these limits are proposed.

Keywords: Reinforced Concrete Column, Flexure, Displacement Limits, Assessment

ÖZ

EĞİLME YÖNÜNDEN KRİTİK BETONARME KOLONLARIN PERFORMANSA DAYALI DEPLASMAN LİMİTLERİNİN İNCELENMESİ

Solmaz, Taylan
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Türkiye'deki yapılarda karşılaştığımız sistemlerin başında gelen betonarme çerçeveler, kullanım süreleri boyunca çeşitli kuvvetlere maruz kalırlar. Betonarme çerçeve sistemlere sahip binaların sismik performansları, bu yapıların birincil elemanları olarak sınıflandırılan kolonlar tarafından tayin edilmektedir. Güncel yönetmelikler göz önüne alınırsa, bu yönetmelikler betonarme kolonlarda güvenilir sismik performans sağlamak amacıyla çeşitli şartlar barındırırlar. Verilen şartların doğruluğunu değerlendirmek amacıyla, eğilme yönünden kritik kolonlar için analitik ve parametrik çalışmalar yapılmaktadır. Bu çalışmalarda, toplam 30 adet eğilme yönünden kritik kolon PEER veri tabanından (2005) seçilerek analitik olarak incelenmektedir. Analitik çalışmalardan elde edilen sismik davranış deneylerden elde edilen sismik davranışa yeterince yakın olduğunda, performansa dayalı deplasman limitleri TDY (2007), FEMA 356 (2000), Eurocode 8 (2003) ve ASCE/SEI 41 Güncelleştirmesi (2009) için işaretlenmektedir. Bununla birlikte, parametrik çalışma bölümünde toplam 144 adet eğilme yönünden kritik kolon çeşitli parametrelerin örneğin kolon geometrisi, beton dayanımı, eksenel yük oranı, enine donatı oranı ve boyuna donatının akma dayanımının, performansa dayalı deplasman limitlerinin üzerindeki etkilerini göstermek amacıyla oluşturulmaktadır. TDY (2007), FEMA 356 (2000), Eurocode 8 (2003) ve ASCE/SEI 41 Güncelleştirmesi (2009) sağladığı performansa dayalı deplasman limitlerinin, deneysel davranışlardan elde edilen limitlere göre aşırı güvenli olduğu görülmektedir. Diğer yandan, Eurocode 8 (2003) ve ASCE/SEI 41 Güncelleştirmesi (2009) tarafından belirtilen performansa dayalı deplasman limitlerinin, deneysel davranışı TDY (2007) ve FEMA 356 (2000) tarafından belirtilen performansa dayalı deplasman limitlerine göre daha iyi yansıttıkları görülmektedir. Bu performans limitlerinin iyileştirilmesi için önerilerde bulunulmaktadır.

Anahtar Kelimeler: Betonarme Kolon, Eğilme, Deplasman Limitleri, Değerlendirme

To My Family

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My beloved Ceren…I am grateful that you had given me your love and peace in my most difficult times. I am so lucky that you are walking by my side and I hope you will always be next to me…

Last but not least, I want to thank to my family for their support, encouragement, and love throughout my whole life.

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LIST OF ABBREVIATIONS AND SYMBOLS

A_o: Cross sectional area of the transverse reinforcement

B: Width of the column section

CP: Collapse prevention performance level

d_b: Bar diameter

$(DR)_{IO}$: Drift ratio at immediate occupancy performance level

$(DR)_{LS}$: Drift ratio at life safety performance level

$(DR)_{CP}$: Drift ratio at collapse prevention performance level

$EI_{cracked}$: Flexural rigidity of the cracked section

$EI_{initial}$: Flexural rigidity of the initial section

f_c: Concrete compressive strength

f_y: Yielding strength of longitudinal reinforcement

f_{yw}: Yielding strength of transverse reinforcement

H: Height of the column section

IO: Immediate occupancy performance level

K: Initial slope of bar stress vs. loaded-end slip relation

L/H: Slenderness ratio

L_{col}: Length of the column

L_p: Plastic hinge length

LS: Life safety performance level

N/N_0: Axial load ratio

R_c: Power index of the unloading/reloading curve

R_e: Power index of the envelope curve

s: Spacing of transverse reinforcement

$\tilde{s}$: Normalized loaded-end slip

s_y: Loaded-end slip when bar stress equals to the bar yield strength

s_u: Loaded-end slip when bar stress equals to the bar ultimate strength

ε_{co}: Unconfined concrete strain under maximum stress

ε_{coc}: Confined concrete strain under maximum stress

ρ_s: Transverse reinforcement ratio

ρ_{sm}: Volumetric ratio of the confinement reinforcement required at the critical section

$\tilde{\sigma}$: Normalized bar stress

σ_u: Ultimate bar stress

σ_y: Yielding bar stress

ρ: Longitudinal reinforcement ratio

σ: Bar stress

ϕ: Curvature of the end section

ϕ_y: Yield curvature of the end section

CHAPTER 1

INTRODUCTION

1.1. General

Buildings, bridges and other civil infrastructures must be designed and constructed to withstand the effects of man-made and natural hazards. The most common type of constructions are the reinforced concrete frame buildings, that are exposed to various types of forces during their lifetime, such as static forces in the form of dead and live loads and dynamic forces in the form of wind and earthquakes. Amplitude, direction and location of dynamic forces especially due to earthquake, vary significantly with time, causing considerable inertia effects on buildings. Under dynamic forces, behavior of buildings depends upon the dynamic characteristics of buildings which are affected by both their stiffness and mass properties, whereas the static behavior is only dependent upon the stiffness characteristics. The design of structures for non-seismic loading is well established and correlated by practical experience so that estimates of reliability are robust. This is far from true for earthquake design. Seismic response of a structure is a nonlinear dynamic problem and structural analysis should be able to take into account the nonlinear behavior of members for evaluating the actual response of structures; however until the beginning of 21th century linear elastic procedures governed the earthquake design.

Turkey is located in a seismically active region. At the end of 20th century, Turkish cities, where most of the population exists, were exposed to seismic activities. These seismic activities were moderate and severe earthquakes which caused losses of tens of thousands of civilians. The reason of these losses was the destruction of deficient reinforced concrete structures when their seismic performances were taken into account. Significant earthquakes, leading to social and economical losses, made engineers pay attention to the increasing seismic risk which becomes vital for people in urban places.

Buildings designed as earthquake resistant structures should be able to resist frequent, minor earthquakes without any significant damage to the nonstructural components. Such structures should resist moderate earthquakes without significant structural damage. In the case of severe seismic action, the structure should be able to resist earthquakes without a major failure of the structural system to maintain life and to minimize major economical and cultural losses.

Columns are the primary and the most important load carrying components for a reinforced concrete frame structure. Most of the failures in previous major earthquakes for a reinforced concrete frame structure are directly related to seismic behavior of the columns existing in that frame. Displacement demands arisen from seismic movements should be met by columns. As a result, this type of structural members should have sufficient strength and ductility to answer these demands.

There are three different types of failure modes for reinforced concrete columns:

- Shear Failure: This type of failure occurs when the shear resistance of the member does not respond to shear force arisen from the seismic motion. Column which experiences shear failure has almost no deformability hence the failure is brittle and unexpected. An inclined crack begins and widens at the end part of the column until the column loses the lateral and vertical capacities suddenly. A typical hysteretic load-displacement behavior of such column is shown in Figure 1.1.
- Flexural Failure: Columns that experience flexural failure are ductile because they have sufficient shear strength to maintain the seismic performance till the end of flexural capacity without shear failure. Flexural cracks are approximately perpendicular to member axis and observed at the sections where bending moment capacities are exceeded (plastic hinge regions). The

load-displacement response of a typical flexural column is illustrated in Figure 1.2.

- Flexure-Shear Failure: Column starts its performance with flexural yielding but as a result of seismic detailing deficiencies, shear failure dominates the behavior. This means flexural cracks are followed by inclined cracks formed because of exceeded shear capacity. Column failure occurs when one of these cracks widens and propagates into the compression zone. The cyclic response of this type of column is presented in Figure 1.3.

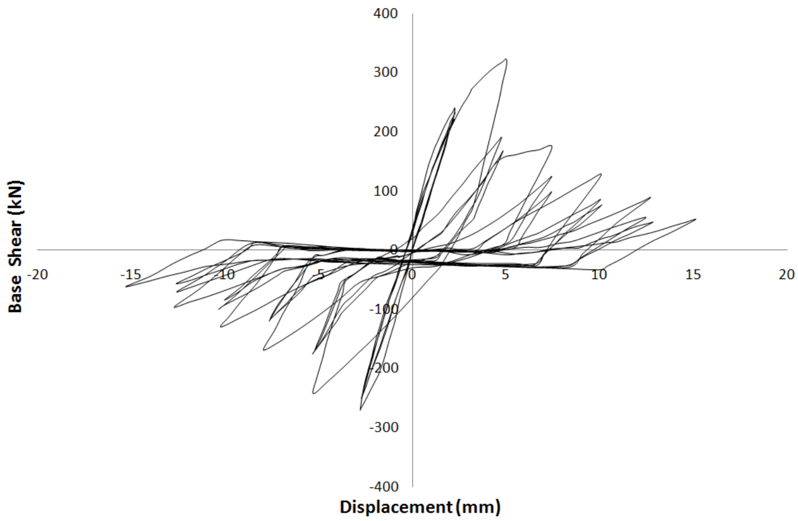


Figure 1.1 Cyclic Test Results of a Column Failed in Shear Failure Mode (PEER (2005))

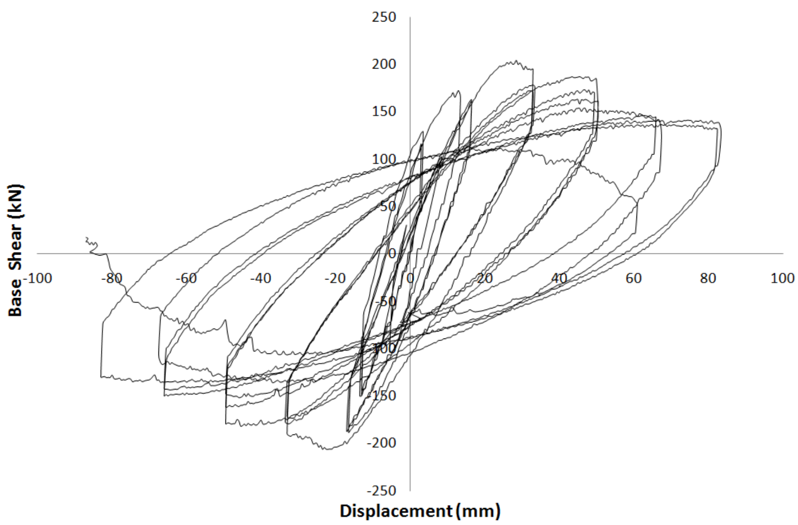


Figure 1.2 Cyclic Test Results of a Column Failed in Flexure Failure Mode (PEER (2005))

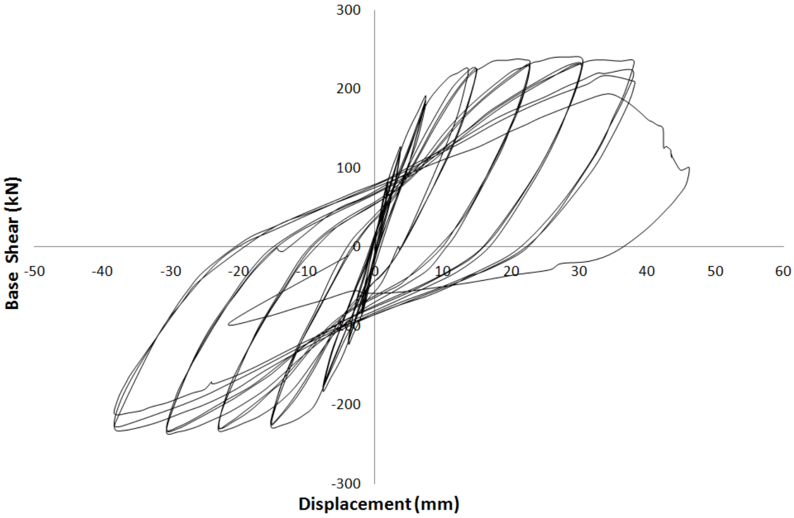


Figure 1.3 Cyclic Test Results of a Column Failed in Flexure-Shear Failure Mode (PEER (2005))

1.2. Literature Survey

Acun and Sucuoglu (2010) conducted an experimental study in which column specimens were designed only for pure flexure. Totally, 12 columns were grouped into two according to their seismic detailing. First group was representing deficient specimens when code provisions were taken into account, and the other group was representing the specimens with conforming seismic detailing and material properties. All variables were kept constant except the imposed displacement histories. At the end of experimental studies, deformation based performance limits were derived. Main observations obtained from this research can be stated as;

- Seismic codes ASCE/SEI 41 (2007) and Eurocode 8 (2003) are very conservative while considering rotation limits of life safety and collapse prevention performance levels,
- When ASCE/SEI 41 (2007) and Eurocode 8 (2003) are compared, Eurocode 8 provides closer performance limits than ASCE/SEI 41 (2007),
- Imposed displacement histories considerably affect target drift demands; on the other hand capacity curves are not affected significantly.

Erduran and Yakut (2004) studied drift based damage functions for reinforced concrete columns. Finite element program ANSYS v6.1 was used in order to evaluate the effects of selected parameters on damageability of reinforced concrete columns. Concrete strength, axial load ratio, slenderness ratio, amount of longitudinal reinforcement, yielding strength of longitudinal reinforcement, and amount of transverse reinforcement were subscribed as major parameters in analytical studies. Erduran and Yakut (2004) pointed out that;

- Deformation capacities of evaluated columns are affected significantly from the parameters such as axial load ratio, slenderness ratio, yielding strength of longitudinal reinforcement, and amount of transverse reinforcement,
- Ultimate ductility is influenced critically from axial load ratio and amount of transverse reinforcement,
- Drift ratio at yielding point is influenced from slenderness ratio and yielding strength of longitudinal reinforcement,
- Deformation capacities of evaluated columns are not affected from concrete strength and amount of longitudinal reinforcement. On the other hand, these parameters importantly change the load carrying capacity.

Erguner (2009) examined performance limits analytically for shear critical reinforced concrete columns. PEER structural column database (2005) was used to select columns. From this database 6 column specimens failed in shear failure mode and 10 column specimens failed in flexure-shear failure mode were evaluated. While evaluating these columns different models were employed for load-deformation estimation. These approaches were axial-shear-flexure interaction approach as defined by Mostafaei and Kabayesawa (2006), axial-shear-flexure interaction approach with proposed modifications, axial-shear-flexure interaction approach with constitutive proposed by Hsu (1988) and compression bar buckling model according to Dhakal and Maekawa (2002), drift capacity model as defined by Elwood (2003), and procedure defined in Turkish Earthquake Code (TEC) (2007). In addition to the selected column specimens, parametric studies were conducted by using the database of shear critical columns reported by Elwood (2003). In conclusion, Erguner (2009) emphasized that;

- Axial-shear-flexure interaction played an important role while determining the behavior of reinforced concrete columns,
- Axial-shear-flexure interaction approach with proposed modifications estimated the behavior of flexure-shear critical columns accurately,
- Main parameters which affected the drift ratio at shear and axial failure were the transverse reinforcement ratio and the axial load level,
- Bond slip effects and shear deformations changed ultimate drift ratio significantly,
- Determination of failure mode according to the procedures given in TEC (2007) was misleading and over conservative,
- Performance limits stated in nonlinear procedure of TEC (2007) showed little deformability between the performance levels of life safety and collapse prevention.

Vintzileou and Stathatos (2007) assessed experimental test results of more than 450 reinforced concrete columns. Main parameters evaluated in this study were the effective transverse reinforcement ratio, hoop arrangement, spacing of transverse reinforcement, etc. In addition, main objective of this research was to evaluate the efficiencies of seismic codes, Eurocode 8 (2003) and Greek Code for the Design of RC Structure (EKOS) (2000). Following statements can be concluded according to this study;

- Investigated codes provide consistent performance limits,
- Axial load ratio, effective transverse reinforcement ratio, hoop arrangement, and the spacing of transverse reinforcement significantly affect seismic behavior of reinforced concrete columns,
- The most important parameter affecting the seismic behavior is the arrangement of hoops.

Lam et al. (2003) investigated drift capacity of reinforced concrete columns with low lateral confinement and high axial load. 90˚ and 135˚ hooks were used while detailing the transverse reinforcement. Total numbers of 9 square shaped columns were tested experimentally. In conclusion the results were derived as;

- Columns with low shear span and small amount of transverse reinforcement experienced brittle failure under the effect of shear force,
- Transverse reinforcement ratio significantly affects ultimate drift ratio. For instance when the transverse reinforcement ratio increased to 0.003 from 0.001, ultimate drift ratio became two times of initial value,
- Usage of 90˚ hoops, instead of 135˚ hoops, reduced the drift capacity to 60% of the initial value.

Hwang and Yun (2004) conducted experimental studies to see the effects of lateral reinforcement on flexural behavior of high strength (~70 MPa) reinforced concrete columns. Total numbers of 8 specimens with constant axial load ratio (30%) were subjected to cyclic horizontal load. Main parameters used in these studies were transverse reinforcement ratio (1.58, 2.25%), yielding strength of transverse reinforcement (549, 779 MPa), and tie configuration. Hwang and Yun (2004) concluded that specimens with the transverse reinforcement ratio of 2.25% behaved in a ductile manner with a displacement ductility factor of 4 and a curvature ductility factor of 15. In addition, detailing of the transverse reinforcement significantly affected the ductility. Moreover, the provisions of ACI 318-02 (2002) estimated the nominal moment capacity conservatively.

Lu et al. (2005) evaluated seismic performance of flexure critical reinforced concrete columns and proposed probabilistic drift limits by considering various uncertainties originated from material and geometric properties. Three distinctive performance levels were investigated and some conclusions were stated;

- Drift limits corresponding to the performance level of immediate occupancy had overall mean value of 1.08% with a coefficient of variation equal to 10.5%,
- Drift limits corresponding to the performance level of life safety were changing between 2.0% and 4.5% with a coefficient of variation varying between 30% and 40%,
- Drift limits corresponding to the performance level of collapse prevention were changing between 3.0% and 7.8% with a coefficient of variation varying between 30% and 45%.

Panagiotakos and Fardis (2001) assessed the deformations of reinforced concrete members at yielding and failure points. By using a database, consists of approximately 1000 cyclic tests, expressions for the deformations of reinforced concrete members at yielding and failure points were developed in terms of member geometric and mechanical characteristics. In conclusion the results were derived as;

- Ductility of the steel is quite important for member deformability. Deformation capacity is reduced to half of its initial value when brittle cold-worked steel is used,
- Bond-slip effects increase the deformability by approximately 40% on the average,
- Full cycling at the peak deformation demand reduces the deformation capacity by 40% on the average,
- The shear-span ratio seems to be the most important ratio in increasing member deformation capacity,
- Deformation capacity decreases almost linearly with increasing axial load ratio.

1.3. Objective and Scope

While evaluating performance based seismic design and assessment methodology for a column, estimation of the seismic behavior and damage states of particular deformation levels are vitally important issues. In order to predict ductility, strength and stiffness properties of a column, load-deformation relationship should be accurately constituted. This relationship induces a judgment technique to predict important performance limit points such as first yielding, ultimate strength, and flexural failure.

Main objectives of this study can be summarized as follows:

1. Estimating performance based displacement limits for flexure critical reinforced concrete columns,

2. Comparing estimated performance based displacement limits with the performance limits obtained from different seismic provisions which are Turkish Earthquake Code (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009),

3. Investigating the effects of parameters, such as concrete strength, axial load ratio, yielding strength of longitudinal reinforcement, and transverse reinforcement ratio, on capacity curves and performance based displacement limits,

4. Comparing estimated flexural rigidities with the flexural rigidities obtained from different seismic provisions which are Turkish Earthquake Code (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009).

In Chapter 2, columns with flexural failure mode are selected from Pacific Earthquake Engineering Research Center’s Structural Performance Database (2005) and displacement limits are evaluated analytically with a finite element analysis program named as Open System for Earthquake Engineering Simulation (OpenSees) (2005). In addition, code limits for each performance levels of immediate occupancy, life safety, and collapse prevention are presented for different seismic provisions; Turkish Earthquake Code (2007), FEMA 356 (2000), and Eurocode 8 (2003). These limits are compared with the estimated limits obtained from analytical studies.

In Chapter 3, parametric studies are conducted in order to reflect the properties of columns constructed in Turkey. 144 column specimens are evaluated and performance limits are estimated in this part of the study. In addition, estimated performance limits are compared with the limits obtained from TEC (2007), FEMA 356 (2000), EC 8 (2003), and ASCE/SEI 41 Update (2009). Also flexural rigidities obtained from different seismic provisions are compared with the estimated flexural rigidities. Moreover, effects of selected parameters on seismic performance are illustrated.

In Chapter 4, conclusions are presented with some recommendations.

CHAPTER 2

EVALUATION OF FLEXURE CRITICAL COLUMNS SELECTED FROM PACIFIC EARTHQUAKE ENGINEERING RESEARCH (PEER) CENTER'S STRUCTURAL PERFORMANCE DATABASE (2005)

2.1. Introduction

Flexure critical column specimens are picked from previous experimental studies. Pacific Earthquake Engineering Research Center's Structural Performance Database (PEER) (2005), which was generated at the University of Washington, is used to compute experimental and analytical behavior of the flexure critical column specimens. 306 rectangular columns and 177 circular columns, cyclically and monotonically tested, are available in the database to perform analytical analyses. The database supplies the force-displacement histories, geometric properties, sectional properties, type of failure mode, and other related documentation for each column test.

PEER database (2005) includes 306 rectangular columns, 220 of them failing in a flexural mode, 35 of them failing in the mode of combined flexure and shear, and 51 of them failing in a shear mode. In order to select flexure critical column specimens from this database, the histograms generated by Haselton et al. (2008) were also considered. These histograms have a constant primary axis which shows the numbers of specimens corresponding to different design parameters such as axial load ratio, concrete compressive strength, yielding strength of reinforcement, longitudinal reinforcement ratio, transverse reinforcement ratio, and slenderness ratio etc. In

Figure 2.1 Haselton et al. (2008) have illustrated the range of design parameters of these columns. In this figure, y-axes represent the total number of specimens for all charts and x-axes show some variables respectively which are axial load ratio, axial load over axial load at the balanced condition, concrete compressive strength, slenderness ratio, yielding strength of longitudinal reinforcement, spacing of transverse reinforcement over effective depth, transverse reinforcement ratio, effective ratio of transverse reinforcement (in region of close spacing at column end), total reinforcement ratio, and ratio of total area of longitudinal reinforcement over ratio of longitudinal reinforcement in compression zone.

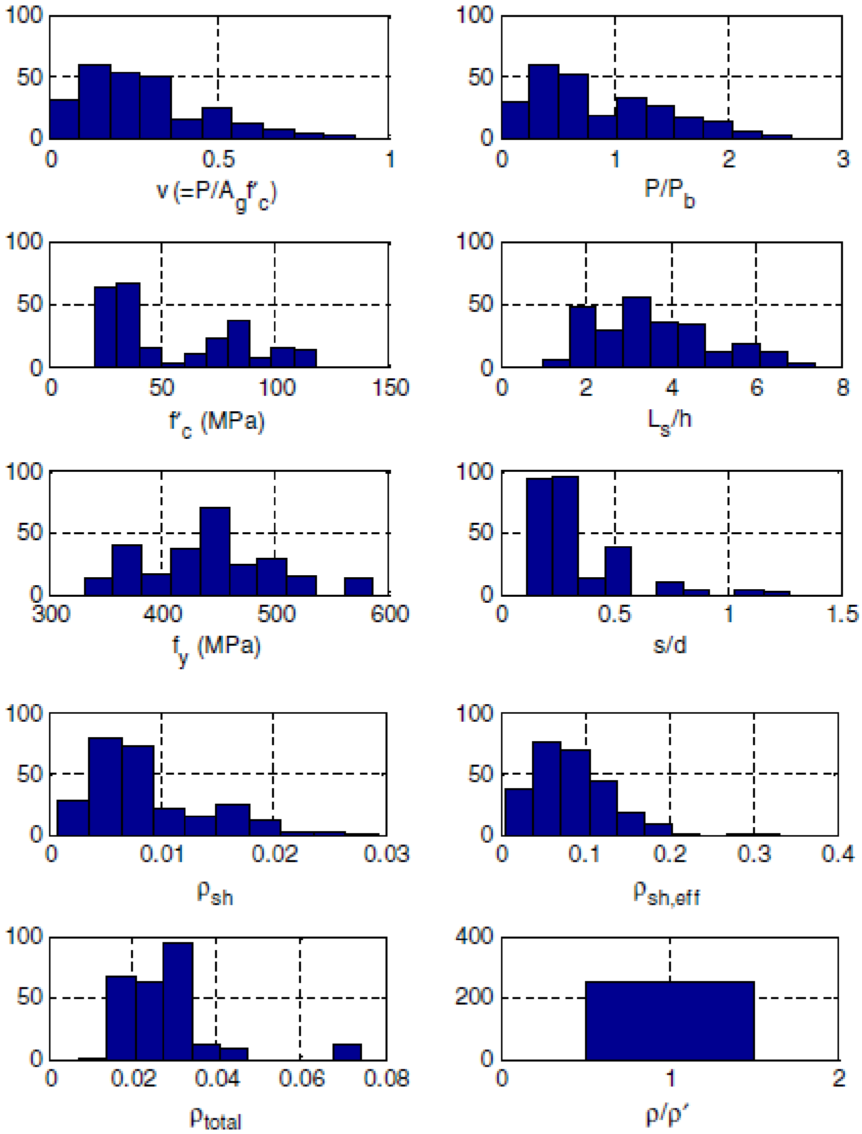


Figure 2.1 Histograms Showing the Range of Column Design Parameters for 255 Experimental Tests (Haselton et. al. (2008))

Rectangular columns, whose failure modes are flexural, are selected from the database. Selected columns have the following common features:

- Characteristic compressive strength $f_c \leq 50\ Mpa$
- Axial load ratio $\frac{N}{A_g\, f_c} \leq 0.70$
- Column length $L_{col} \geq 1.00\ m$ (half-height)
- Flexure dominant members

Where:

N: Axial load

A_g: Area of the cross section

f_c: Concrete compressive strength

L_{col}: Length of the column

These features limit the number of convenient experimental tests. As a result, 30 rectangular columns are extracted from the database and are tested analytically with the software OpenSees (2005). The properties of the selected columns are summarized in Table 2.1.

Table 2.1 Flexure Critical Columns Selected From PEER Database (2005)

Specimen No	Specimen Name	B (mm)	H (mm)	L (mm)	L/H	f_c (MPa)	f_y (MPa)	f_{yw} (MPa)	N/N_0	ρ	ρ_s	$(EI)_{initial}$ (kNm^2)	$(EI)_{cracked}$ (kNm^2)	$(EI)_{cracked}/(EI)_{initial}$	Failure Type
22	Tanaka and Park 1990, No.5	550	550	1650	3.00	32.00	511	325	0.100	0.0208	0.0180	240,853.44	79,989.02	0.33	Flexural
23	Tanaka and Park 1990, No.6	550	550	1650	3.00	32.00	511	325	0.100	0.0208	0.0240	239,088.84	77,145.63	0.32	Flexural
24	Tanaka and Park 1990, No.7	550	550	1650	3.00	32.10	511	325	0.300	0.0208	0.0214	207,255.63	87,372.06	0.42	Flexural
25	Tanaka and Park 1990, No.8	550	550	1650	3.00	32.10	511	325	0.300	0.0208	0.0293	238,558.86	99,322.15	0.42	Flexural
26	Park and Paulay 1990, No.9	400	600	1784	2.97	26.90	432	305	0.100	0.0189	0.0245	218,056.84	86,727.55	0.40	Flexural
30	Ohno and Nishioka 1984, L1	400	400	1600	4.00	24.80	362	325	0.032	0.0142	0.0080	57,094.63	21,725.75	0.38	Flexural
104	Saatcioglu and Ozcebe 1989,U1	350	350	1000	2.86	43.60	430	470	0.000	0.0321	0.0070	22,656.71	20,450.32	0.90	Flexural
106	Saatcioglu and Ozcebe 1989,U4	350	350	1000	2.86	32.00	438	470	0.153	0.0321	0.0206	45,884.75	23,967.06	0.52	Flexural
107	Saatcioglu and Ozcebe 1989,U6	350	350	1000	2.86	37.30	437	425	0.131	0.0321	0.0103	44,229.34	22,028.25	0.50	Flexural
108	Saatcioglu and Ozcebe 1989,U7	350	350	1000	2.86	39.00	437	425	0.126	0.0321	0.0195	47,486.21	24,359.68	0.51	Flexural
133	Wehbe et al. 1998, A1	380	610	2335	3.83	27.20	448	428	0.098	0.0223	0.0095	217,777.75	95,257.67	0.44	Flexural
134	Wehbe et al. 1998, A2	380	610	2335	3.83	27.20	448	428	0.239	0.0223	0.0095	235,976.00	109,351.74	0.46	Flexural
135	Wehbe et al. 1998, B1	380	610	2335	3.83	28.10	448	428	0.092	0.0223	0.0152	220,439.77	89,656.35	0.41	Flexural
166	Saatcioglu and Grira 1999, BG2	350	350	1645	4.70	34.00	456	570	0.428	0.0195	0.0190	35,484.12	17,140.74	0.48	Flexural
167	Saatcioglu and Grira 1999, BG3	350	350	1645	4.70	34.00	456	570	0.200	0.0195	0.0190	38,345.45	16,918.17	0.44	Flexural
169	Saatcioglu and Grira 1999, BG5	350	350	1645	4.70	34.00	456	570	0.462	0.0293	0.0290	42,157.56	21,289.76	0.51	Flexural
170	Saatcioglu and Grira 1999, BG6	350	350	1645	4.70	34.00	478	570	0.456	0.0293	0.0290	42,118.67	21,276.36	0.51	Flexural
171	Saatcioglu and Grira 1999, BG7	350	350	1645	4.70	34.00	456	570	0.462	0.0293	0.0145	42,073.18	22,210.80	0.53	Flexural
172	Saatcioglu and Grira 1999, BG8	350	350	1645	4.70	34.00	456	570	0.231	0.0293	0.0145	44,793.09	22,616.99	0.50	Flexural
173	Saatcioglu and Grira 1999, BG9	350	350	1645	4.70	34.00	428	580	0.462	0.0328	0.0145	42,918.47	24,140.08	0.56	Flexural
174	Saatcioglu and Grira 1999, BG10	350	350	1645	4.70	34.00	428	570	0.462	0.0328	0.0290	43,362.96	23,071.88	0.53	Flexural
187	Mo and Wang 2000, C1-1	400	400	1400	3.50	24.90	497	460	0.113	0.0215	0.0153	61,444.90	25,024.27	0.41	Flexural
188	Mo and Wang 2000, C1-2	400	400	1400	3.50	26.70	497	460	0.158	0.0215	0.0153	62,105.26	26,055.49	0.42	Flexural
189	Mo and Wang 2000, C1-3	400	400	1400	3.50	26.10	497	460	0.216	0.0215	0.0153	64,983.16	28,941.04	0.45	Flexural
190	Mo and Wang 2000, C2-1	400	400	1400	3.50	25.30	497	460	0.111	0.0215	0.0174	61,885.75	25,091.47	0.41	Flexural
191	Mo and Wang 2000, C2-2	400	400	1400	3.50	27.10	497	460	0.156	0.0215	0.0174	62,569.91	26,439.48	0.42	Flexural
192	Mo and Wang 2000, C2-3	400	400	1400	3.50	26.80	497	460	0.210	0.0215	0.0174	62,196.65	27,244.04	0.44	Flexural
193	Mo and Wang 2000, C3-1	400	400	1400	3.50	26.38	497	460	0.107	0.0215	0.0170	63,106.76	25,392.85	0.40	Flexural
194	Mo and Wang 2000, C3-2	400	400	1400	3.50	27.48	497	460	0.154	0.0215	0.0170	67,675.63	28,296.32	0.42	Flexural
195	Mo and Wang 2000, C3-3	400	400	1400	3.50	26.90	497	460	0.209	0.0215	0.0170	61,656.41	27,126.43	0.44	Flexural

B: Width of the column section

H: Height of the column section

L: Length of the column

ρ: Longitudinal reinforcement ratio (A_s/BH)

ρ_s: Transverse reinforcement ratio (A_{sw}/Bs)

$(EI)_{initial}$: Flexural rigidity of the initial section

f_{yw}: Yielding strength of the transverse reinforcement

N/N_0: Axial load ratio (N/A_gf_c)

L/H: Slenderness ratio

f_c: Compressive strength of concrete

f_y: Yielding strength of longitudinal reinforcement

$(EI)_{cracked}$: Flexural rigidity of the cracked section

2.2. Modeling and Analysis

2.2.1. General

Seismic behavior of flexure critical reinforced concrete columns are influenced by several parameters such as axial load ratio, concrete compressive strength, yielding strength of reinforcement, longitudinal reinforcement ratio, and transverse reinforcement ratio. Thus, these parameters should be modeled accurately with a reliable computer program. Open System for Earthquake Engineering Simulation (OpenSees) (2005) is a computer program which was developed by Pacific Earthquake Engineering Research Center with the support of National Science Foundation. In this study, seismic performances of evaluated columns are investigated with OpenSees version 2.2.0. Total numbers of 30 columns, selected from PEER database (2005), are tested analytically to find the most reliable model. Capacity curves of these columns are obtained by performing pushover analyses. This monotonic loading may accurately reflect the behavior of experimental cyclic loading even if bond slip effects are considered.

Displacement controlled nonlinear static analyses are performed by applying incremental displacements at the tip of the column. Because of applying incremental displacements monotonically, effects of cyclic degradation cannot be observed. While applying incremental displacements, at the critical section of the flexural member, element forces in addition to stress-strain values of concrete and steel are recorded for each step. Also, chord rotations are calculated by dividing recorded tip displacement values to column length (half-height). As a result, for each step material strains, chord rotations, and element forces are related to each other. This relationship provides an opportunity to estimate performance limits for each performance level in terms of material strains or chord rotations.

2.2.2. Fiber Based Analysis

Reinforced concrete flexural components are modeled by using the concept of fiber analysis. Unidirectional concrete and steel fibers represent the flexural component in this type of analysis. A fiber section has a general geometric configuration formed by subregions of simpler, regular shapes (quadrilateral, circular or triangular regions) called patches. In addition, layers of reinforcement bars can be specified. Concrete and steel fiber behaviors can be modeled and defined in the direction of the member length, so fiber based analysis may be used for all type of flexural components regardless of cross sectional shape and the direction of the horizontal load. Figure 2.2 shows the sectional properties of the model used in OpenSees (2005).

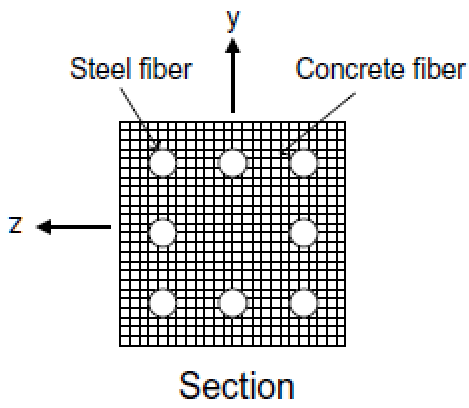


Figure 2.2 Modeling the Sectional Properties with OpenSees (2005)

Basically, fiber based analysis exercises the method of direct stiffness. Direct stiffness method solves the equation of equilibrium for the whole system, provides the nodal displacements. Deriving the element forces from the nodal displacements continues with the process of regenerating the stiffness of the component. The element stiffness and forces are derived by integrating the section stiffness and forces numerically corresponding to a section deformation, which is obtained from the element end deformations. Strain values in each fiber are calculated from the section deformations with the assumption that “plane sections remain plane”.

2.2.2.1. Material Model for Concrete Fibers

Modified Kent and Park model (1982) is used to define concrete behavior accurately. Kent and Park model (1982) was modified with the idea inspired from the relationship of Roy and Sozen confined concrete model (1964). Figure 2.3 shows the stress-strain relationships of unconfined and confined concrete models used in this study.

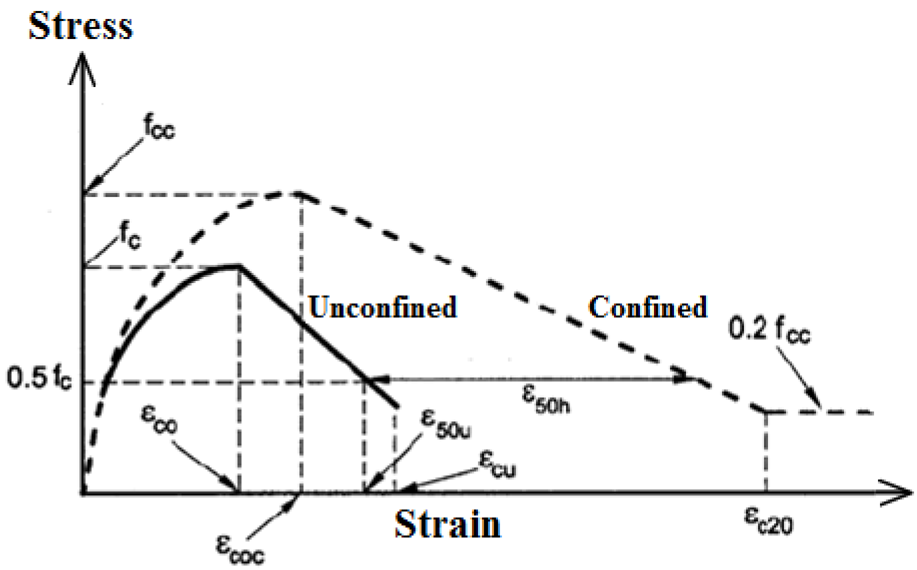


Figure 2.3 Unconfined and Confined Concrete Compressive Stress-Strain Relations of Modified Kent and Park Model (1982)

For confined and unconfined concrete regions, two different stress-strain relations are applied. Unconfined concrete compressive strength f_c increases with the confinement to a value of f_{cc}. In addition, compressive strain which corresponds to the maximum stress value, ε_{co}, increases to ε_{coc}. For both unconfined and confined concrete models, first part of the stress-strain curves has a second order parabolic region as Hognestad model suggests. Second part of the curves that show the decreasing part of the stress values, are first order lines with negative slope. Negative slope of confined part is smaller than the negative slope of unconfined part. Unconfined concrete has a limited maximum strain $\varepsilon_{cu} = 0.004$, on the other hand for confined concrete there is no such a limitation of compressive strain.

Modified Kent and Park model (1982) uses the following equations:

For ascending branches;

Unconfined concrete $\Rightarrow$ $$\sigma_c = f_c\left[\frac{2\varepsilon_c}{\varepsilon_{co}} - \left(\frac{\varepsilon_c}{\varepsilon_{co}}\right)^2\right] \qquad \text{Eq. 2.1}$$

Confined concrete $\Rightarrow$ $$\sigma_c = f_{cc}\left[\frac{2\varepsilon_c}{\varepsilon_{coc}} - \left(\frac{\varepsilon_c}{\varepsilon_{coc}}\right)^2\right] \qquad \text{Eq. 2.2}$$

For descending branches;

Unconfined Concrete

$$\sigma_c = f_c[1 - Z_u(\varepsilon_c - \varepsilon_{co})] \qquad \text{Eq. 2.3}$$

$$Z_u = \frac{0.5}{\varepsilon_{50u} - \varepsilon_{co}} \qquad \text{Eq. 2.4}$$

$$\varepsilon_{50u} = \frac{3 + 0.285 f_c}{142 f_c - 1000} \geq \varepsilon_{co} \qquad \text{Eq. 2.5}$$

Confined Concrete

$$K = 1 + \frac{\rho_s f_{ywk}}{f_c} \qquad \text{Eq. 2.6}$$

$$\sigma_c = f_{cc}[1 - Z_c(\varepsilon_c - \varepsilon_{coc})] \geq 0.2 f_{cc} \qquad \text{Eq. 2.7}$$

$$\varepsilon_{coc} = K\varepsilon_{co} \qquad \text{Eq. 2.8}$$

$$Z_c = \frac{0.5}{\varepsilon_{50u} + \varepsilon_{50h} - \varepsilon_{coc}} \qquad \text{Eq. 2.9}$$

$$\varepsilon_{50h} = 0.75\rho_s \left(\frac{b_k}{s}\right)^{1/2} \qquad \text{Eq. 2.10}$$

$$\rho_s = \frac{A_o \times l_s}{s \times b_k \times h_k} \qquad \text{Eq. 2.11}$$

Where;

f_c : Unconfined concrete compressive strength (Mpa)

f_{cc} : Confined concrete compressive strength (Mpa)

ε_{co} : Unconfined concrete strain under maximum stress f_c

ε_{coc} : Confined concrete strain under maximum stress f_{cc}

Z_u, Z_c : Dimensionless slope of the descending branches of unconfined and confined concrete

b_k : Smaller dimension of the core concrete region from one end of the stirrup to the other end

h_k : Larger dimension of the core concrete region from one end of the stirrup to the other end

ρ_s : Volumetric ratio of the transverse reinforcement

A_o : Cross sectional area of the transverse reinforcement (mm^2)

l_s : Total length of the transverse reinforcement in the cross section

f_{ywk} : Minimum yield strength of the transverse reinforcement (mm)

s : Spacing of the transverse reinforcement (mm)

In Opensees (2005), "Concrete01 Material" is used to construct a uniaxial Kent and Park concrete material object with degraded linear unloading/reloading stiffness according to the work of Karsan-Jirsa with zero tensile strength.

2.2.2.2. Material Model for Steel Fibers

For compression and tension zone, the stress versus strain curve is taken as identical while conducting pushover analyses. Idealized one dimensional stress-strain curve is convenient in order to provide the simplicity of calculations. While assessing the flexure critical columns in this study, it is assumed that reinforcing steel has a linear hardening region. In Opensees (2005), "Steel01 Material" is used to construct a uniaxial bilinear steel material object with kinematic hardening and optional isotropic hardening described by a nonlinear evolution equation (See Figure 2.4).

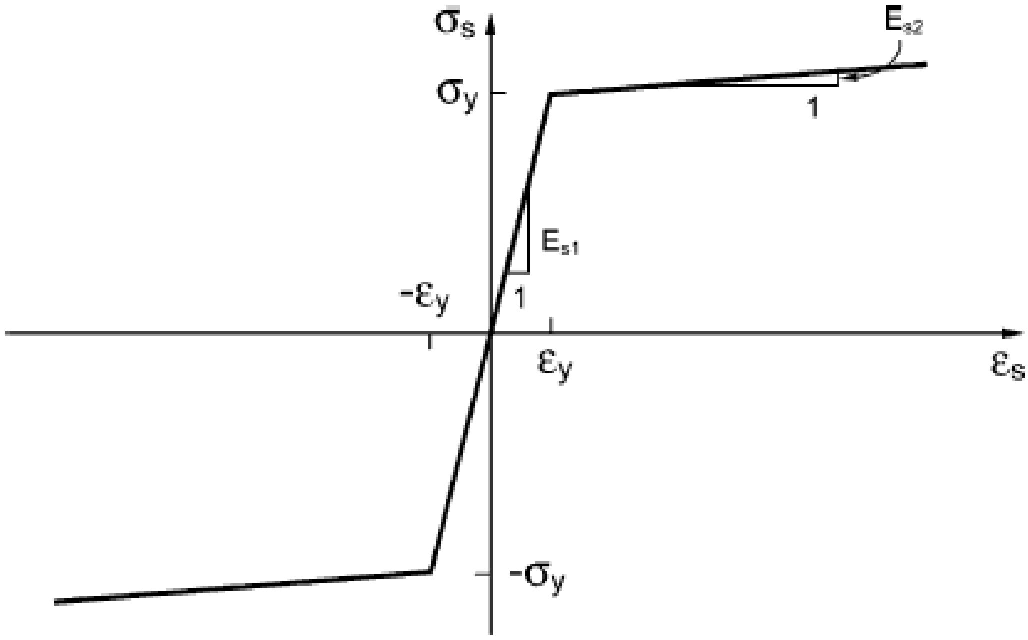


Figure 2.4 Reinforcing Steel Stress-Strain Relation

2.2.3. Modeling Reinforced Concrete Members Including Bond Slip Effects

Experimental behavior of reinforced concrete members, which are subjected to both static and dynamic loads, is extremely related to the effects of bond slip. Strain penetration effects are caused by the slippage between fully fixed longitudinal reinforcing bars and the concrete section of the connecting member. In linear and nonlinear analyses of reinforced concrete members, ignoring the effects of strain penetration causes miscalculation of the deflections and member elongations. In addition member stiffness and hysteretic energy dissipation capacity are overestimated if one ignores the strain penetration effects.

Inelastic deformations at plastic hinge region of a structural member include two components which are the flexural deformation that causes inelastic strains in the longitudinal bars and concrete and member end rotation due to reinforcement slip (See Figure 2.5).

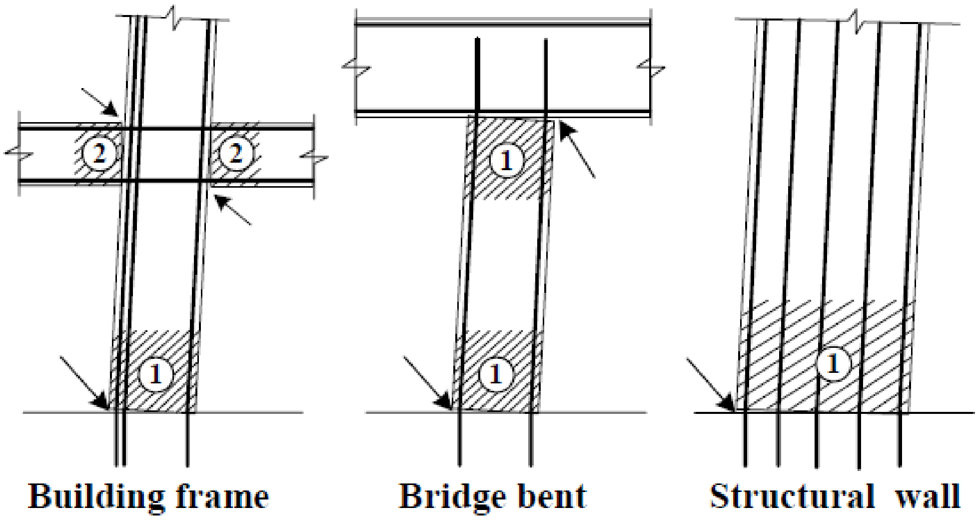


Figure 2.5 Inelastic Regions in Properly Designed Reinforced Concrete Structures (Zhao and Sritharan (2007))

In order to estimate the member end rotation due to reinforcement slip, bond slip effects should be accurately modeled by using a zero-length section element accessible in OpenSees (2005). Zero-length section element is used in a section analysis for which the strain values of concrete and steel fibers are calculated. Stress-strain relationships of concrete and steel fibers are necessary for the calculation of fiber forces which provide the section moment by integrating these forces all over the section.

While handling bond slip effects with zero-length section element, an identical node is needed. Figure 2.6 shows the usage of zero-length section element in OpenSees (2005).

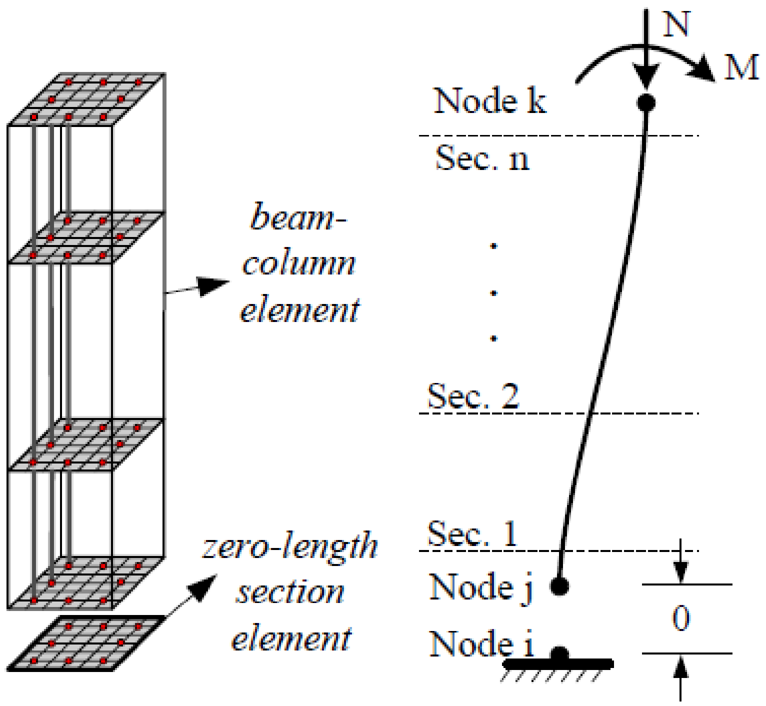


Figure 2.6 Fiber Based Modeling of Strain Penetration Effects (Zhao and Sritharan (2007))

In order to prevent sliding, the translational movement of the nodes should be connected to each other. Zero-length section element has unit length as a result the deformation of the element (rotation) is equal to the deformation of the section (curvature).

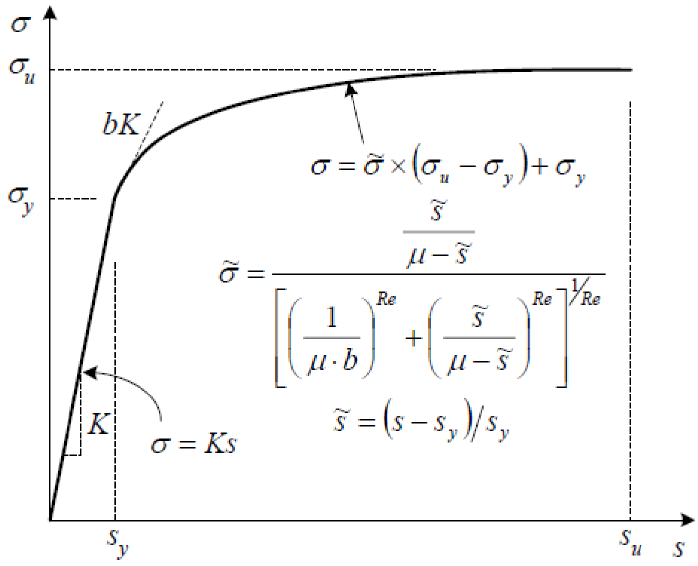


Figure 2.7 Envelope Curve for the Bar Stress versus Loaded-End Slip Relationship (Zhao and Sritharan (2007))

The material model for the steel fibers in the zero-length element section must closely stand for the bond slip of anchored reinforcing bars. Figure 2.7 shows the relationship between stress and slip for the used material model for the steel fibers. As seen from the figure, bar slip may be used instead of strain value of reinforcing steel as a result of the unit length assumption.

$$S_y\ (mm) = \ 0.40 \left(\frac{d_b(mm)}{4} \frac{f_y(MPa)}{\sqrt{f_c(MPa)}} (2\alpha + 1) \right)^{1/\alpha} + 0.34 \qquad \text{Eq. 2.12}$$

$$\alpha = 0.40 \qquad \text{Eq. 2.13}$$

$$S_u = 30 \sim 40\ S_y \qquad \text{Eq. 2.14}$$

$$b = 0.30 \sim 0.50 \qquad \text{Eq. 2.15}$$

Where;

S_y : Yield slip

S_u : Ultimate slip

b : Stiffness reduction factor

The material model for the concrete fibers in the zero-length element section should overcome the large deformations expected to the extreme concrete fibers. Material model Concrete01, available in OpenSees (2005), can be used with a perfectly plastic behavior once the strength decreases to 80% of the confined compressive strength.

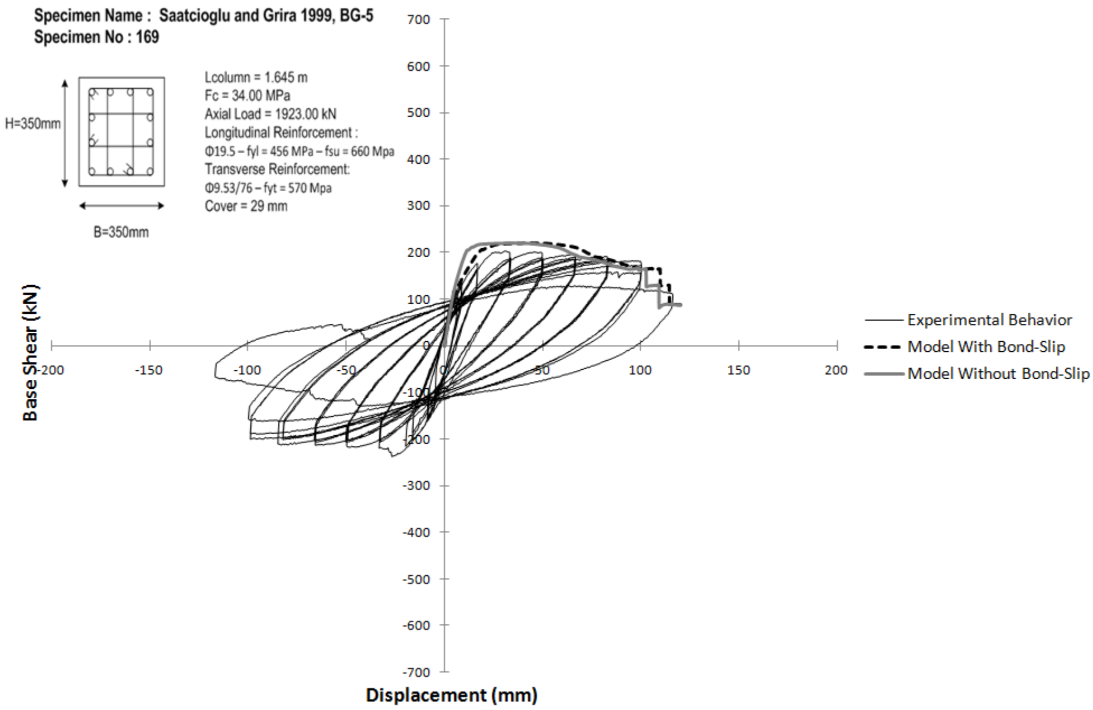


Figure 2.8 Graphical Illustration of Modeling with and without Bond-Slip Effects

Figure 2.8 illustrates the difference between considering bond-slip effects and ignoring them. Member stiffness and hysteretic energy dissipation capacity are overestimated when bond-slip effects are ignored. In addition deflections and member elongations are miscalculated while modeling without bond-slip effects. For the specimen shown in Figure 2.8, capacity curve obtained from analytical study fits well with the backbone curve obtained from experimental study. For the rest of the columns selected from PEER database (2005), capacity curves obtained from analytical studies and backbone curves obtained from experimental studies are graphically compared in the Appendix part of the thesis in Figure A.1. In addition analytical studies show that 15-20% of the drift ratio at collapse prevention performance level (ultimate point) is caused by the effects of bond-slip.

2.3. Estimated Performance Limits

Capacity curves, which are obtained from the nonlinear static analyses, are approximated as bilinear curves. These curves have an initial elastic branch until the stiffness changes, and afterwards plastic behavior is observed. Priestley et. al. (2007) defined first yield point as the point where the outer part of tension reinforcement reaches yielding strain or the outer part of concrete fiber reaches the strain value of 0.002. The line which is obtained from the first yield point is extended up to the point where the outer part of tension reinforcement reaches the strain value of 0.015 or the outer part of concrete fiber reaches the strain value of 0.004. The elastic part obtained from this extrapolated line is combined with the plastic part up to the ultimate point to complete the bilinear curve.

In this study, estimated immediate occupancy is a performance limit where the elastic branch gives place to plastic branch. Thus, performance limit of immediate occupancy has a strain value of 0.015 for outer part of the tension reinforcement or strain value of 0.004 for the outer part of concrete fiber. In addition to this, estimated performance limit of collapse prevention is the ultimate point where the shear capacity drops 20 percent from the maximum value. Estimated performance limit of life safety is taken as 75 percent of the ultimate point (estimated collapse prevention). Figure 2.9 shows the performance limits on an idealized capacity curve.

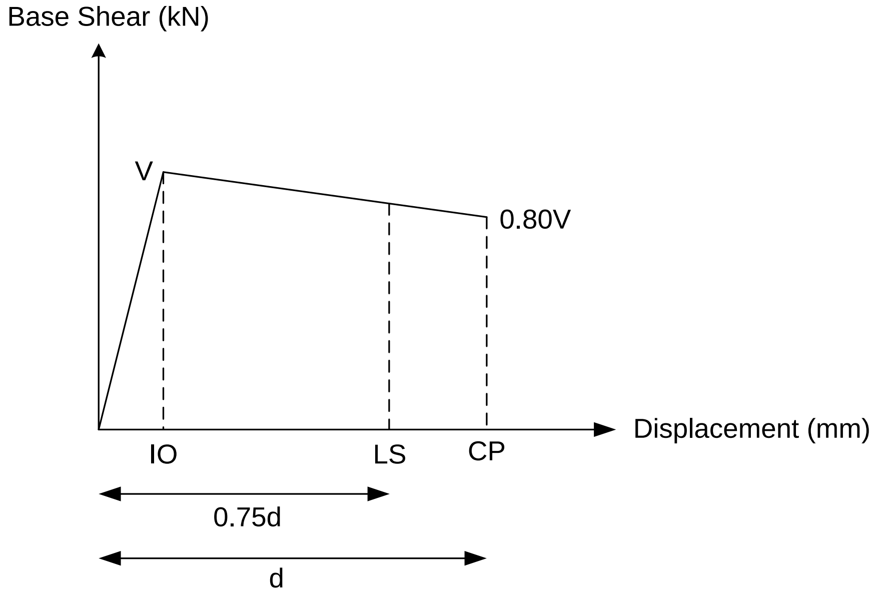


Figure 2.9 Illustration of Estimated Performance Limits

Flexure critical columns selected from PEER database (2005) are analyzed and capacity curves are obtained. After converting capacity curves into bilinear curves, estimated performance limits for each performance level are pointed out and presented in Appendix B;

- Table B.1 provides moment, chord rotation, base shear, and displacement values at the performance level of immediate occupancy.

- Table B.2 provides moment, chord rotation, base shear, and displacement values at the performance level of life safety.

- Table B.3 provides moment, chord rotation, base shear, and displacement values at the performance level of collapse prevention.

- Table B.4 illustrates estimated drift ratios obtained for each performance level respectively.

2.4. Application of Seismic Assessment Guidelines to Selected Column Database

2.4.1. General

In the scope of this study, four different seismic assessment guidelines are evaluated. These guidelines are respectively Turkish Earthquake Code (2007), American pre-standard, FEMA 356 (2000), European seismic code, Eurocode 8 (2003), and ASCE/SEI 41 Update (2009).

Turkish Earthquake Code (2007) is the one which was regenerated in 2007 as a result of the deficiencies based on the seismic code written in 1998. New code consists of a part that includes provisions for seismic assessment and retrofitting methods of existing buildings. In order to assess and decide the performance level of existing reinforced concrete structures, performance based analysis procedure is required. This procedure is totally different from the one which consists of force based capacity design method. To estimate performance level of a structure, all components in the critical sections should be investigated for a code specified demand.

FEMA 356 (2000) is the American pre-standard and commentary for the seismic rehabilitation of buildings. The document presents deformation limits, which are in the form of plastic rotations, for different structural members and these limits should be compared with the deformation demands obtained from nonlinear structural analysis.

Eurocode 8 (2003) includes a part for the assessment of reinforced concrete columns that recommends the calculation of chord rotations with the given equations in the code. These equations are functions of many variables such as axial load ratio, longitudinal reinforcement ratio, transverse reinforcement ratio, and yield strength of the transverse reinforcement. Calculated chord rotations should be compared with the demands obtained from nonlinear analysis.

2.4.2. Application of TEC (2007) to Selected Column Database

"Assessment and Strengthening of Existing Buildings" is the seventh chapter of the new code which introduces some new techniques to assess and rehabilitate the existing buildings. In this part of the code, performance level of reinforced concrete structural members can be evaluated by using elastic and inelastic approaches. Linear elastic procedure, which was not included in the content of this study, recommends calculating capacity and demand respectively to make a prediction about the performance of structural members. In the nonlinear static procedure, in order to predict the performance level, the strain limits of concrete and steel are used as the main parameters. In addition, Turkish Earthquake Code (2007) defines three damage levels which are taking the ductility capacity and predicted failure mode into account. Seismic performance of a structure can be determined by considering the distribution of structural damage along the building. Figure 2.10 illustrates the damage levels of a ductile member described in TEC (2007).

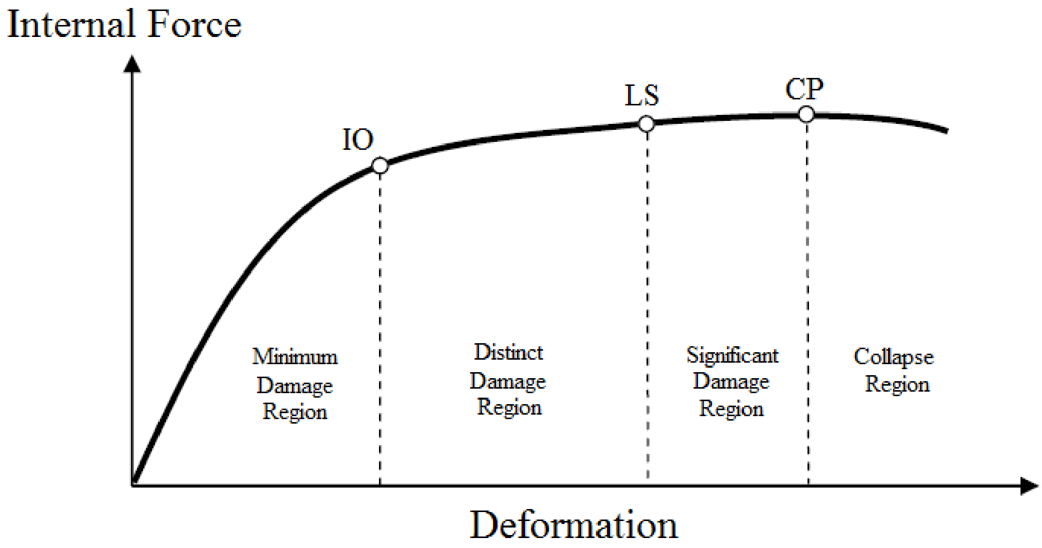


Figure 2.10 Damage Levels of a Ductile Member (TEC (2007))

Structural components can be divided into two groups when their failure modes are considered. Members that are controlled by the shear force, experience a brittle failure. All other failure types can be classified as ductile, and the member which experiences this type of failure can be named as a ductile member. When the damage levels are considered, brittle members are allowed up to the point of IO because inelastic behavior at a critical section of a member plays role after this limit point.

According to the TEC (2007), linear and nonlinear procedures show small differences while defining a member as brittle or ductile. Shear capacity of the critical section of the column should be calculated according to TS500 (2000) and should be compared with the flexural shear capacity of that section. If the flexural shear capacity is greater than the shear capacity of the critical section, the type of failure is classified as brittle; otherwise failure is classified as ductile.

TEC (2007) emphasizes that plastic hinge analysis assumes that the total post-yield displacement of a reinforced concrete component may be broken up into two parts, which are the behavior up to the yielding point of the critical section and the deformation which occurs after yielding. According to the code provisions, length of plastic hinge (L_p) may be defined as the half of the section depth (H).

The equation for the calculation of plastic hinge length:

$$L_p = H/2 \qquad \text{Eq. 2.16}$$

For a reinforced concrete column, sectional damage state should be calculated by determining the strain values of concrete fibers and reinforcement. Strain limits are provided as:

For Immediate Occupancy (IO):

$$(\varepsilon_{cunconfined})_{IO} = 0.0035 \text{ ; } (\varepsilon_s)_{IO} = 0.01 \qquad \text{Eq. 2.17}$$

For Life Safety (LS):

$$(\varepsilon_{cconfined})_{LS} = 0.0035 + 0.01 \left(\rho_s / \rho_{sm} \right) \leq 0.0135 \text{ ; } (\varepsilon_s)_{LS} = 0.04 \qquad \text{Eq. 2.18}$$

For Collapse Prevention (CP):

$$(\varepsilon_{cconfined})_{CP} = 0.004 + 0.014 \left(\rho_s / \rho_{sm} \right) \leq 0.018 \text{ ; } (\varepsilon_s)_{CP} = 0.06 \qquad \text{Eq. 2.19}$$

Where;

$\varepsilon_{cunconfined}$: Cover concrete strain at the outer fiber of the unconfined region

$\varepsilon_{cconfined}$: Core concrete strain at the outer fiber of the confined region

ε_s : Steel strain at the critical section

ρ_s : Volumetric ratio of the confinement reinforcement present at the critical section

ρ_{sm}: Volumetric ratio of the confinement reinforcement required at the critical section

The approximate distribution of curvature along the member height is used to compute the displacements as shown in Figure 2.11.

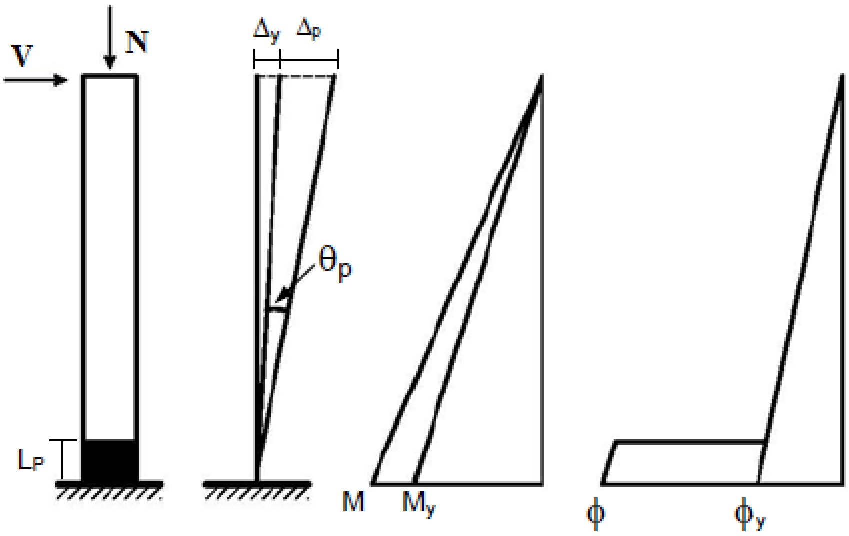


Figure 2.11 Lumped plasticity idealization of a cantilever member (Ozmen et. al. (2007))

For a ductile member up to the yielding point, top displacement is calculated as:

$$\Delta = \frac{\phi L^2}{3} \quad \text{Eq. 2.20}$$

For a ductile member after the yielding point, top displacement is calculated as:

$$\Delta = \Delta_y + \Delta_p \quad \text{Eq. 2.21}$$

$$\Delta_y = \frac{\phi_y L^2}{3} \quad \text{Eq. 2.22}$$

$$\Delta_p = (\phi - \phi_y)L_p(L - 0.5L_p) \quad \text{Eq. 2.23}$$

$$\Delta = \frac{\phi_y L^2}{3} + (\phi - \phi_y)L_p(L - 0.5L_p) \quad \text{Eq. 2.24}$$

Where;

Δ: Total displacement at the free end of the column

Δ_y: Elastic displacement at the free end of the column

Δ_p: Plastic displacement at the free end of the column

Φ: Total curvature at the critical section of the column

Φ_y: Elastic curvature at the critical section of the column

Φ_p: Plastic curvature at the critical section of the column

L: Length of the column

L_p: Length of the plastic hinge

On the other hand, for a brittle member plastic deformation capacity is almost zero so load-deformation relation of a brittle member may be taken as linearly elastic.

Flexure critical columns selected from PEER database (2005) are analyzed and capacity curves are obtained. According to TEC (2007), performance limits for each performance level are pointed out;

- Table B.5 provides moment, chord rotation, base shear, and displacement values at the performance level of immediate occupancy.

- Table B.6 provides moment, chord rotation, base shear, and displacement values at the performance level of life safety.

- Table B.7 provides moment, chord rotation, base shear, and displacement values at the performance level of collapse prevention.

- Table B.8 illustrates estimated drift ratios obtained for each performance level respectively.

- Figure 2.12 shows the graphical explanation of performance limits obtained by TEC (2007) for four sample columns showing different behavior.

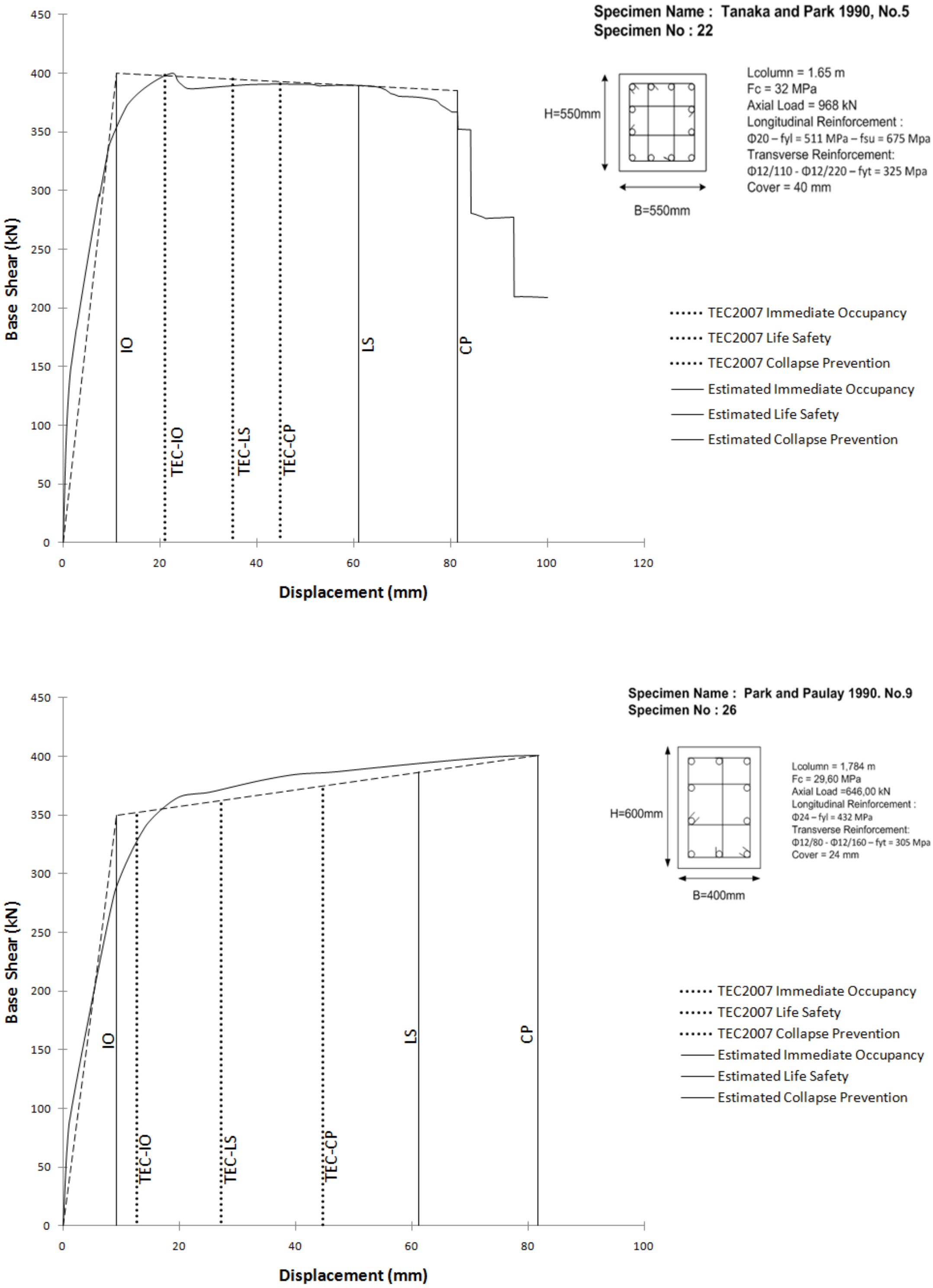
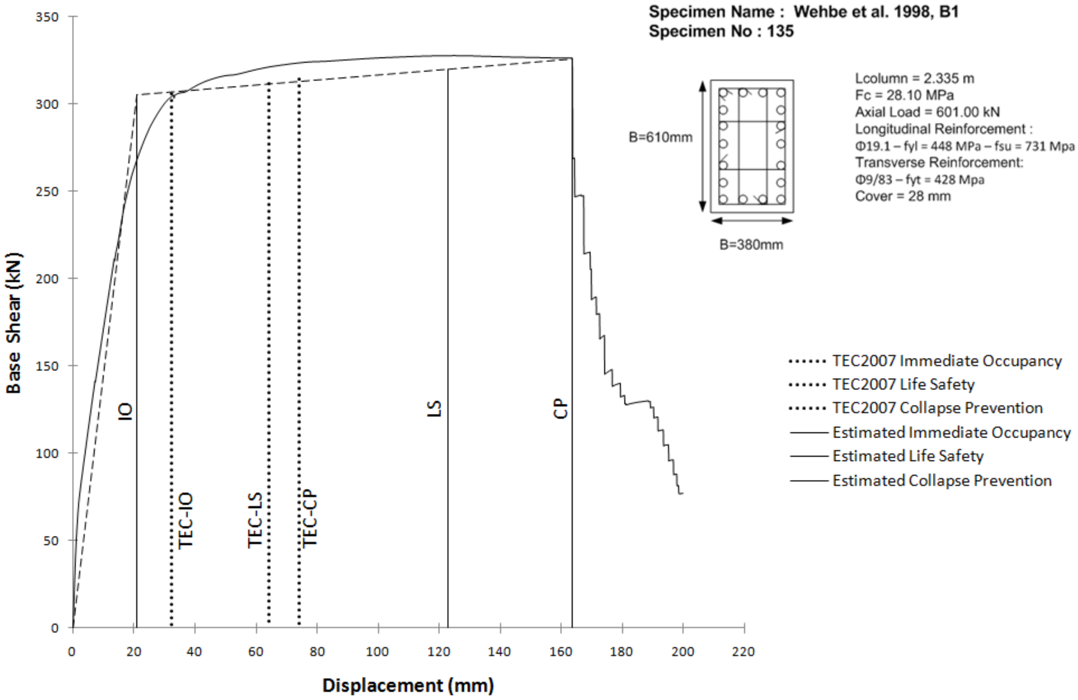


Figure 2.12 Performance Limits Obtained by TEC (2007)



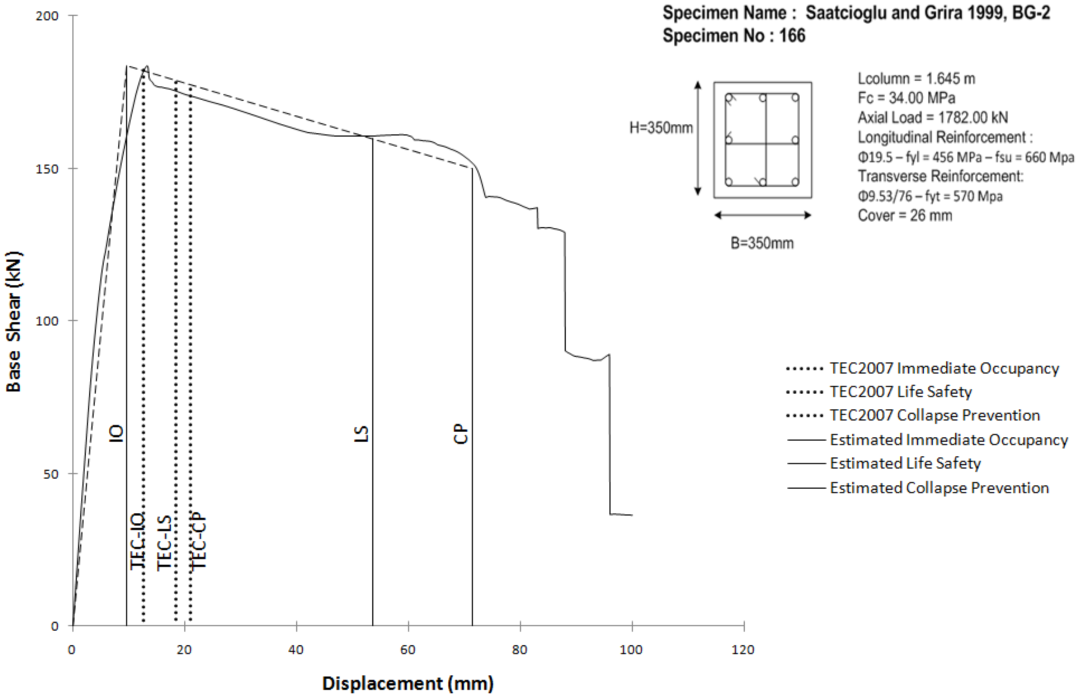


Figure 2.12 (cont'd) Performance Limits Obtained by TEC (2007)

2.4.3. Application of FEMA 356 (2000) to Selected Column Database

According to the American pre-standard FEMA 356 (2000), in order to generate an analytical model of a structure, nonlinear force-deformation relation of structural components should be considered. Exposing this analytical model to lateral load that increases monotonically, a base shear-lateral displacement relationship is developed. When the experienced displacement reaches the value of target displacement, the demands, in terms of plastic hinge rotations, element forces, and story drifts, at that displacement are compared with a series of specified acceptability criteria. Materials of construction, structural component type, importance of structural component (primary or secondary), and a preselected performance level identify the acceptability criteria.

While assessing a reinforced concrete member, specified values for plastic hinge rotation may be used as a parameter. Each performance level has an acceptable limiting value of plastic hinge rotation. According to FEMA 356 (2000), these limiting values are directly related with the type of structural component. For a beam, dominated mode of behavior (shear or flexure), $((\rho - \rho')\ /\rho_{bal.})$ ratio, the spacing of the stirrups, and $(V/(b_w\, d\ (f_c)^{1/2})$ ratio, affect the value of plastic hinge rotation. On the other hand, for a column, dominated mode of behavior (shear or flexure), $N/(bdf_c)$ ratio (axial load ratio), the spacing of stirrups, and $(V/(b_w\, d\ (f_c)^{1/2})$ ratio, affect the value of plastic hinge rotation.

The variables in these parameters are;

ρ: Tension reinforcement ratio at the critical section
ρ': Compression reinforcement ration at the critical section
$\rho_{bal.}$: Reinforcement ratio which produces balanced strain conditions
V: Shear force at the critical section
b_w : Width of the web reinforcement
d: Flexural depth of the section
f_c: Concrete compressive strength

N: Axial load at the critical section

b: Width of the section

Performance based rotation limits given in FEMA 356 (2000) for columns which are controlled by flexure is shown in Figure 2.13. In this figure, for each parameter limit values are given to calculate the plastic rotation angles. The values in between these limits should be interpolated to decide the plastic rotation angles corresponding to each performance level. Flexure critical columns selected from PEER database (2005) are analyzed and capacity curves are obtained. According to FEMA 356 (2000), performance limits for each performance level are pointed out;

- Table B.10 provides moment, chord rotation, base shear, and displacement values at the performance level of immediate occupancy.

- Table B.11 provides moment, chord rotation, base shear, and displacement values at the performance level of life safety.

- Table B.12 provides moment, chord rotation, base shear, and displacement values at the performance level of collapse prevention.

- Table B.13 illustrates estimated drift ratios obtained for each performance level respectively.

- Figure 2.15 shows the graphical explanation of performance limits obtained by FEMA 356 (2000) for the example columns.

Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures— Reinforced Concrete Columns

Conditions			Modeling Parameters[4]			Acceptance Criteria[4]				
						Plastic Rotation Angle, radians				
						Performance Level				
							Component Type			
			Plastic Rotation Angle, radians		Residual Strength Ratio		Primary		Secondary	
			a	b	c	IO	LS	CP	LS	CP
i. Columns controlled by flexure[1]										
$\frac{P}{A_g f'_c}$	Trans. Reinf.[2]	$\frac{V}{b_w d \sqrt{f'_c}}$								
≤ 0.1	C	≤ 0.25	0.02	0.03	0.2	0.005	0.015	0.02	0.02	0.03
≤ 0.1	C	≥ 0.50	0.016	0.024	0.2	0.005	0.012	0.016	0.016	0.024
≥ 0.4	C	≤ 0.25	0.015	0.025	0.2	0.003	0.012	0.015	0.018	0.025
≥ 0.4	C	≥ 0.50	0.012	0.02	0.2	0.003	0.01	0.012	0.013	0.02
≤ 0.1	NC	≤ 0.25	0.006	0.015	0.2	0.005	0.005	0.006	0.01	0.015
≤ 0.1	NC	≥ 0.50	0.005	0.012	0.2	0.005	0.004	0.005	0.008	0.012
≥ 0.4	NC	≤ 0.25	0.003	0.01	0.2	0.002	0.002	0.003	0.006	0.01
≥ 0.4	NC	≥ 0.50	0.002	0.008	0.2	0.002	0.002	0.002	0.005	0.008
ii. Columns controlled by shear[1, 3]										
All cases [5]			—	—	—	—	—	—	.0030	.0040
iii. Columns controlled by inadequate development or splicing along the clear height[1,3]										
Hoop spacing ≤ d/2			0.01	0.02	0.4	0.005	0.005	0.01	0.01	0.02
Hoop spacing > d/2			0.0	0.01	0.2	0.0	0.0	0.0	0.005	0.01
iv. Columns with axial loads exceeding $0.70P_o$[1, 3]										
Conforming hoops over the entire length			0.015	0.025	0.02	0.0	0.005	0.01	0.01	0.02
All other cases			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1. When more than one of the conditions i, ii, iii, and iv occurs for a given component, use the minimum appropriate numerical value from the table.
2. "C" and "NC" are abbreviations for conforming and nonconforming transverse reinforcement. A component is conforming if, within the flexural plastic hinge region, hoops are spaced at ≤ $d/3$, and if, for components of moderate and high ductility demand, the strength provided by the hoops (V_s) is at least three-fourths of the design shear. Otherwise, the component is considered nonconforming.
3. To qualify, columns must have transverse reinforcement consisting of hoops. Otherwise, actions shall be treated as force-controlled.
4. Linear interpolation between values listed in the table shall be permitted.
5. For columns controlled by shear, see Section 6.5.2.4.2 for acceptance criteria.

Figure 2.13 Plastic Hinge Rotation Limits for Reinforced Concrete Columns (FEMA356 (2000))

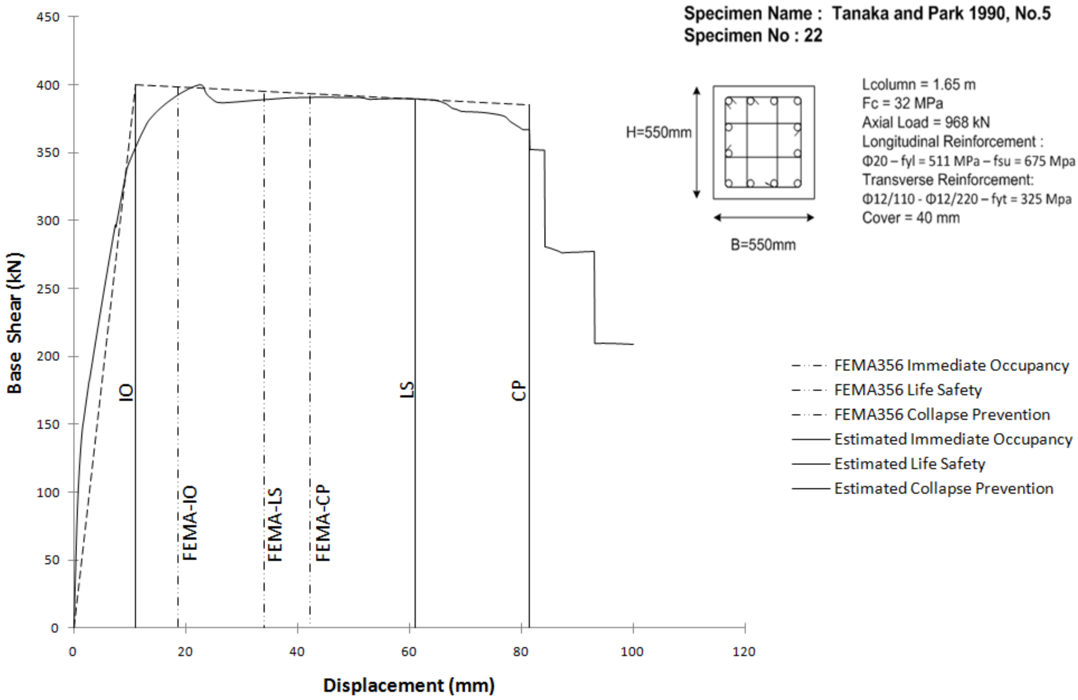
Performance based rotation limits given in ASCE/SEI 41 Updated (2009) for columns which are controlled by flexure is shown in Figure 2.14.

Table 6-8 Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures-Reinforced Concrete Columns

Conditions			Modeling Parameters[3]			Acceptance Criteria[3, 4]				
						Plastic Rotations Angle, radians				
						Performance Level				
			Plastic Rotations Angle, radians		Residual Strength Ratio		Component Type			
							Primary		Secondary	
			a	b	c	IO	LS	CP	LS	CP
Condition i. [1]										
$\frac{P}{A_g f'_c}$ [2]	$\rho = \frac{A_v}{b_w s}$									
≤ 0.1	≥ 0.006		0.035	0.060	0.2	0.005	0.026	0.035	0.045	0.060
≥ 0.6	≥ 0.006		0.010	0.010	0.0	0.003	0.008	0.009	0.009	0.010
≤ 0.1	$= 0.002$		0.027	0.034	0.2	0.005	0.020	0.027	0.027	0.034
≥ 0.6	$= 0.002$		0.005	0.005	0.0	0.002	0.003	0.004	0.004	0.005
Condition ii. [1]										
$\frac{P}{A_g f'_c}$ [2]	$\rho = \frac{A_v}{b_w s}$	$\frac{V}{b_w d \sqrt{f'_c}}$								
≤ 0.1	≥ 0.006	≤ 3	0.032	0.060	0.2	0.005	0.024	0.032	0.045	0.060
≤ 0.1	≥ 0.006	≥ 6	0.025	0.060	0.2	0.005	0.019	0.025	0.045	0.060
≥ 0.6	≥ 0.006	≤ 3	0.010	0.010	0.2	0.003	0.008	0.009	0.009	0.010
≥ 0.6	≥ 0.006	≥ 6	0.008	0.008	0.2	0.003	0.006	0.007	0.007	0.008
≤ 0.1	≤ 0.0005	≤ 3	0.012	0.012	0.0	0.005	0.009	0.010	0.010	0.012
≤ 0.1	≤ 0.0005	≥ 6	0.006	0.006	0.0	0.004	0.005	0.005	0.005	0.006
≥ 0.6	≤ 0.0005	≤ 3	0.004	0.004	0.0	0.002	0.003	0.003	0.003	0.004
≥ 0.6	≤ 0.0005	≥ 6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Condition iii. [1]										
$\frac{P}{A_g f'_c}$ [2]	$\rho = \frac{A_v}{b_w s}$									
≤ 0.1	≥ 0.006		0.0	0.060	0.0	0.0	0.0	0.0	0.045	0.060
≥ 0.6	≥ 0.006		0.0	0.008	0.0	0.0	0.0	0.0	0.007	0.008
≤ 0.1	≤ 0.0005		0.0	0.006	0.0	0.0	0.0	0.0	0.005	0.006
≥ 0.6	≤ 0.0005		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Condition iv. Columns controlled by inadequate development or splicing along the clear height[1]										
$\frac{P}{A_g f'_c}$ [2]	$\rho = \frac{A_v}{b_w s}$									
≤ 0.1	≥ 0.006		0.0	0.060	0.4	0.0	0.0	0.0	0.045	0.060
≥ 0.6	≥ 0.006		0.0	0.008	0.4	0.0	0.0	0.0	0.007	0.008
≤ 0.1	≤ 0.0005		0.0	0.006	0.2	0.0	0.0	0.0	0.005	0.006
≥ 0.6	≤ 0.0005		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1. Refer to Section 6.4.2.2.2 for definition of conditions i, ii, and iii. Columns will be considered to be controlled by inadequate development or splices when the calculated steel stress at the splice exceeds the steel stress specified by Equation 6-2. Where more than one of the conditions i, ii, iii, and iv occurs for a given component, use the minimum appropriate numerical value from the table.
2. Where $P > 0.7A_g f'_c$, the plastic rotation angles shall be taken as zero for all performance levels unless columns have transverse reinforcement consisting of hoops with 135 degree hooks spaced at $\leq d/3$ and the strength provided by the hoops (V_s) is at least three-fourths of the design shear. Axial load, P, shall be based on the maximum expected axial loads due to gravity and earthquake loads
3. Linear interpolation between values listed in the table shall be permitted.
4. Primary and secondary component demands shall be within secondary component acceptance criteria where the full backbone curve is explicitly modeled including strength degradation and residual strength in accordance with Section 3.4.3.2.

Figure 2.14 Plastic Hinge Rotation Limits for Reinforced Concrete Columns (ASCE/SEI 41 (2009))



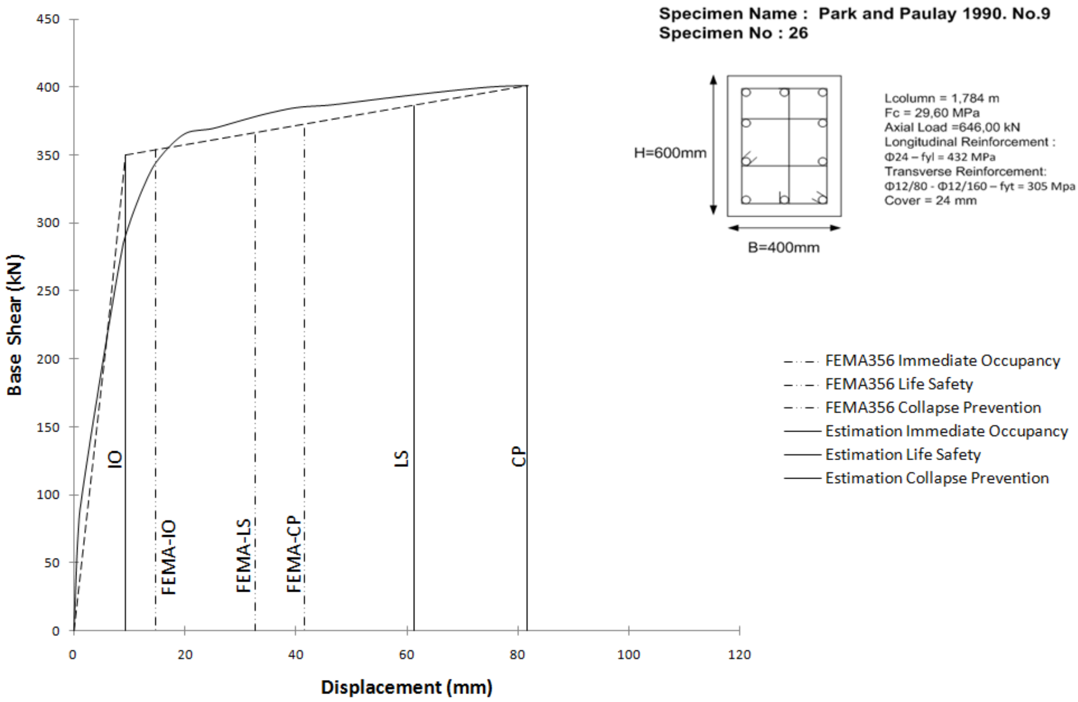
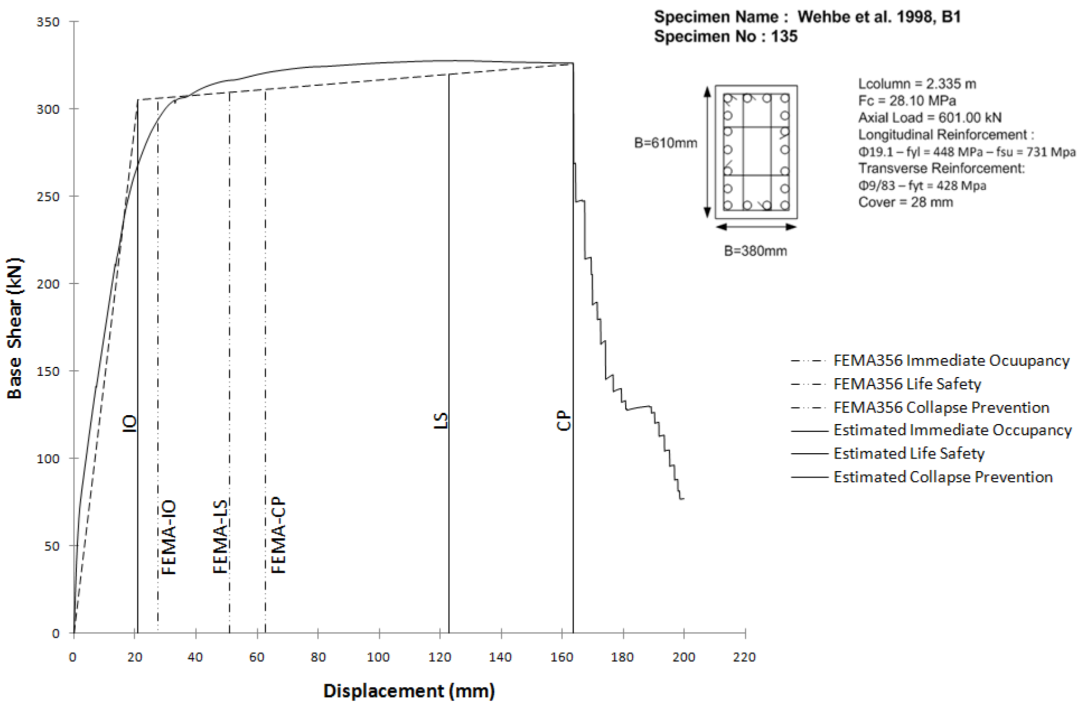


Figure 2.15 Performance Limits Obtained by FEMA 356 (2000)



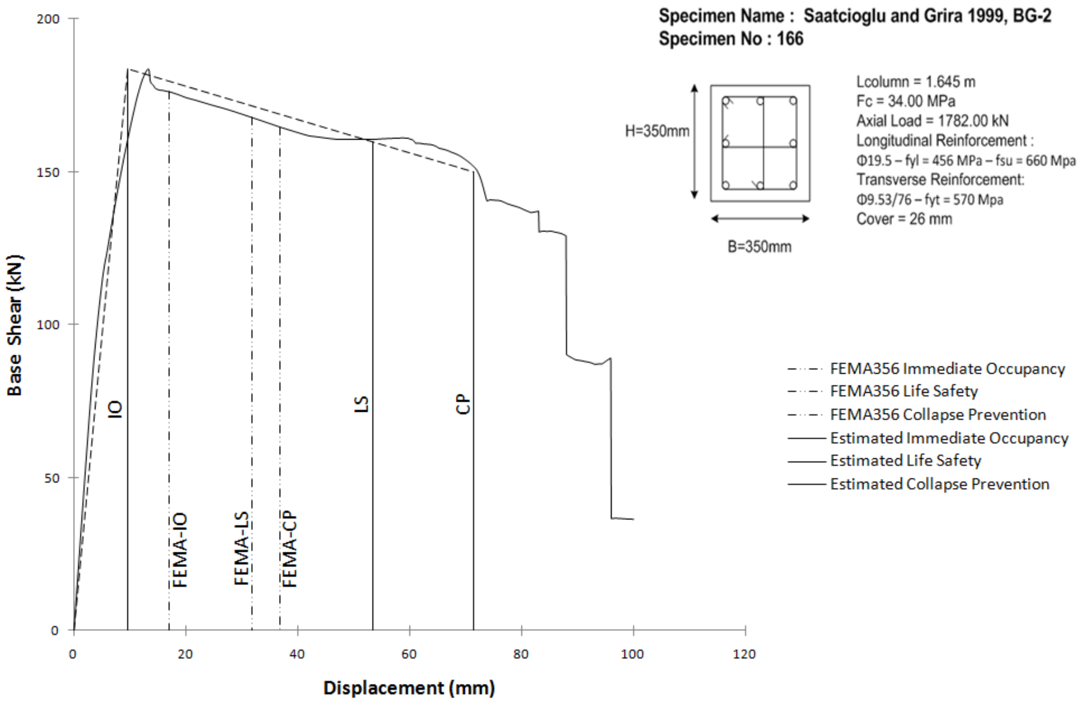


Figure 2.15 (cont'd) Performance Limits Obtained by FEMA 356 (2000)

2.4.4. Application of Eurocode 8 (2003) to Selected Column Database

Eurocode 8 (2003) examines the subject of designing structures for earthquake resistance. The code has a part that includes assessment and retrofitting of buildings. According to Eurocode 8 (2003) performance limit states shall be characterized as follows:

Limit State of Damage Limitation (DL): The structure is safe to occupy after the earthquake and it suffers very limited structural damage, all vertical and lateral load resisting components retain their pre-earthquake stiffness and strength. Partition walls, which are not primary members of structural components, may show distributed cracking. Permanent inelastic displacements may be neglected. Structural components do not need to be retrofitted.

Limit State of Significant Damage (SD): Some structural elements may suffer severe damage that does not lead to partial collapse, with some remaining stiffness and strength, and vertical members are adequate to support vertical loads. Components which are non-structural may be damaged but none of them have failed out of plane. The structure is not economically convenient to be repaired. Injuries may take place after the seismic movement and overall risk to loss of life is low.

Limit State of Near Collapse (NC): The structure is damaged considerably and not safe to occupy, with low remaining lateral stiffness and strength, however vertical members are still adequate to support vertical loads. Most of the components which are non-structural have collapsed. Extreme inelastic displacements which lead to partial collapse may be observed. The structure is near collapse and may probably not endure another seismic movement.

For concrete members which are subjected to cyclic loading, the total chord rotation capacity for the limit state of NC (sum of elastic and plastic behavior) should be calculated from the following expression:

$$\theta_{um} = \frac{1}{\gamma_{el}} 0.016(0.3^{\nu}) \left[\frac{\max(0.01;\omega')}{\max(0.01;\omega)} f_c\right]^{0.225} \left(\frac{L_v}{h}\right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c}\right)} (1.25^{100\,\rho_d}) \quad \text{Eq. 2.25}$$

Where;

γ_{el}: Equal 1.5 for the primary seismic elements and 1.0 for secondary seismic elements

h: Depth of the cross-section

$L_v = M/V$; Ratio of moment versus shear at the end section

$\nu = N/bhf_c$ (b: Width of the compression zone, N: Axial force)

ω, ω': Mechanical reinforcement ratio of the tension and compression

f_c, f_{yw}: Concrete compressive strength and steel yield strength (MPa)

$\rho_{sx} = A_{sx}/b_w s_h$; Ratio of transverse steel to parallel to the direction x of loading (s_h is the stirrup spacing)

ρ_d: Steel ratio of diagonal reinforcement

α: Confinement effectiveness factor

$$\alpha = \left(1 - \frac{s_h}{2b_o}\right)\left(1 - \frac{s_h}{2h_o}\right)(1 - \frac{\sum b_i^2}{6h_o b_o})$$

b_o, h_o: Dimensions of confined core to the centerline of the hoop

b_i: Centerline spacing of longitudinal bars laterally restrained by a stirrup corner or a cross-tie along the perimeter of the cross-section

For concrete members which are subjected to cyclic loading, the total chord rotation capacity corresponding to limit state of significant damage should be calculated from the following expression:

$$\theta_{SD} = \frac{3}{4}\theta_{um} \quad \text{Eq. 2.26}$$

For concrete members which are subjected to cyclic loading, the total chord rotation capacity corresponding to limit state of damage limitation should be calculated from the following expression:

$$\theta_y = \phi_y \frac{L_v+\alpha_v z}{3} + 0.00135\left(1+1.5\frac{h}{L_v}\right) + \frac{\varepsilon_y}{d-d'}\frac{d_b f_y}{6\sqrt{f_c}} \qquad \text{Eq. 2.27}$$

ϕ_y: Yield curvature of the end section

$\alpha_v z$: Tension shift of the bending moment diagram

f_y: Steel yield stress

ε_y: Steel strain at yielding

d_b: Diameter of the tension reinforcement

Flexure critical columns selected from PEER database (2005) are analyzed and capacity curves are obtained. According to Eurocode 8 (2003), performance limits for each performance level are pointed out;

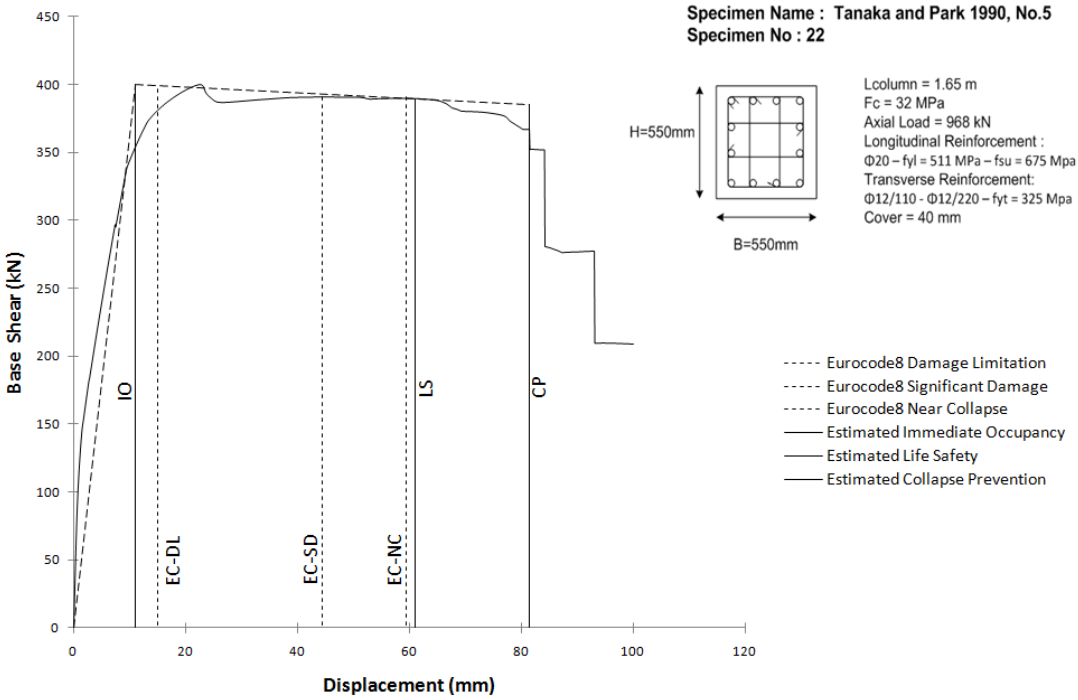
- Table B.14 provides moment, chord rotation, base shear, and displacement values at the performance level of immediate occupancy.

- Table B.15 provides moment, chord rotation, base shear, and displacement values at the performance level of life safety.

- Table B.16 provides moment, chord rotation, base shear, and displacement values at the performance level of collapse prevention.

- Table B.17 illustrates estimated drift ratios obtained for each performance level respectively.

- Figure 2.16 shows the graphical explanation of performance limits obtained by Eurocode 8 (2003) for the example columns.



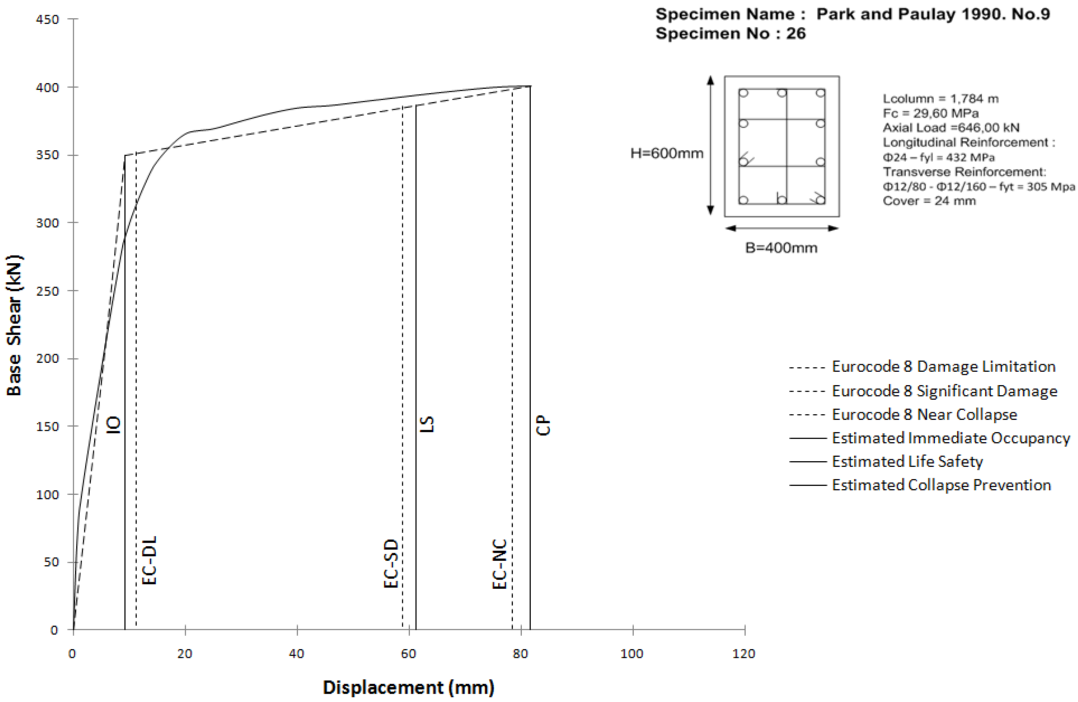
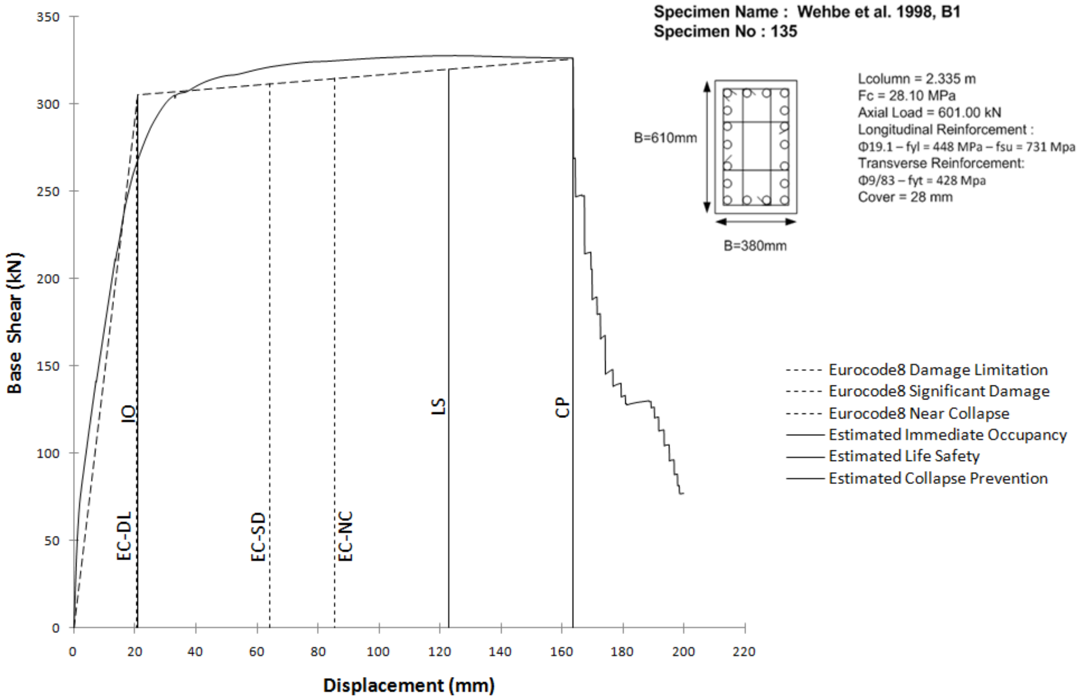


Figure 2.16 Performance Limits Obtained by Eurocode 8 (2003)



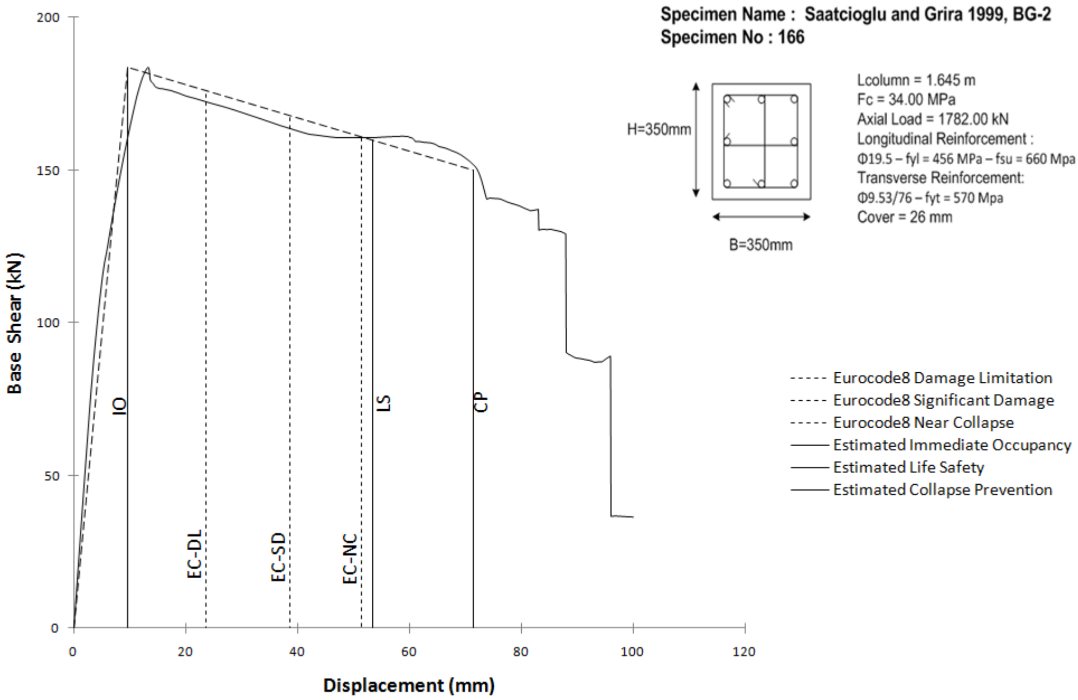


Figure 2.16 (cont'd) Performance Limits Obtained by Eurocode 8 (2003)

2.5. Comparison of Performance Limits

Performance limits corresponding to each performance level obtained by different seismic guidelines are compared in Tables 2.2, 2.3, and 2.4 respectively.

Table 2.2 shows the comparison of immediate occupancy performance level obtained from different seismic guidelines. Estimated drift ratios for each specimen are normalized to 1% and drift ratios obtained from TEC (2007), FEMA 356 (2000), and Eurocode 8 (2003) are regenerated to see the differences between them.

Table 2.2 Comparison of Immediate Occupancy Performance Level Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED Immediate Occupancy	TEC2007 Immediate Occupancy	EC8 Damage Limitation	FEMA356 Immediate Occupancy
	Normalized Drift Ratio	Normalized Drift Ratio	Normalized Drift Ratio	Normalized Drift Ratio
22	1.00	1.91	1.36	1.68
23	1.00	1.88	1.30	1.33
24	1.00	1.80	2.14	2.02
25	1.00	1.58	2.20	2.00
26	1.00	1.37	1.21	1.60
30	1.00	1.60	1.29	1.71
104	1.00	2.01	0.67	1.18
106	1.00	1.63	0.80	1.25
107	1.00	1.73	0.96	1.29
108	1.00	1.78	1.00	1.34
133	1.00	1.59	0.94	1.83
134	1.00	1.41	1.01	1.26
135	1.00	1.55	0.99	1.32
166	1.00	1.31	2.45	1.77
167	1.00	1.49	1.20	1.28
169	1.00	1.39	1.62	1.73
170	1.00	1.39	1.62	1.71
171	1.00	1.40	1.69	1.75
172	1.00	1.33	1.00	1.26
173	1.00	1.35	1.48	1.62
174	1.00	1.35	1.47	1.67
187	1.00	1.65	1.13	1.38
188	1.00	1.50	1.19	1.36
189	1.00	1.34	1.12	1.38
190	1.00	1.72	1.01	1.33
191	1.00	1.57	0.96	1.30
192	1.00	1.43	1.14	1.38
193	1.00	1.81	1.01	1.33
194	1.00	1.62	0.96	1.28
195	1.00	1.44	1.14	1.42

Table 2.3 shows the comparison of life safety performance level obtained from different seismic guidelines. Estimated drift ratios for each specimen are normalized to 1% and drift ratios obtained from TEC (2007), FEMA 356 (2000), and Eurocode 8 (2003) are regenerated to see the differences between them.

Table 2.3 Comparison of Life Safety Performance Level Obtained from Different Seismic Guidelines

Specimen No	**ESTIMATED Life Safety**	**TEC2007 Life Safety**	**EC8 Significant Damage**	**FEMA356 Life Safety**
	Normalized Drift Ratio	**Normalized Drift Ratio**	**Normalized Drift Ratio**	**Normalized Drift Ratio**
22	1.00	0.57	0.73	0.56
23	1.00	0.44	0.57	0.40
24	1.00	0.51	0.69	0.59
25	1.00	0.45	0.57	0.47
26	1.00	0.45	0.96	0.53
30	1.00	0.55	0.67	0.52
104	1.00	0.68	0.41	0.36
106	1.00	0.32	0.31	0.31
107	1.00	0.32	0.35	0.32
108	1.00	0.35	0.42	0.37
133	1.00	0.38	0.51	0.38
134	1.00	0.63	0.79	0.67
135	1.00	0.52	0.52	0.42
166	1.00	0.34	0.72	0.60
167	1.00	0.52	0.65	0.47
169	1.00	0.55	0.54	0.56
170	1.00	0.54	0.53	0.54
171	1.00	1.06	0.99	1.05
172	1.00	0.79	0.77	0.66
173	1.00	0.89	0.99	1.04
174	1.00	0.51	0.61	0.54
187	1.00	0.51	0.61	0.46
188	1.00	0.48	0.61	0.47
189	1.00	0.51	0.63	0.49
190	1.00	0.55	0.65	0.46
191	1.00	0.58	0.67	0.52
192	1.00	0.57	0.75	0.59
193	1.00	0.58	0.67	0.47
194	1.00	0.49	0.59	0.44
195	1.00	0.57	0.76	0.61

Table 2.4 shows the comparison of collapse prevention performance level obtained from different seismic guidelines. Estimated drift ratios for each specimen are normalized to 1% and drift ratios obtained from TEC (2007), FEMA 356 (2000), and Eurocode 8 (2003) are regenerated to see the differences between them.

Table 2.4 Comparison of Collapse Prevention Performance Level Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED Collapse Prevention	TEC2007 Collapse Prevention	EC8 Near Collapse	FEMA356 Collapse Prevention
	Normalized Drift Ratio	Normalized Drift Ratio	Normalized Drift Ratio	Normalized Drift Ratio
22	1.00	0.55	0.73	0.52
23	1.00	0.45	0.57	0.38
24	1.00	0.51	0.69	0.53
25	1.00	0.57	0.57	0.42
26	1.00	0.55	0.96	0.51
30	1.00	0.64	0.67	0.48
104	1.00	0.78	0.41	0.32
106	1.00	0.31	0.31	0.28
107	1.00	0.27	0.35	0.29
108	1.00	0.29	0.42	0.34
133	1.00	0.31	0.51	0.35
134	1.00	0.54	0.79	0.60
135	1.00	0.45	0.52	0.38
166	1.00	0.29	0.72	0.52
167	1.00	0.43	0.65	0.42
169	1.00	0.47	0.54	0.47
170	1.00	0.48	0.53	0.46
171	1.00	0.86	0.99	0.89
172	1.00	0.70	0.78	0.58
173	1.00	0.69	0.94	0.84
174	1.00	0.45	0.61	0.46
187	1.00	0.43	0.61	0.42
188	1.00	0.42	0.61	0.43
189	1.00	0.45	0.63	0.44
190	1.00	0.46	0.64	0.42
191	1.00	0.50	0.67	0.47
192	1.00	0.49	0.75	0.53
193	1.00	0.49	0.66	0.43
194	1.00	0.43	0.59	0.40
195	1.00	0.49	0.76	0.54

Table 2.5 and Table 2.6 illustrate statistical analysis results obtained according to different seismic guidelines. Table 2.5 shows real drift ratios; on the other hand Table 2.6 shows normalized drift ratios corresponding to each seismic guideline. When Tables 2.5 and 2.6 are evaluated, following results can be derived;

- For the performance level of immediate occupancy, average drift ratios for TEC (2007), Eurocode 8 (2003), and FEMA 356 (2000) are respectively 1.37, 1.04, and 1.27%,

- For the performance level of life safety, average drift ratios for TEC (2007), Eurocode 8 (2003), and FEMA 356 (2000) are respectively 2.33, 2.71, and 2.22%,

- For the performance level of collapse prevention, average drift ratios for TEC (2007), Eurocode 8 (2003), and FEMA 356 (2000) are respectively 2.84, 3.62, and 2.65%,

- According to evaluation of capacity curves obtained from analytical studies, estimated drift ratios for each performance level have average values of 0.88, 4.51, and 6.02%,

- When standard deviations are compared, it is seen that estimated values and TEC (2007) provide higher values than Eurocode 8 (2003) and FEMA 356 (2000). In addition, FEMA 356 provides closer standard deviation values for all performance levels; on the other hand for all other provisions, standard deviation values are increasing from the performance level of immediate occupancy to the performance level of collapse prevention.

Table 2.5 Statistical Analysis Results Obtained According to Different Seismic Guidelines

		Drift Ratio (%)		
Procedure	**Stat.**	**IO**	**LS**	**CP**
TEC 2007	μ	1.37	2.33	2.84
	σ	0.37	0.57	0.88
	cov	0.27	0.24	0.31
EUROCODE 8	μ	1.04	2.71	3.62
	σ	0.19	0.37	0.48
	cov	0.18	0.13	0.13
FEMA 356	μ	1.27	2.22	2.65
	σ	0.19	0.17	0.19
	cov	0.15	0.08	0.07
ESTIMATED	μ	0.88	4.51	6.02
	σ	0.20	1.25	1.67
	cov	0.23	0.28	0.28

Table 2.6 Statistical Analysis Results Obtained for the Comparison of Different Seismic Guidelines

		Normalized Drift Ratios		
Procedure	**Stat.**	**IO**	**LS**	**CP**
TEC 2007	μ	1.56	0.54	0.49
	σ	0.19	0.15	0.14
	cov	0.12	0.29	0.28
EUROCODE 8	μ	1.27	0.64	0.64
	σ	0.41	0.16	0.16
	cov	0.32	0.25	0.25
FEMA 356	μ	1.49	0.53	0.47
	σ	0.24	0.17	0.13
	cov	0.16	0.31	0.28
ESTIMATED	μ	1.00	1.00	1.00
	σ	0.00	0.00	0.00
	cov	0.00	0.00	0.00

When Figures 2.12, 2.14, and 2.15 are interpreted, for most of the flexure critical columns, TEC (2007), FEMA 356 (2000), and EC 8 (2003) give lower limits for the seismic performance levels of life safety and collapse prevention while evaluating these columns by nonlinear static procedures. Although the columns in database evaluated according to their capacity curve do not even reach the life safety performance, TEC (2007), FEMA 356 (2000), and EC 8 (2003) considered these columns as reaching the performance limit of collapse prevention.

In addition if Tables 2.2, 2.3, and 2.4 are examined, following conclusions can be stated;

- All the evaluated codes/guidelines overestimate the immediate occupancy performance limit leading to relatively unconservative results. Performance level of "Immediate Occupancy" is best estimated by Eurocode 8 (2003) procedure. When normalized statistical results are interpreted, it is seen that 1.27 times estimated drift ratio is equal to the drift ratio obtained from Eurocode 8 (2003). FEMA 356 (2000) and TEC (2007) give overestimated drift ratios compared to Eurocode 8 (2003).

- Performance level of "Life Safety" for flexure critical reinforced concrete columns is underestimated when evaluated codes are considered leading to much conservative assessments. Eurocode 8 provides closer results compared to FEMA 356 (2000) and TEC (2007). Drift ratio for estimated performance level of life safety can be calculated by dividing the drift ratios calculated from FEMA 356 (2000) to 0.53 and TEC (2007) to 0.54.

- "Collapse Prevention" limit state is also best estimated by EC 8 (2003). Evaluated PEER database column's have an average value of 3.62% of drift ratio. Even if EC 8 (2003) best estimates this limit state, still it underestimates the ultimate drift ratio. On the other hand, collapse prevention limit estimated from FEMA 356 (2000) and TEC (2007) is more conservative than EC 8 (2003), respectively with the average drift ratios of 2.65% and 2.84%.

CHAPTER 3

PARAMETRIC STUDIES

3.1. General

Once the analytical models, produced with OpenSees (2005), accurately reflect the experimental seismic response of columns selected from PEER database (2005), parametric studies are performed to closely show the effect of different variables, which are column geometry, concrete strength, axial load ratio, transverse reinforcement ratio, and yielding strength of the reinforcement, on the capacity curves of columns. In addition to this, performance limits estimated from analytical studies and the limits proposed by TEC (2007), FEMA 356 (2000), EC 8 (2003), and ASCE/SEI 41 Update (2009) can be compared. In each analysis, only one variable is changed and all other parameters are kept constant. Figure 3.1 compares the analytical behavior of a reference column with the experimental behavior provided from PEER Database (2005) showing reasonable agreement.

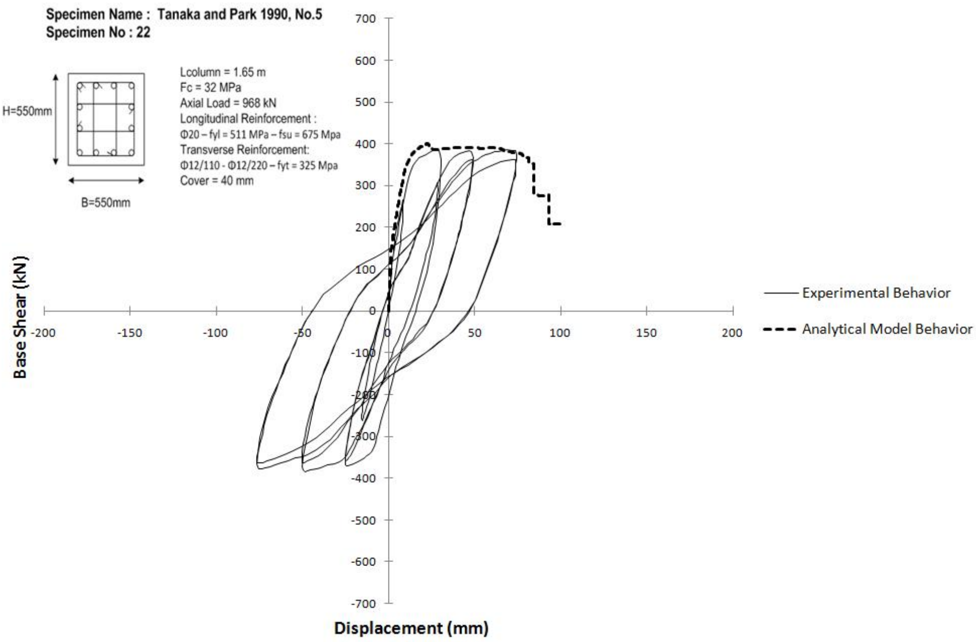


Figure 3.1 Experimental and Analytical Seismic Behavior of the Reference Column

3.2. Column Specimens

Flexure critical column database, selected from PEER (2005), doesn't exactly reflect the properties of columns constructed in Turkey. To handle the deficiencies arisen from the properties of selected database, additional columns are analyzed by utilizing OpenSees (2005). Additional columns have four different cross sectional types that are commonly used. Those sections are 400 mm x 400 mm and 500 mm x 500 mm square columns, 300 mm x 500 mm and 300 mm x 600 mm rectangular columns.

Concrete compressive strength is taken as 10 MPa, 14 MPa, and 20 MPa. Selected yielding strength of longitudinal reinforcement is 220 MPa and 420 MPa, and for the transverse reinforcement this value is 420 MPa. Transverse reinforcement ratio is selected as 0.0075 and 0.02. For all specimens, longitudinal reinforcement ratios are the same with the value of 0.01. Also, spacing between the transverse reinforcement is considered as 100 mm for all specimens. In addition, axial load ratios are chosen as 0.10, 0.25, and 0.40 to reflect accurate properties of the columns constructed in Turkey. After applying these parameters, 144 column specimens are generated. The range of the parameters used in this part of the study is summarized in Table 3.1.

Table 3.1 Range of Parameters Used in Parametric Study

Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)
400x400	10	0.10	0.01	220	0.0075	420
500x500	14	0.25		420	0.02	
300x500	20	0.40				
300x600						

Where:

f_{ck}: Concrete compressive strength

N/N_0: Axial load ratio

ρ: Longitudinal reinforcement ratio

f_{yk}: Yielding strength of reinforcement

ρ_s: Transverse reinforcement ratio

f_{ywk}: Yielding strength of transverse reinforcement

Figure 3.2 shows the geometry and the detailing of the reinforcement of the columns selected for parametric study.

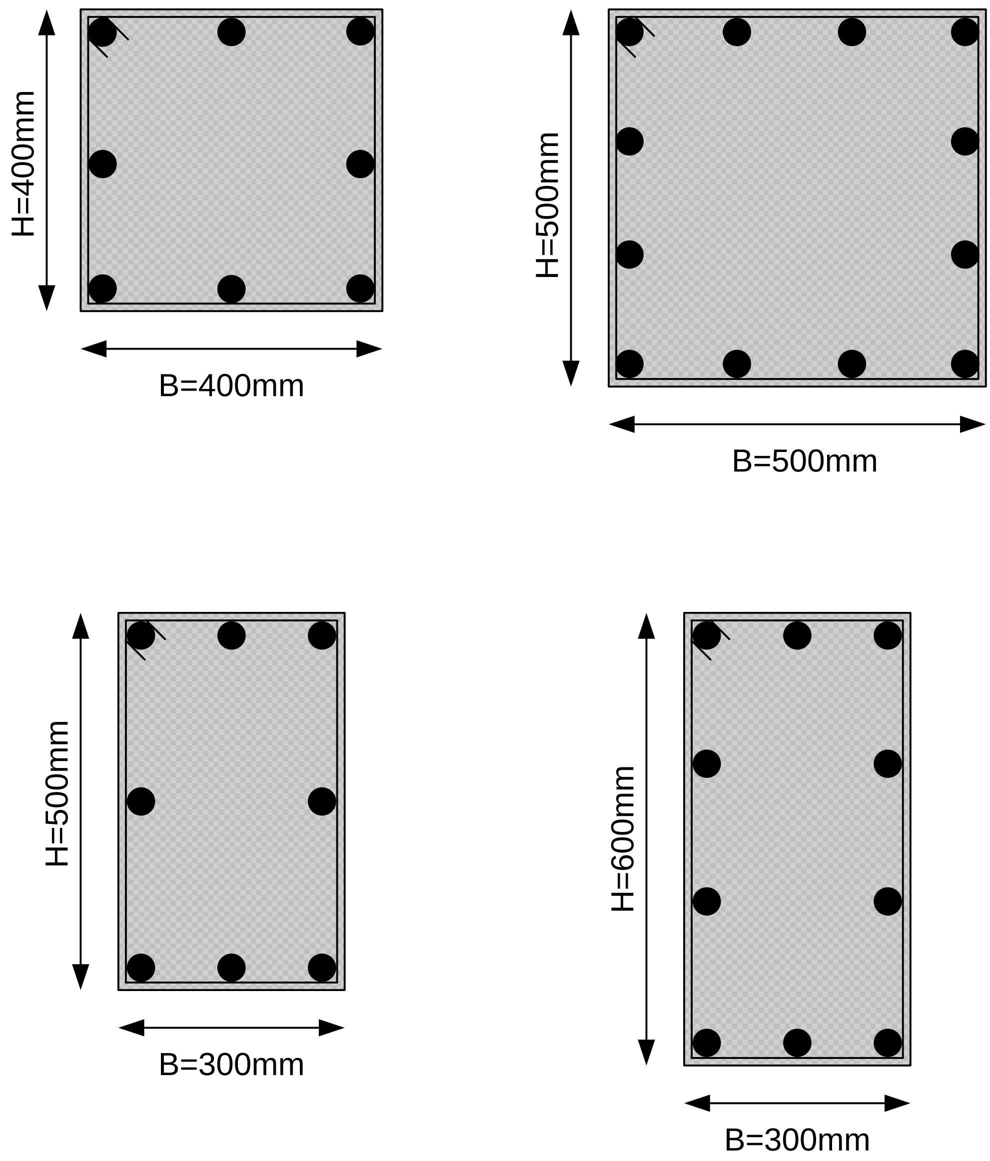


Figure 3.2 Geometric Properties and Detailing of the Reinforcement of the Columns Selected for Parametric Study

3.3. Classification of Failure Types of Members

Setzler and Sezen (2008) studied failure types of the columns by taking sectional properties into account. They divided the failure types into three groups according to the following criteria:

$$\frac{V_n}{V_{flexure}} < 0.95 \quad : \quad \text{Shear Failure}$$

$$0.95 \leq \frac{V_n}{V_{flexure}} \leq 1.40 \quad : \quad \text{Flexure-Shear Failure}$$

$$\frac{V_n}{V_{flexure}} > 1.40 \quad : \quad \text{Flexure Failure}$$

According to TS500 (2000):

$$V_n = V_c + V_w \qquad \text{Eq. 3.1}$$

$$V_{cr} = 0.65 f_{ctk} b_w d \left(1 + \gamma \frac{N_d}{A_c}\right) \qquad \text{Eq. 3.2}$$

$$V_c = 0.80 V_{cr} \qquad \text{Eq. 3.3}$$

$$V_w = \frac{A_{sw}}{s} f_{ywk} d \qquad \text{Eq. 3.4}$$

Where:

V_n : Shear strength of the section

$V_{flexure}$: Lateral load that causes the column to reach its moment capacity

V_{cr} : Diagonal cracking strength of the section

V_c : Concrete contribution to the shear strength of the section

V_w : Transverse reinforcement contribution to the shear strength of the section

$f_{ctk} = 0.35\sqrt{f_{ck}}$; Concrete tensile strength

f_{ck} : Concrete compressive strength

b_w : Width of the section perpendicular to shear force

d : Effective depth of the section

$\gamma = 0.07$; Constant represents the effect of axial force on cracking strength

N_d : Axial load

A_c : Cross sectional area

A_{sw} : Transverse reinforcement area

s : Spacing of transverse reinforcement

f_{ywk} : Yielding strength of transverse reinforcement

Table C.1 provides the properties of flexure critical columns analyzed with OpenSees (2005) for the parametric study part of the thesis. In this table, dimensions, concrete compressive strength, axial load ratio, longitudinal reinforcement ratio, yielding strength of longitudinal reinforcement, transverse reinforcement ratio, yielding strength of transverse reinforcement, and spacing of transverse reinforcement are given for each specimen. In addition, flexure failure type is ensured according to the method proposed by Setzler and Sezen (2008).

3.4. Flexural Rigidity of Evaluated Columns According to Different Seismic Provisions

Flexure critical columns, studied in this section, are also evaluated according to their flexural rigidities. Table 3.2 indicates the flexural rigidity of evaluated columns according to the estimation, TEC (2007), FEMA 356 (2000), EC 2 (2004), and ASCE/SEI 41 Update (2009).

According to the estimated rigidities, initial values are taken from the beginning of monotonic loading; on the other hand cracked rigidity values are taken from the yielding point of longitudinal reinforcement.

According to TEC (2007) for reinforced concrete columns;

$$Axial\ Load\ Ratio \leq 0.10 \quad ; \quad (EI)_{cracked} = 0.40(EI)_{initial} \qquad \text{Eq. 3.5}$$

$$Axial\ Load\ Ratio \geq 0.40 \quad ; \quad (EI)_{cracked} = 0.80(EI)_{initial} \qquad \text{Eq. 3.6}$$

According to FEMA 356 (2000) for reinforced concrete columns;

$$Axial\ Load\ Ratio \leq 0.30 \quad ; \quad (EI)_{cracked} = 0.50(EI)_{initial} \qquad \text{Eq. 3.7}$$

$$Axial\ Load\ Ratio \geq 0.50 \quad ; \quad (EI)_{cracked} = 0.70(EI)_{initial} \qquad \text{Eq. 3.8}$$

According to EC 2 (2004) for reinforced concrete columns;

$$(EI)_{cracked} = E_s A_s d^2 (1-\xi)\left(1 - {}^{\xi}/_{3}\right) \qquad \text{Eq. 3.9}$$

Where;

E_s: Modulus of elasticity of longitudinal reinforcement

A_s: Area of longitudinal reinforcement

d: Effective depth

$$\xi = \frac{x}{d} = -n\rho + \sqrt{(n\rho)^2 + 2n\rho} \qquad \text{Eq. 3.10}$$

x: Depth of compression zone

$$n = {}^{E_s}/_{E_c} \qquad \text{Eq. 3.11}$$

ρ: Longitudinal reinforcement ratio

E_c: Modulus of elasticity of concrete

According to ASCE/SEI 41 Update (2009) for reinforced concrete columns;

$$Axial\ Load\ Ratio \leq 0.10 \quad ; \quad (EI)_{cracked} = 0.30(EI)_{initial} \qquad \text{Eq. 3.12}$$

$$Axial\ Load\ Ratio \geq 0.50 \quad ; \quad (EI)_{cracked} = 0.70(EI)_{initial} \qquad \text{Eq. 3.13}$$

Table 3.2 illustrates the initial flexural rigidity values and the ratio of initial and cracked rigidities calculated according to estimation, TEC (2007), FEMA 356 (2000), EC 2 (2004), and ASCE/SEI 41 Update (2009).

Table 3.2 Flexural Rigidity of Evaluated Columns

Specimen Number	Axial Load Ratio	$(EI)_{initial}$ (kNm^2)	Estimated $(EI)_{cracked}/(EI)_{initial}$	TEC 2007 $(EI)_{cracked}/(EI)_{initial}$	FEMA 356 $(EI)_{cracked}/(EI)_{initial}$	EC 8 $(EI)_{cracked}/(EI)_{initial}$	ASCE 41 Update $(EI)_{cracked}/(EI)_{initial}$
1	0.10	38,826.15	0.40	0.40	0.50	0.53	0.30
2	0.10	38,425.03	0.40	0.40	0.50	0.53	0.30
3	0.10	38,826.09	0.35	0.40	0.50	0.53	0.30
4	0.10	38,424.97	0.36	0.40	0.50	0.53	0.30
5	0.25	34,966.20	0.49	0.60	0.50	0.58	0.45
6	0.25	37,557.44	0.48	0.60	0.50	0.54	0.45
7	0.25	37,802.15	0.40	0.60	0.50	0.54	0.45
8	0.25	37,557.40	0.40	0.60	0.50	0.54	0.45
9	0.40	33,733.12	0.52	0.80	0.60	0.60	0.60
10	0.40	33,773.59	0.54	0.80	0.60	0.60	0.60
11	0.40	36,248.73	0.42	0.80	0.60	0.56	0.60
12	0.40	33,773.62	0.43	0.80	0.60	0.60	0.60
13	0.10	43,137.00	0.41	0.40	0.50	0.50	0.30
14	0.10	43,312.66	0.40	0.40	0.50	0.49	0.30
15	0.10	43,312.68	0.35	0.40	0.50	0.49	0.30
16	0.10	43,312.68	0.35	0.40	0.50	0.49	0.30
17	0.25	42,073.68	0.50	0.60	0.50	0.51	0.45
18	0.25	42,934.94	0.49	0.60	0.50	0.50	0.45
19	0.25	49,401.09	0.37	0.60	0.50	0.43	0.45
20	0.25	40,179.69	0.41	0.60	0.50	0.53	0.45
21	0.40	40,084.68	0.54	0.80	0.60	0.53	0.60
22	0.40	40,671.20	0.55	0.80	0.60	0.53	0.60
23	0.40	47,445.82	0.41	0.80	0.60	0.45	0.60
24	0.40	40,677.13	0.44	0.80	0.60	0.53	0.60
25	0.10	51,569.63	0.39	0.40	0.50	0.44	0.30
26	0.10	51,720.59	0.39	0.40	0.50	0.44	0.30
27	0.10	51,569.60	0.33	0.40	0.50	0.44	0.30
28	0.10	51,720.56	0.33	0.40	0.50	0.44	0.30
29	0.25	46,014.00	0.51	0.60	0.50	0.49	0.45
30	0.25	49,650.99	0.51	0.60	0.50	0.45	0.45
31	0.25	49,274.68	0.41	0.60	0.50	0.46	0.45
32	0.25	49,651.07	0.41	0.60	0.50	0.45	0.45
33	0.40	46,110.91	0.59	0.80	0.60	0.49	0.60
34	0.40	46,792.93	0.57	0.80	0.60	0.48	0.60
35	0.40	46,110.91	0.44	0.80	0.60	0.49	0.60
36	0.40	46,826.82	0.45	0.80	0.60	0.48	0.60
37	0.10	95,599.49	0.40	0.40	0.50	0.55	0.30
38	0.10	95,866.65	0.40	0.40	0.50	0.55	0.30
39	0.10	95,599.42	0.35	0.40	0.50	0.55	0.30
40	0.10	95,866.58	0.36	0.40	0.50	0.55	0.30
41	0.25	82,758.14	0.50	0.60	0.50	0.64	0.45
42	0.25	84,747.43	0.50	0.60	0.50	0.62	0.45
43	0.25	90,117.20	0.41	0.60	0.50	0.58	0.45
44	0.25	90,925.88	0.41	0.60	0.50	0.58	0.45
45	0.40	86,843.90	0.53	0.80	0.60	0.61	0.60
46	0.40	88,453.97	0.55	0.80	0.60	0.60	0.60
47	0.40	86,845.53	0.43	0.80	0.60	0.61	0.60
48	0.40	88,455.32	0.45	0.80	0.60	0.60	0.60

Table 3.2 (cont'd) Flexural Rigidity of Evaluated Columns

Specimen Number	Axial Load Ratio	$(EI)_{initial}$ (kNm^2)	Estimated $(EI)_{cracked}/(EI)_{initial}$	TEC 2007 $(EI)_{cracked}/(EI)_{initial}$	FEMA 356 $(EI)_{cracked}/(EI)_{initial}$	EC 8 $(EI)_{cracked}/(EI)_{initial}$	ASCE 41 Update $(EI)_{cracked}/(EI)_{initial}$
49	0.10	106,490.07	0.40	0.40	0.50	0.52	0.30
50	0.10	106,630.67	0.41	0.40	0.50	0.52	0.30
51	0.10	96,708.03	0.36	0.40	0.50	0.57	0.30
52	0.10	96,883.25	0.36	0.40	0.50	0.57	0.30
53	0.25	95,141.67	0.51	0.60	0.50	0.58	0.45
54	0.25	101,460.57	0.52	0.60	0.50	0.55	0.45
55	0.25	95,141.83	0.41	0.60	0.50	0.58	0.45
56	0.25	103,860.14	0.41	0.60	0.50	0.53	0.45
57	0.40	91,337.93	0.54	0.80	0.60	0.61	0.60
58	0.40	99,816.23	0.56	0.80	0.60	0.55	0.60
59	0.40	91,337.85	0.43	0.80	0.60	0.61	0.60
60	0.40	99,816.18	0.45	0.80	0.60	0.55	0.60
61	0.10	126,658.00	0.39	0.40	0.50	0.46	0.30
62	0.10	127,077.99	0.39	0.40	0.50	0.46	0.30
63	0.10	126,657.94	0.33	0.40	0.50	0.46	0.30
64	0.10	127,077.93	0.33	0.40	0.50	0.46	0.30
65	0.25	112,246.80	0.51	0.60	0.50	0.52	0.45
66	0.25	121,167.43	0.52	0.60	0.50	0.48	0.45
67	0.25	120,089.53	0.41	0.60	0.50	0.48	0.45
68	0.25	113,181.43	0.42	0.60	0.50	0.51	0.45
69	0.40	115,321.70	0.60	0.80	0.60	0.50	0.60
70	0.40	115,318.88	0.58	0.80	0.60	0.50	0.60
71	0.40	115,321.70	0.46	0.80	0.60	0.50	0.60
72	0.40	112,719.87	0.45	0.80	0.60	0.52	0.60
73	0.10	58,120.95	0.41	0.40	0.50	0.54	0.30
74	0.10	58,290.88	0.41	0.40	0.50	0.54	0.30
75	0.10	58,121.43	0.36	0.40	0.50	0.54	0.30
76	0.10	58,290.84	0.37	0.40	0.50	0.54	0.30
77	0.25	50,334.34	0.51	0.60	0.50	0.63	0.45
78	0.25	55,298.78	0.51	0.60	0.50	0.57	0.45
79	0.25	54,875.54	0.42	0.60	0.50	0.58	0.45
80	0.25	55,298.65	0.43	0.60	0.50	0.57	0.45
81	0.40	52,864.45	0.54	0.80	0.60	0.60	0.60
82	0.40	53,757.09	0.56	0.80	0.60	0.59	0.60
83	0.40	52,864.37	0.44	0.80	0.60	0.60	0.60
84	0.40	53,757.01	0.45	0.80	0.60	0.59	0.60
85	0.10	64,630.48	0.41	0.40	0.50	0.51	0.30
86	0.10	64,702.86	0.42	0.40	0.50	0.51	0.30
87	0.10	64,630.64	0.36	0.40	0.50	0.51	0.30
88	0.10	64,703.06	0.36	0.40	0.50	0.51	0.30
89	0.25	57,763.38	0.51	0.60	0.50	0.58	0.45
90	0.25	63,098.83	0.51	0.60	0.50	0.53	0.45
91	0.25	57,763.19	0.42	0.60	0.50	0.58	0.45
92	0.25	63,098.87	0.42	0.60	0.50	0.53	0.45
93	0.40	59,663.34	0.55	0.80	0.60	0.56	0.60
94	0.40	60,590.21	0.56	0.80	0.60	0.55	0.60
95	0.40	59,671.61	0.44	0.80	0.60	0.56	0.60
96	0.40	60,597.38	0.46	0.80	0.60	0.55	0.60

Table 3.2 (cont'd) Flexural Rigidity of Evaluated Columns

Specimen Number	Axial Load Ratio	$(EI)_{initial}$ (kNm^2)	Estimated $(EI)_{cracked}/(EI)_{initial}$	TEC 2007 $(EI)_{cracked}/(EI)_{initial}$	FEMA 356 $(EI)_{cracked}/(EI)_{initial}$	EC 8 $(EI)_{cracked}/(EI)_{initial}$	ASCE 41 Update $(EI)_{cracked}/(EI)_{initial}$
97	0.10	76,777.49	0.40	0.40	0.50	0.45	0.30
98	0.10	77,014.25	0.40	0.40	0.50	0.45	0.30
99	0.10	76,777.25	0.34	0.40	0.50	0.45	0.30
100	0.10	77,014.21	0.34	0.40	0.50	0.45	0.30
101	0.25	68,034.49	0.52	0.60	0.50	0.51	0.45
102	0.25	68,566.41	0.52	0.60	0.50	0.51	0.45
103	0.25	68,034.55	0.41	0.60	0.50	0.51	0.45
104	0.25	68,566.75	0.42	0.60	0.50	0.51	0.45
105	0.40	63,997.79	0.55	0.80	0.60	0.55	0.60
106	0.40	69,890.03	0.57	0.80	0.60	0.50	0.60
107	0.40	68,181.87	0.46	0.80	0.60	0.51	0.60
108	0.40	69,891.73	0.47	0.80	0.60	0.50	0.60
109	0.10	98,112.44	0.42	0.40	0.50	0.58	0.30
110	0.10	98,380.14	0.42	0.40	0.50	0.58	0.30
111	0.10	98,111.96	0.37	0.40	0.50	0.58	0.30
112	0.10	98,380.42	0.37	0.40	0.50	0.58	0.30
113	0.25	86,452.64	0.51	0.60	0.50	0.66	0.45
114	0.25	87,247.39	0.52	0.60	0.50	0.65	0.45
115	0.25	94,422.12	0.42	0.60	0.50	0.60	0.45
116	0.25	87,247.40	0.42	0.60	0.50	0.65	0.45
117	0.40	90,217.67	0.55	0.80	0.60	0.63	0.60
118	0.40	93,025.72	0.55	0.80	0.60	0.61	0.60
119	0.40	90,217.52	0.44	0.80	0.60	0.63	0.60
120	0.40	93,026.85	0.45	0.80	0.60	0.61	0.60
121	0.10	114,026.62	0.40	0.40	0.50	0.52	0.30
122	0.10	114,168.91	0.40	0.40	0.50	0.52	0.30
123	0.10	114,026.55	0.34	0.40	0.50	0.52	0.30
124	0.10	114,169.26	0.35	0.40	0.50	0.52	0.30
125	0.25	107,459.25	0.51	0.60	0.50	0.55	0.45
126	0.25	101,705.37	0.51	0.60	0.50	0.59	0.45
127	0.25	107,442.67	0.42	0.60	0.50	0.55	0.45
128	0.25	101,705.59	0.41	0.60	0.50	0.59	0.45
129	0.40	102,865.93	0.55	0.80	0.60	0.58	0.60
130	0.40	104,577.96	0.57	0.80	0.60	0.57	0.60
131	0.40	102,865.86	0.45	0.80	0.60	0.58	0.60
132	0.40	104,577.89	0.46	0.80	0.60	0.57	0.60
133	0.10	129,368.96	0.51	0.40	0.50	0.48	0.30
134	0.10	129,772.69	0.41	0.40	0.50	0.48	0.30
135	0.10	129,368.96	0.34	0.40	0.50	0.48	0.30
136	0.10	129,772.84	0.34	0.40	0.50	0.48	0.30
137	0.25	115,239.17	0.53	0.60	0.50	0.54	0.45
138	0.25	125,821.23	0.52	0.60	0.50	0.50	0.45
139	0.25	115,239.93	0.42	0.60	0.50	0.54	0.45
140	0.25	116,223.28	0.42	0.60	0.50	0.54	0.45
141	0.40	118,041.28	0.57	0.80	0.60	0.53	0.60
142	0.40	120,054.69	0.58	0.80	0.60	0.52	0.60
143	0.40	118,045.04	0.46	0.80	0.60	0.53	0.60
144	0.40	120,141.48	0.47	0.80	0.60	0.52	0.60

Figure 3.3 provides the relationship between axial load ratio and the ratio between initial and cracked flexural rigidities.

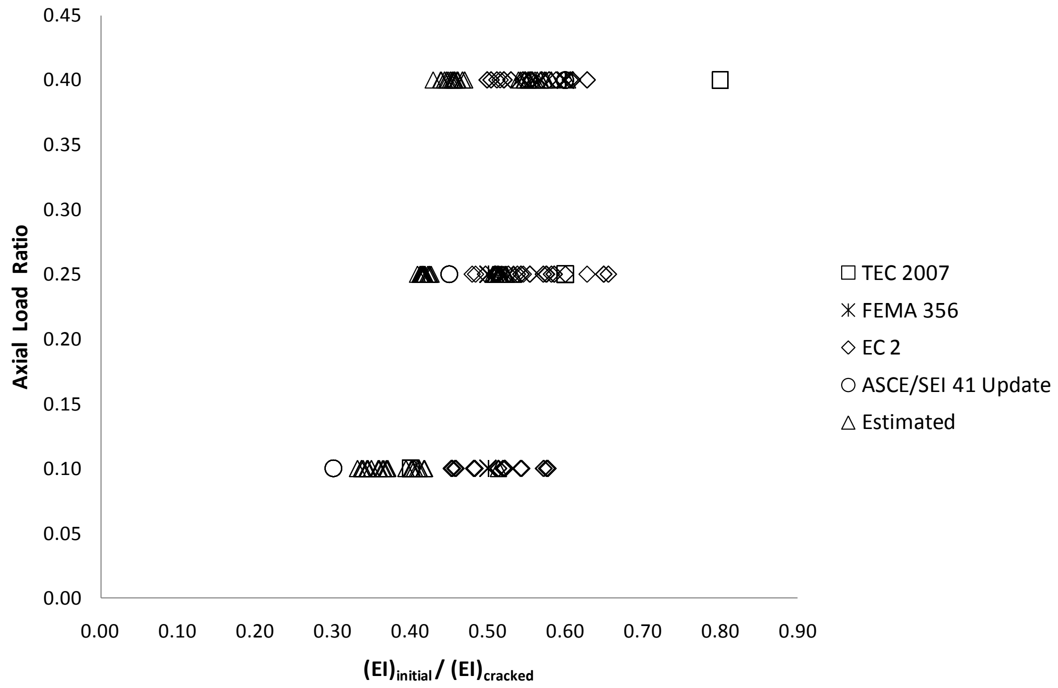


Figure 3.3 Relationship between Axial Load Ratio and Initial Flexural Rigidity to Cracked Flexural Rigidity Ratio for Different Seismic Provisions

Table 3.2 and Figure 3.3 show that for low levels of axial load, TEC (2007) and ASCE/SEI 41 Update (2009) provide closer flexural rigidities than FEMA 356 (2000) and EC 2 (2004). On the other hand, with increasing levels of axial load ASCE/SEI 41 Update (2009) estimates more accurately than other seismic provisions. In addition to this, FEMA 356 (2000) and EC 2 (2004) estimate flexural rigidities closer than TEC (2007) for high levels of axial load.

3.5. Effect of Each Parameter on Capacity Curves of Columns

The effects of each parameter will be individually discussed according to their influence on the yielding drift and the ultimate drift of columns.

3.5.1. Effect of Concrete Strength

In order to examine the effect of concrete strength on capacity curves, three different strength levels are used in this study. These three levels, which are 10 MPa, 14 MPa, and 20 MPa, are widely encountered in Turkey. According to the results obtained from the analyses, it is observed that the lateral load capacities of the columns increase significantly with the increasing concrete strength. In addition to this, as a result of increasing axial load level, ultimate drift ratios show variation. On the other hand yielding drift ratio is not significantly affected by the compressive strength changes. Figure 3.4 represents the effect of concrete strength on capacity curves for axial load levels of 0.10 and 0.25, respectively.

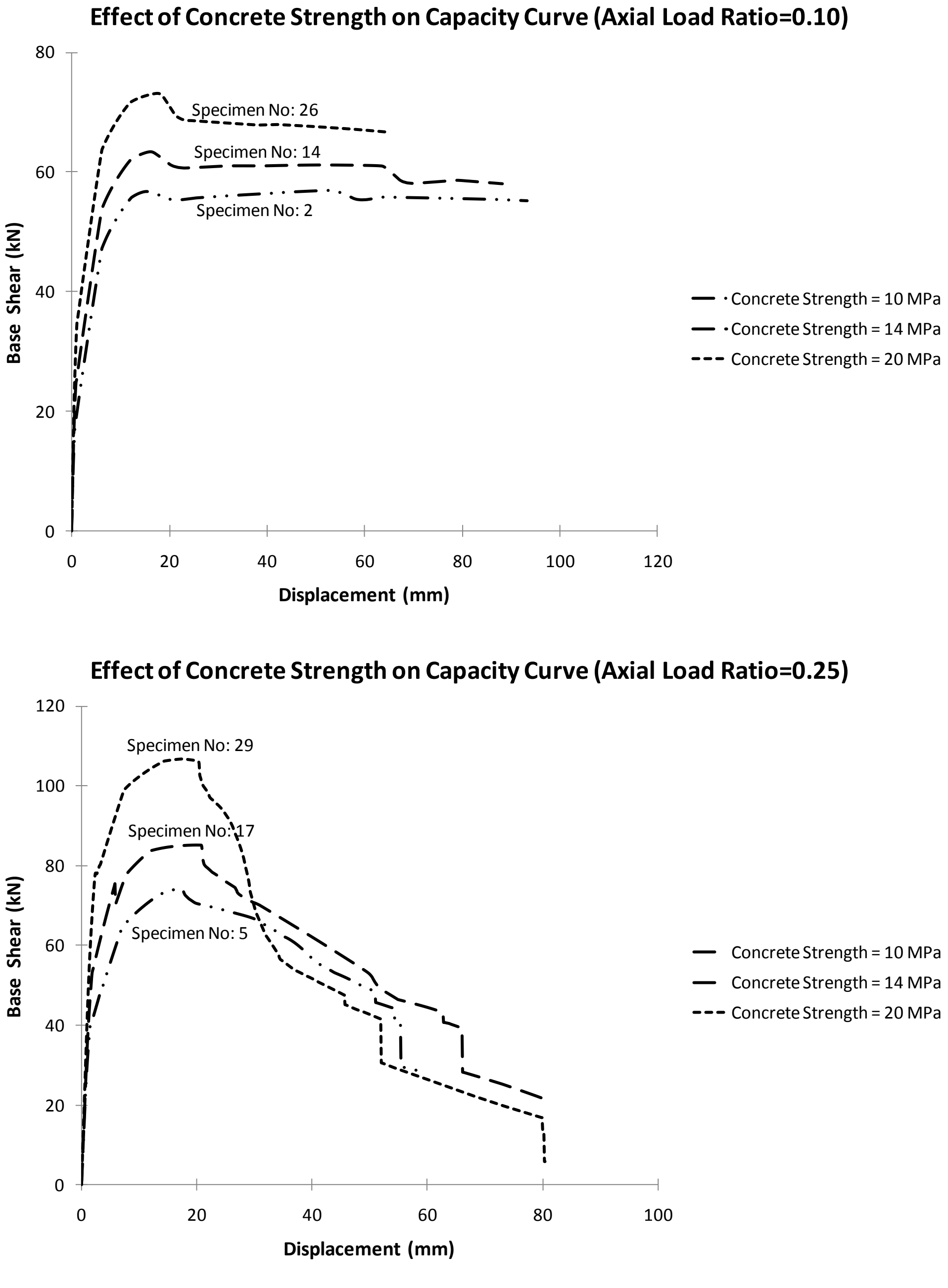
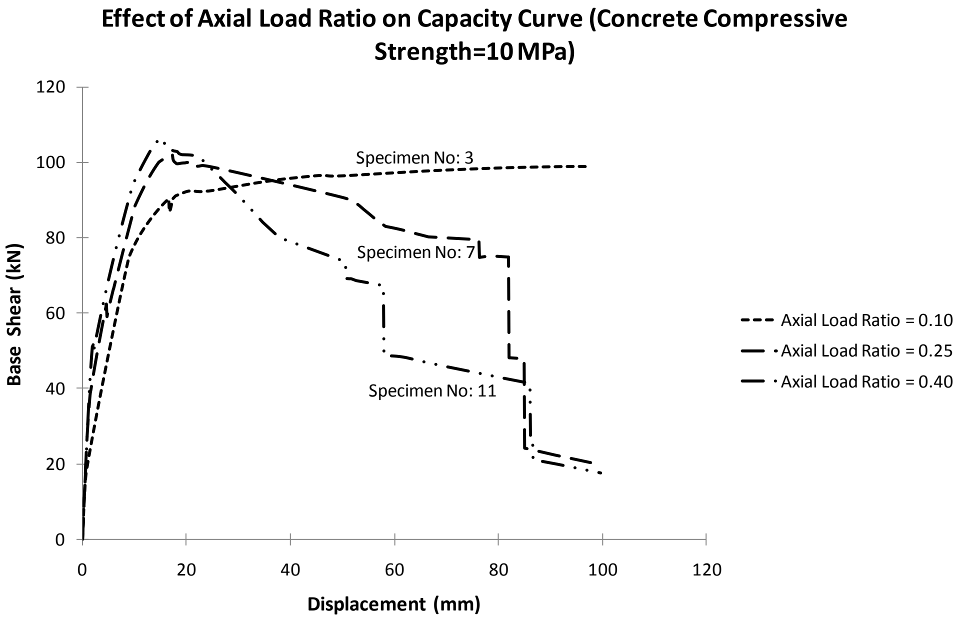


Figure 3.4 Effect of Concrete Strength on Capacity Curves for Axial Load Ratio of a) 0.10 and b) 0.25

3.5.2. Effect of Axial Load Ratio

Three different axial load ratios, with the percentage values of 10, 25, and 40 respectively, are evaluated in the analyses. It can be stated that the yielding drift ratio is not seriously affected by a change based on axial load ratio. On the other hand, ultimate drift ratio seriously decreases with the effect of increasing axial load ratio. Figure 3.5 symbolizes the effect of axial load ratio on capacity curves.



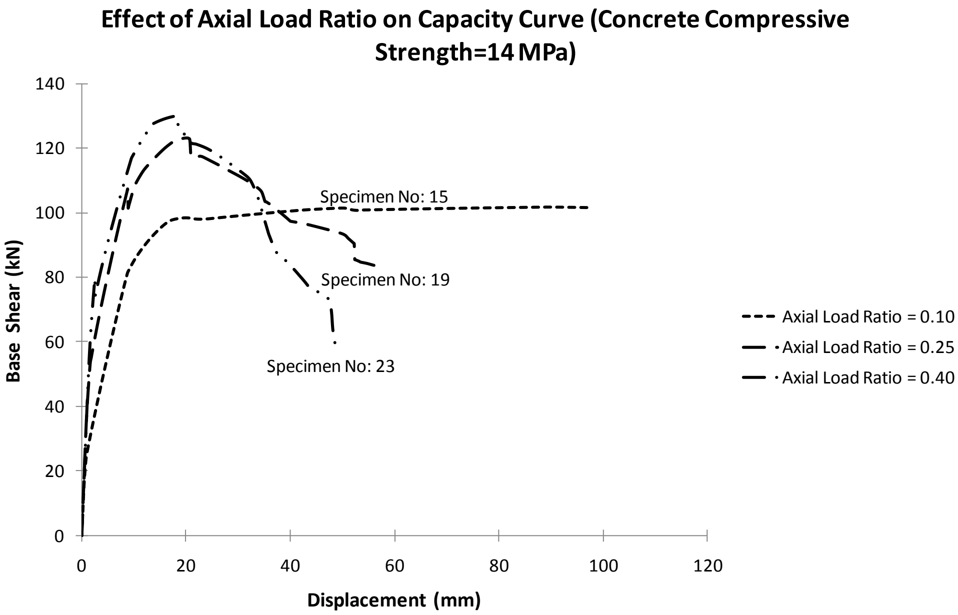


Figure 3.5 Effect of Axial Load Ratio on Capacity Curves for Concrete Compressive Strength of a) 10 MPa b) 14 MPa

3.5.3. Effect of Yielding Strength of Longitudinal Reinforcement

Drift ratio at the yielding point of longitudinal reinforcement changes with varying yielding strength. The analytical results illustrate that increasing yielding strength causes high values of drift ratio at the yielding point compared to the one with lower yielding strength. Figure 3.6 symbolizes the effect of yielding strength of longitudinal reinforcement on capacity curves.

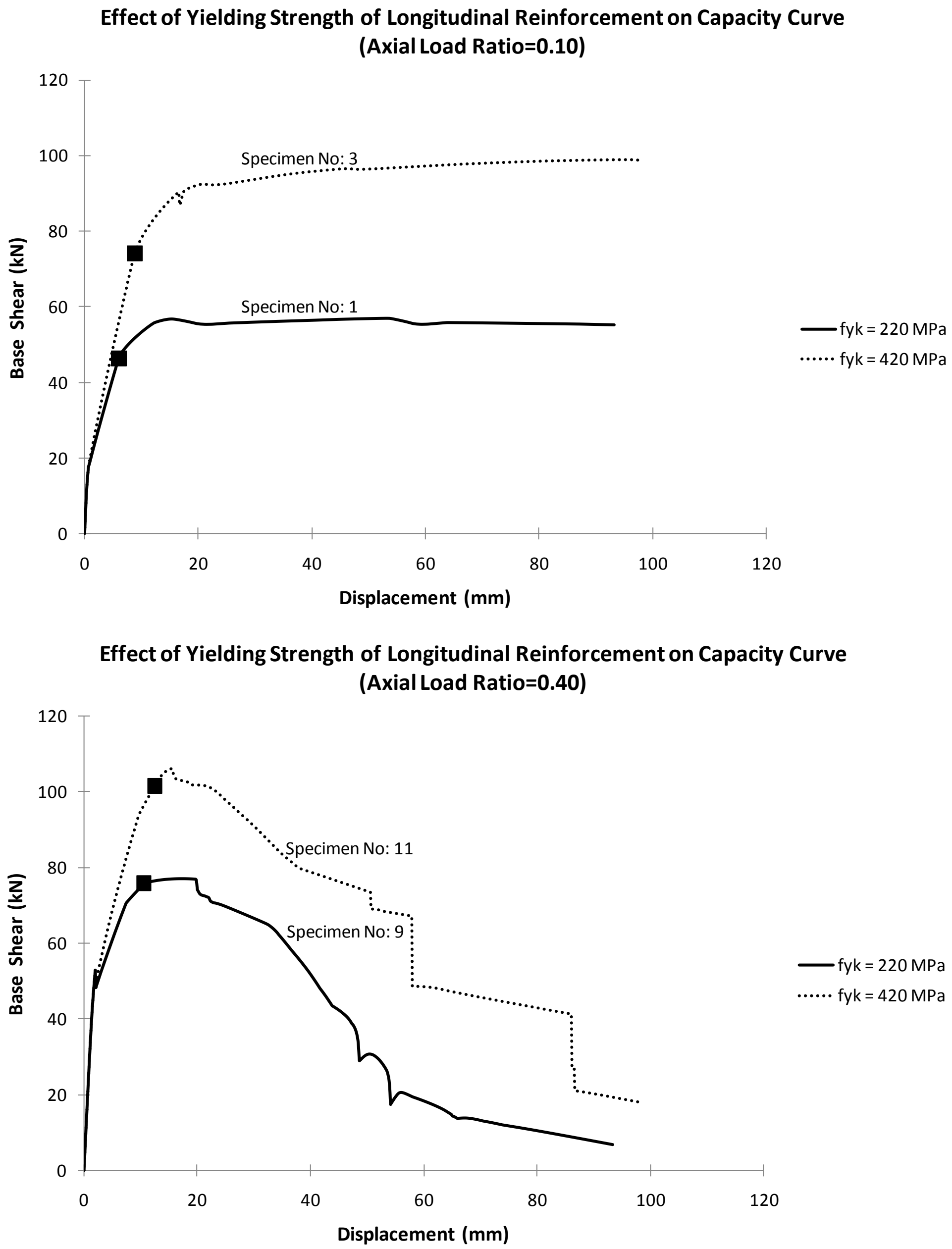


Figure 3.6 Effect of Yielding Strength of Longitudinal Reinforcement on Capacity Curves for Axial Load Ratio of a) 0.10 and b) 0.40

3.5.4. Effect of Transverse Reinforcement Ratio

According to the results taken from the analyses, the amount of transverse reinforcement has no considerable effect on the drift ratio at the yielding point. In addition to this, for low levels of axial load, ultimate drift ratio does not change significantly. On the other hand, for high levels of axial load, ultimate drift ratio increases considerably with increasing amount of transverse reinforcement (See Figure 3.7).

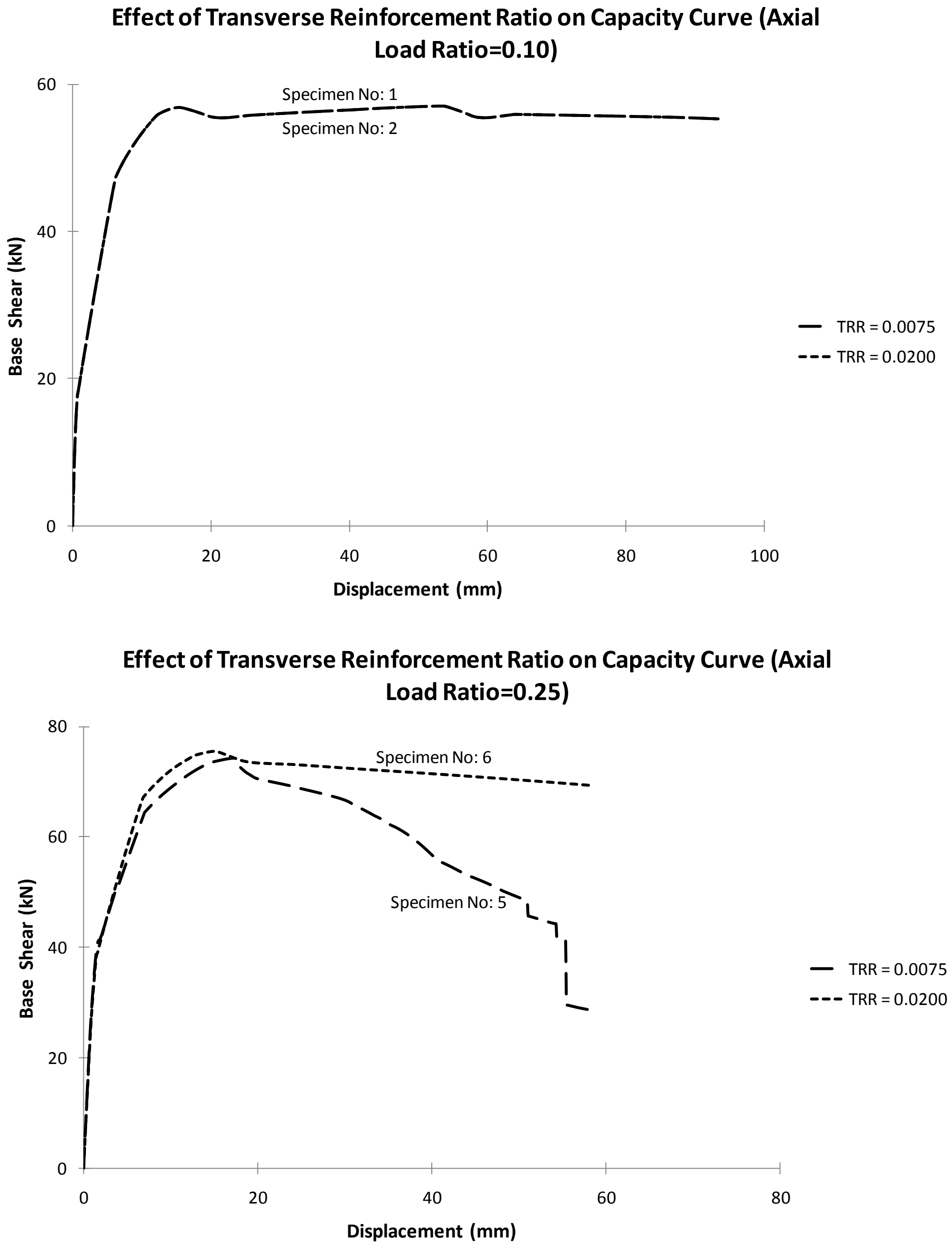


Figure 3.7 Effect of Transverse Reinforcement Ratio on Capacity Curves for Axial Load Ratio of a) 0.10 and b) 0.25

3.6. Estimated Performance Limits

In this study, the estimated immediate occupancy is a performance limit where the elastic branch gives place to plastic branch. Thus, performance limit of immediate occupancy has a strain value of 0.015 for outer part of the tension reinforcement or strain value of 0.004 for the outer part of concrete fiber. In addition to this, estimated performance limit of collapse prevention is the ultimate point where the shear capacity drops 20 percent from the maximum value. Estimated performance limit of life safety is taken as 75 percent of the ultimate point (estimated collapse prevention). Figure 2.9 shows the performance limits on an idealized capacity curve.

Flexure critical columns selected for parametric study are analyzed and capacity curves are obtained. After converting capacity curves into bilinear curves, estimated performance limits for each performance level are pointed out (See Table C.2).

3.7. Application of Codes to Columns Selected for Parametric Study

Flexure critical columns selected for parametric study are analyzed and capacity curves are obtained. According to TEC (2007), FEMA 356 (2000), EC 8 (2003), and ASCE/SEI 41 Update (2009), performance limits for each performance level are pointed out;

- Table C.3 provides drift ratios corresponding to performance levels of immediate occupancy, life safety, and collapse prevention according to TEC (2007),

- Table C.4 provides drift ratios corresponding to performance levels of immediate occupancy, life safety, and collapse prevention according to FEMA 356 (2000),

- Table C.5 provides drift ratios corresponding to performance levels of immediate occupancy, life safety, and collapse prevention according to EC 8 (2003),

- Table C.6 provides drift ratios corresponding to performance levels of immediate occupancy, life safety, and collapse prevention according to ASCE/SEI 41 Update (2009).

3.8. Comparison of Performance Limits

Performance limits corresponding to each performance level obtained by different seismic guidelines are compared in Table 3.3. Estimated drift ratios for each specimen are normalized to 1% and drift ratios obtained from TEC (2007), FEMA 356 (2000), EC 8 (2003), and ASCE/SEI 41 Update (2009) are regenerated to see the differences between them. It is worth noting that all columns in the parametric database are classified as flexure critical according to ASCE/SEI 41 Update (2009) (i.e. condition i limits are used) (See Figure 2.14). When Table 3.3 is examined, for most of the flexure critical columns, TEC (2007) and FEMA 356 (2000) give underestimated seismic performance while evaluating these columns by nonlinear static procedures. When flexure critical columns reach performance limit of collapse prevention according to TEC (2007) and FEMA 356 (2000) most of them do not even reach performance limit of life safety according to experimental and analytical test results. In addition to this ASCE/SEI 41 Update (2009) provide inconsistent displacement limits for life safety and collapse prevention performance levels. For low levels of axial load, ASCE/SEI 41 Update (2009) provides conservative displacement limits but for high levels of axial load ASCE/SEI 41 Update becomes unconservative. On the other hand, EC 8 (2003) implements closer results than other seismic provisions. The following general observations can be made:

- Performance level of “Immediate Occupancy” is not accurately estimated by TEC (2007), FEMA 356 (2000), EC 8 (2003), and ASCE/SEI 41 Update (2009). All evaluated seismic provisions are unconservative for immediate occupancy performance level. In between these provisions, EC 8 (2003) implements closer displacement limits,

- Performance level of “Life Safety” for flexure critical reinforced concrete columns is underestimated when evaluated codes are considered. EC 8 (2003) and ASCE/SEI 41 Update (2009) provide closer results compared to TEC (2007) and American pre-standard FEMA 356 (2000). On the other hand, with increasing axial load levels, these seismic provisions provide unconservative results for some cases.

- “Collapse Prevention” limit state is also underestimated by seismic provisions. EC 8 (2003) and ASCE/SEI 41 Update (2009) provide closer results compared to TEC (2007) and FEMA 356 (2000). On the other hand, with increasing axial load levels, these seismic provisions provide unconservative results.

Table 3.3 Comparison of Performance Levels Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED			TEC 2007			FEMA 356			EC 8			ASCE 41 UPDATE		
	Normalized Drift Ratio IO	Normalized Drift Ratio LS	Normalized Drift Ratio CP	Normalized Drift Ratio IO	Normalized Drift Ratio LS	Normalized Drift Ratio CP	Normalized Drift Ratio IO	Normalized Drift Ratio LS	Normalized Drift Ratio CP	Normalized Drift Ratio IO	Normalized Drift Ratio LS	Normalized Drift Ratio CP	Normalized Drift Ratio IO	Normalized Drift Ratio LS	Normalized Drift Ratio CP
1	1.00	1.00	1.00	2.38	0.48	0.51	1.88	0.41	0.39	1.00	0.52	0.52	1.88	0.51	0.50
2	1.00	1.00	1.00	2.36	0.48	0.51	1.85	0.41	0.39	0.99	0.80	0.80	1.85	0.60	0.59
3	1.00	1.00	1.00	1.85	0.52	0.63	1.48	0.43	0.40	1.05	0.50	0.50	1.48	0.53	0.50
4	1.00	1.00	1.00	1.79	0.47	0.57	1.48	0.37	0.35	1.05	0.66	0.66	1.48	0.54	0.51
5	1.00	1.00	1.00	2.02	0.93	0.78	1.59	0.96	0.88	0.97	1.05	1.04	1.60	1.04	0.98
6	1.00	1.00	1.00	2.39	0.50	0.53	1.70	0.38	0.35	1.12	0.67	0.67	1.77	0.49	0.47
7	1.00	1.00	1.00	1.40	0.70	0.63	1.39	0.64	0.58	1.02	0.62	0.62	1.40	0.69	0.64
8	1.00	1.00	1.00	1.57	0.65	0.56	1.36	0.64	0.58	1.07	0.99	0.99	1.39	0.81	0.75
9	1.00	1.00	1.00	3.27	1.58	1.27	2.52	1.92	1.67	1.56	1.71	1.71	2.57	1.70	1.54
10	1.00	1.00	1.00	2.63	0.90	0.75	2.08	0.88	0.77	1.53	1.32	1.31	2.23	0.95	0.87
11	1.00	1.00	1.00	1.28	0.93	0.76	0.93	0.95	0.85	1.10	0.98	0.98	0.95	0.83	0.77
12	1.00	1.00	1.00	1.31	0.64	0.52	1.33	0.74	0.64	1.19	0.98	0.98	1.41	0.80	0.71
13	1.00	1.00	1.00	2.58	0.49	0.51	1.94	0.43	0.41	1.04	0.60	0.59	1.94	0.54	0.53
14	1.00	1.00	1.00	2.58	0.49	0.51	1.94	0.43	0.41	1.04	0.91	0.91	1.94	0.64	0.62
15	1.00	1.00	1.00	1.85	0.49	0.59	1.53	0.41	0.38	1.07	0.52	0.51	1.53	0.50	0.48
16	1.00	1.00	1.00	1.85	0.49	0.59	1.53	0.41	0.38	1.07	0.79	0.79	1.53	0.58	0.56
17	1.00	1.00	1.00	2.61	1.41	1.24	1.64	1.08	0.98	1.00	1.29	1.30	1.66	1.16	1.10
18	1.00	1.00	1.00	2.51	0.62	0.66	1.75	0.48	0.44	1.18	0.92	0.92	1.82	0.63	0.60
19	1.00	1.00	1.00	1.78	0.98	0.82	1.40	1.03	0.92	1.07	1.12	1.12	1.42	1.10	1.02
20	1.00	1.00	1.00	1.52	0.74	0.62	1.42	0.69	0.62	1.14	1.13	1.13	1.46	0.87	0.81
21	1.00	1.00	1.00	2.69	1.33	1.05	2.06	1.54	1.33	1.18	1.41	1.41	2.10	1.37	1.22
22	1.00	1.00	1.00	2.04	1.17	1.05	1.46	0.90	0.79	0.98	1.41	1.41	1.56	0.97	0.88
23	1.00	1.00	1.00	1.49	1.24	0.99	1.35	1.19	1.02	1.06	1.08	1.08	1.37	1.06	0.94
24	1.00	1.00	1.00	1.43	0.82	0.74	1.46	0.77	0.66	1.18	1.07	1.07	1.54	0.82	0.73
25	1.00	1.00	1.00	2.82	0.68	0.66	2.00	0.58	0.55	1.07	0.77	0.77	2.00	0.74	0.72
26	1.00	1.00	1.00	2.86	0.68	0.66	2.02	0.58	0.55	1.09	0.96	0.96	2.02	0.86	0.84
27	1.00	1.00	1.00	1.93	0.51	0.53	1.59	0.43	0.40	1.10	0.53	0.52	1.59	0.54	0.51
28	1.00	1.00	1.00	1.93	0.51	0.53	1.59	0.43	0.40	1.10	0.65	0.65	1.59	0.62	0.60
29	1.00	1.00	1.00	2.65	1.26	0.99	1.71	1.33	1.22	1.14	1.53	1.53	1.73	1.43	1.36
30	1.00	1.00	1.00	2.72	1.05	0.83	1.81	0.85	0.78	1.27	1.27	1.27	1.88	1.11	1.06
31	1.00	1.00	1.00	1.56	1.14	0.92	1.48	1.39	1.24	1.06	1.39	1.39	1.49	1.48	1.37
32	1.00	1.00	1.00	1.71	0.72	0.62	1.51	0.76	0.69	1.26	1.01	1.01	1.56	0.97	0.90
33	1.00	1.00	1.00	1.79	1.29	1.04	1.36	1.66	1.46	1.03	1.68	1.68	1.40	1.45	1.33
34	1.00	1.00	1.00	2.71	1.31	1.15	1.84	1.00	0.87	1.17	1.15	1.15	1.95	1.08	0.97
35	1.00	1.00	1.00	1.57	1.27	1.02	1.82	2.04	1.75	1.34	1.65	1.66	1.85	1.83	1.62
36	1.00	1.00	1.00	1.58	1.03	0.91	1.67	1.02	0.88	1.31	1.07	1.07	1.76	1.10	0.97

Table 3.3 (cont'd) Comparison of Performance Levels Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED Normalized Drift Ratio IO	ESTIMATED Normalized Drift Ratio LS	ESTIMATED Normalized Drift Ratio CP	TEC 2007 Normalized Drift Ratio IO	TEC 2007 Normalized Drift Ratio LS	TEC 2007 Normalized Drift Ratio CP	FEMA 356 Normalized Drift Ratio IO	FEMA 356 Normalized Drift Ratio LS	FEMA 356 Normalized Drift Ratio CP	EC 8 Normalized Drift Ratio IO	EC 8 Normalized Drift Ratio LS	EC 8 Normalized Drift Ratio CP	ASCE 41 UPDATE Normalized Drift Ratio IO	ASCE 41 UPDATE Normalized Drift Ratio LS	ASCE 41 UPDATE Normalized Drift Ratio CP
37	1.00	1.00	1.00	2.40	0.48	0.51	2.12	0.48	0.46	1.14	0.61	0.61	2.12	0.62	0.60
38	1.00	1.00	1.00	2.40	0.48	0.51	2.12	0.48	0.46	1.11	0.94	0.94	2.12	0.73	0.71
39	1.00	1.00	1.00	1.82	0.80	0.81	1.65	0.72	0.68	1.16	0.84	0.84	1.65	0.91	0.88
40	1.00	1.00	1.00	1.80	0.49	0.57	1.65	0.44	0.42	1.14	0.80	0.80	1.65	0.65	0.63
41	1.00	1.00	1.00	2.08	0.76	0.65	1.83	0.88	0.82	1.20	0.97	0.97	1.85	0.95	0.91
42	1.00	1.00	1.00	2.33	0.75	0.77	1.85	0.64	0.59	1.27	1.11	1.11	1.93	0.84	0.80
43	1.00	1.00	1.00	1.39	0.63	0.57	1.48	0.67	0.60	1.10	0.67	0.66	1.50	0.73	0.68
44	1.00	1.00	1.00	1.55	0.68	0.58	1.42	0.67	0.61	1.18	1.11	1.11	1.47	0.89	0.84
45	1.00	1.00	1.00	2.21	1.04	0.91	1.51	0.88	0.78	0.97	0.81	0.81	1.55	0.77	0.71
46	1.00	1.00	1.00	2.62	0.80	0.71	1.55	0.61	0.54	1.15	0.93	0.93	1.68	0.66	0.61
47	1.00	1.00	1.00	1.22	0.83	0.75	1.44	0.90	0.78	1.19	0.78	0.78	1.47	0.81	0.73
48	1.00	1.00	1.00	1.41	0.65	0.59	1.34	0.58	0.51	1.14	0.82	0.82	1.43	0.65	0.59
49	1.00	1.00	1.00	2.55	0.50	0.52	2.20	0.52	0.50	1.19	0.65	0.65	2.20	0.66	0.64
50	1.00	1.00	1.00	2.55	0.50	0.52	2.20	0.52	0.50	1.13	0.89	0.89	2.20	0.78	0.76
51	1.00	1.00	1.00	1.82	0.86	0.71	1.67	0.85	0.79	1.20	0.97	0.97	1.67	1.06	1.02
52	1.00	1.00	1.00	1.89	0.60	0.66	1.67	0.56	0.52	1.22	0.88	0.88	1.67	0.81	0.79
53	1.00	1.00	1.00	2.37	1.04	0.87	1.87	1.19	1.10	1.26	1.31	1.31	1.90	1.29	1.24
54	1.00	1.00	1.00	2.44	0.53	0.55	1.96	0.47	0.44	1.35	0.74	0.75	2.05	0.63	0.60
55	1.00	1.00	1.00	1.43	0.83	0.70	1.54	1.14	1.03	1.24	1.14	1.14	1.56	1.23	1.16
56	1.00	1.00	1.00	1.72	0.68	0.58	1.60	0.76	0.69	1.34	1.10	1.11	1.65	1.00	0.94
57	1.00	1.00	1.00	2.33	1.22	0.95	1.52	1.47	1.29	1.08	1.34	1.34	1.55	1.28	1.18
58	1.00	1.00	1.00	2.97	1.03	0.89	1.58	0.74	0.66	1.14	0.98	0.98	1.70	0.81	0.74
59	1.00	1.00	1.00	1.42	0.98	0.79	1.69	1.74	1.50	1.45	1.48	1.49	1.72	1.57	1.42
60	1.00	1.00	1.00	1.44	0.65	0.58	1.46	0.62	0.54	1.22	0.75	0.76	1.55	0.69	0.62
61	1.00	1.00	1.00	2.76	0.65	0.66	2.26	0.68	0.65	1.22	0.88	0.88	2.26	0.87	0.85
62	1.00	1.00	1.00	2.76	0.65	0.66	2.26	0.68	0.65	1.22	1.09	1.09	2.26	1.02	1.00
63	1.00	1.00	1.00	1.91	0.51	0.54	1.77	0.51	0.48	1.21	0.60	0.61	1.77	0.64	0.61
64	1.00	1.00	1.00	1.95	0.51	0.54	1.78	0.51	0.48	1.22	0.75	0.75	1.78	0.74	0.72
65	1.00	1.00	1.00	3.03	1.20	0.96	1.92	1.25	1.15	1.37	1.42	1.42	1.94	1.35	1.30
66	1.00	1.00	1.00	2.51	0.89	0.87	2.04	0.80	0.75	1.53	1.19	1.18	2.13	1.06	1.02
67	1.00	1.00	1.00	1.64	1.15	1.02	1.53	1.19	1.07	1.12	1.21	1.21	1.54	1.29	1.21
68	1.00	1.00	1.00	1.59	0.73	0.63	1.59	0.78	0.71	1.31	1.02	1.02	1.64	1.01	0.95
69	1.00	1.00	1.00	2.76	0.82	0.73	2.04	0.69	0.62	1.70	0.74	0.74	2.10	0.62	0.58
70	1.00	1.00	1.00	6.24	1.29	1.08	2.42	0.76	0.67	1.73	0.90	0.90	2.60	0.83	0.75
71	1.00	1.00	1.00	2.12	0.75	0.67	2.26	0.77	0.67	1.83	0.68	0.68	2.31	0.69	0.63
72	1.00	1.00	1.00	1.54	0.52	0.41	1.86	0.85	0.73	1.41	0.90	0.90	1.96	0.93	0.83

Table 3.3 (cont'd) Comparison of Performance Levels Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED Normalized Drift Ratio IO	ESTIMATED Normalized Drift Ratio LS	ESTIMATED Normalized Drift Ratio CP	TEC 2007 Normalized Drift Ratio IO	TEC 2007 Normalized Drift Ratio LS	TEC 2007 Normalized Drift Ratio CP	FEMA 356 Normalized Drift Ratio IO	FEMA 356 Normalized Drift Ratio LS	FEMA 356 Normalized Drift Ratio CP	EC 8 Normalized Drift Ratio IO	EC 8 Normalized Drift Ratio LS	EC 8 Normalized Drift Ratio CP	ASCE 41 UPDATE Normalized Drift Ratio IO	ASCE 41 UPDATE Normalized Drift Ratio LS	ASCE 41 UPDATE Normalized Drift Ratio CP
73	1.00	1.00	1.00	2.31	0.48	0.51	2.12	0.48	0.46	1.14	0.55	0.55	2.12	0.63	0.61
74	1.00	1.00	1.00	2.31	0.48	0.51	2.12	0.48	0.46	1.14	0.72	0.72	2.12	0.78	0.76
75	1.00	1.00	1.00	1.84	0.61	0.73	1.66	0.59	0.55	1.15	0.62	0.62	1.66	0.76	0.73
76	1.00	1.00	1.00	1.78	0.47	0.56	1.65	0.44	0.41	1.13	0.61	0.61	1.65	0.69	0.67
77	1.00	1.00	1.00	2.05	0.92	0.75	1.79	1.21	1.11	1.14	1.19	1.19	1.82	1.33	1.27
78	1.00	1.00	1.00	2.42	0.49	0.52	1.89	0.44	0.41	1.24	0.59	0.59	2.00	0.63	0.60
79	1.00	1.00	1.00	1.37	0.70	0.62	1.37	0.70	0.61	1.13	0.68	0.68	1.54	0.84	0.79
80	1.00	1.00	1.00	1.55	0.66	0.57	1.31	0.70	0.61	1.11	0.92	0.92	1.53	1.07	1.01
81	1.00	1.00	1.00	1.71	1.16	0.92	1.51	1.39	1.22	0.94	1.14	1.14	1.55	1.25	1.14
82	1.00	1.00	1.00	2.34	0.83	0.73	1.56	0.67	0.60	1.09	0.78	0.77	1.73	0.80	0.73
83	1.00	1.00	1.00	1.23	0.80	0.66	1.47	1.28	1.11	0.86	1.01	1.01	1.51	1.19	1.08
84	1.00	1.00	1.00	1.37	0.67	0.60	1.37	0.64	0.56	0.84	0.69	0.69	1.49	0.78	0.70
85	1.00	1.00	1.00	2.40	0.50	0.52	2.16	0.52	0.50	1.16	0.60	0.60	2.16	0.67	0.66
86	1.00	1.00	1.00	2.40	0.50	0.52	2.16	0.52	0.50	1.13	0.73	0.73	2.16	0.83	0.82
87	1.00	1.00	1.00	1.82	0.49	0.58	1.69	0.48	0.45	1.16	0.52	0.52	1.69	0.61	0.59
88	1.00	1.00	1.00	1.82	0.49	0.58	1.69	0.48	0.45	1.16	0.63	0.63	1.69	0.75	0.72
89	1.00	1.00	1.00	2.28	1.16	0.92	1.83	1.57	1.45	1.21	1.61	1.61	1.86	1.74	1.66
90	1.00	1.00	1.00	2.56	0.67	0.70	1.95	0.61	0.56	1.33	0.78	0.78	2.05	0.86	0.83
91	1.00	1.00	1.00	1.38	0.97	0.77	1.39	1.51	1.32	1.22	1.53	1.53	1.57	1.83	1.71
92	1.00	1.00	1.00	1.57	0.68	0.58	1.35	0.75	0.65	1.17	0.94	0.94	1.58	1.14	1.07
93	1.00	1.00	1.00	3.00	1.29	1.01	2.27	1.66	1.46	1.37	1.36	1.36	2.33	1.50	1.37
94	1.00	1.00	1.00	2.90	1.04	0.91	1.90	0.87	0.77	1.30	0.94	0.94	2.10	1.03	0.94
95	1.00	1.00	1.00	1.35	1.16	0.94	1.57	1.95	1.70	1.27	1.57	1.58	1.61	1.82	1.65
96	1.00	1.00	1.00	1.43	0.84	0.75	1.43	0.86	0.75	1.23	0.88	0.88	1.56	1.05	0.94
97	1.00	1.00	1.00	2.65	0.64	0.66	2.26	0.68	0.65	1.22	0.83	0.83	2.26	0.88	0.86
98	1.00	1.00	1.00	2.65	0.64	0.66	2.26	0.68	0.65	1.22	0.95	0.95	2.26	1.09	1.07
99	1.00	1.00	1.00	1.90	0.51	0.54	1.77	0.51	0.48	1.20	0.58	0.58	1.77	0.65	0.63
100	1.00	1.00	1.00	1.90	0.51	0.54	1.77	0.51	0.48	1.20	0.66	0.66	1.77	0.80	0.78
101	1.00	1.00	1.00	2.87	1.26	0.98	1.90	1.58	1.45	1.30	1.69	1.69	1.93	1.74	1.67
102	1.00	1.00	1.00	2.61	0.93	0.78	1.93	0.92	0.85	1.37	1.16	1.15	2.04	1.31	1.25
103	1.00	1.00	1.00	1.43	1.18	0.93	1.40	1.87	1.64	1.23	1.98	1.98	1.58	2.26	2.12
104	1.00	1.00	1.00	1.57	0.80	0.66	1.40	0.89	0.78	1.26	1.12	1.11	1.64	1.36	1.28
105	1.00	1.00	1.00	5.98	1.36	1.04	3.38	1.32	1.14	1.82	1.01	1.01	3.45	1.21	1.07
106	1.00	1.00	1.00	4.14	1.22	1.04	2.50	0.99	0.87	1.69	1.01	1.01	2.74	1.17	1.06
107	1.00	1.00	1.00	1.64	1.29	1.03	1.96	2.33	2.00	1.42	1.85	1.84	2.01	2.18	1.95
108	1.00	1.00	1.00	1.53	1.04	0.88	1.61	1.15	0.99	1.28	1.10	1.06	1.74	1.38	1.23

Table 3.3 (cont'd) Comparison of Performance Levels Obtained from Different Seismic Guidelines

Specimen No	ESTIMATED Normalized Drift Ratio IO	ESTIMATED Normalized Drift Ratio LS	ESTIMATED Normalized Drift Ratio CP	TEC 2007 Normalized Drift Ratio IO	TEC 2007 Normalized Drift Ratio LS	TEC 2007 Normalized Drift Ratio CP	FEMA 356 Normalized Drift Ratio IO	FEMA 356 Normalized Drift Ratio LS	FEMA 356 Normalized Drift Ratio CP	EC 8 Normalized Drift Ratio IO	EC 8 Normalized Drift Ratio LS	EC 8 Normalized Drift Ratio CP	ASCE 41 UPDATE Normalized Drift Ratio IO	ASCE 41 UPDATE Normalized Drift Ratio LS	ASCE 41 UPDATE Normalized Drift Ratio CP
109	1.00	1.00	1.00	1.73	0.49	0.57	1.74	0.56	0.54	0.96	0.61	0.61	1.74	0.73	0.72
110	1.00	1.00	1.00	2.33	0.49	0.58	2.35	0.56	0.54	1.29	0.78	0.78	2.35	0.91	0.90
111	1.00	1.00	1.00	1.84	0.89	0.81	1.82	0.93	0.88	1.28	0.98	0.98	1.82	1.25	1.21
112	1.00	1.00	1.00	1.79	0.49	0.56	1.82	0.50	0.47	1.25	0.67	0.67	1.82	0.82	0.80
113	1.00	1.00	1.00	2.04	0.79	0.69	1.98	1.10	1.02	1.14	1.06	1.06	2.01	1.22	1.18
114	1.00	1.00	1.00	2.32	0.77	0.65	2.04	0.80	0.75	1.23	1.01	1.01	2.16	1.15	1.11
115	1.00	1.00	1.00	1.39	0.64	0.58	1.60	0.75	0.68	1.08	0.69	0.69	1.62	0.87	0.82
116	1.00	1.00	1.00	1.60	0.69	0.61	1.65	0.75	0.68	1.24	0.93	0.93	1.73	1.12	1.07
117	1.00	1.00	1.00	2.19	1.09	0.94	1.61	1.06	0.94	1.07	0.87	0.87	1.66	0.95	0.89
118	1.00	1.00	1.00	2.67	0.77	0.67	1.66	0.65	0.58	1.25	0.74	0.74	1.86	0.80	0.74
119	1.00	1.00	1.00	1.19	0.95	0.81	1.51	1.16	1.01	1.26	0.93	0.94	1.56	1.10	1.01
120	1.00	1.00	1.00	1.41	0.66	0.59	1.43	0.66	0.57	1.26	0.72	0.72	1.58	0.84	0.77
121	1.00	1.00	1.00	2.47	0.51	0.53	2.43	0.60	0.57	1.34	0.67	0.67	2.43	0.78	0.77
122	1.00	1.00	1.00	2.47	0.51	0.53	2.43	0.60	0.57	1.34	0.80	0.80	2.43	0.97	0.96
123	1.00	1.00	1.00	1.82	0.53	0.60	1.86	0.57	0.54	1.28	0.60	0.60	1.86	0.74	0.72
124	1.00	1.00	1.00	1.82	0.51	0.58	1.86	0.54	0.51	1.28	0.69	0.69	1.86	0.87	0.85
125	1.00	1.00	1.00	3.04	1.28	1.11	1.98	1.24	1.15	1.27	1.23	1.22	2.01	1.37	1.32
126	1.00	1.00	1.00	2.42	0.74	0.64	2.10	0.85	0.79	1.51	1.03	1.04	2.23	1.22	1.18
127	1.00	1.00	1.00	1.49	0.63	0.56	1.62	0.74	0.67	1.10	0.70	0.70	1.64	0.85	0.81
128	1.00	1.00	1.00	1.59	0.70	0.60	1.68	0.81	0.74	1.40	0.95	0.95	1.76	1.20	1.14
129	1.00	1.00	1.00	5.13	1.32	1.01	2.93	1.25	1.11	1.91	1.03	1.03	3.02	1.13	1.04
130	1.00	1.00	1.00	3.13	0.95	0.81	1.68	0.75	0.66	1.28	0.80	0.80	1.88	0.92	0.84
131	1.00	1.00	1.00	1.70	1.21	0.95	2.17	1.85	1.60	1.79	1.50	1.50	2.23	1.74	1.59
132	1.00	1.00	1.00	1.43	0.65	0.59	1.53	0.70	0.61	1.30	0.71	0.71	1.68	0.88	0.80
133	1.00	1.00	1.00	2.67	0.55	0.57	2.53	0.66	0.63	1.60	0.54	0.54	2.53	0.86	0.85
134	1.00	1.00	1.00	2.67	0.55	0.57	2.53	0.66	0.63	1.42	0.62	0.61	2.53	1.07	1.06
135	1.00	1.00	1.00	1.91	0.52	0.58	1.94	0.58	0.55	1.33	0.45	0.45	1.94	0.75	0.73
136	1.00	1.00	1.00	1.90	0.52	0.58	1.93	0.58	0.55	1.30	0.51	0.51	1.93	0.93	0.90
137	1.00	1.00	1.00	3.04	1.25	0.97	2.12	1.61	1.50	1.48	1.69	1.68	2.16	1.79	1.73
138	1.00	1.00	1.00	2.53	0.73	0.62	2.23	0.98	0.92	1.67	1.22	1.21	2.37	1.43	1.38
139	1.00	1.00	1.00	1.52	1.13	0.90	1.71	1.91	1.74	1.40	1.91	1.91	1.73	2.19	2.08
140	1.00	1.00	1.00	1.63	0.72	0.60	1.72	0.90	0.82	1.46	1.05	1.04	1.81	1.33	1.26
141	1.00	1.00	1.00				2.66	0.84	0.73	1.61	0.68	0.68	2.73	0.76	0.70
142	1.00	1.00	1.00	6.12	1.23	1.02	2.16	0.73	0.65	1.56	0.76	0.76	2.40	0.90	0.82
143	1.00	1.00	1.00	1.83	1.26	0.99	2.32	2.45	2.10	1.82	2.02	2.01	2.38	2.31	2.09
144	1.00	1.00	1.00	1.64	0.85	0.75	1.78	0.96	0.83	1.49	0.95	0.95	1.94	1.20	1.08

Table 3.4 and Table 3.5 illustrate statistical analysis results obtained according to different seismic guidelines. Table 3.4 shows real drift ratios; on the other hand Table 3.5 shows normalized drift ratios corresponding to each seismic guideline. When Tables 3.4 and 3.5 are evaluated, following results can be derived;

- For the performance level of immediate occupancy, average drift ratios for TEC (2007), Eurocode 8 (2003), FEMA 356 (2000), and ASCE/SEI 41 (2009) are respectively 1.03, 0.66, 0.88, and 0.91%,

- For the performance level of life safety, average drift ratios for TEC (2007), Eurocode 8 (2003), FEMA 356 (2000), and ASCE/SEI 41 (2009) are respectively 1.77, 2.17, 1.81, and 2.22%,

- For the performance level of collapse prevention, average drift ratios for TEC (2007), Eurocode 8 (2003), FEMA 356 (2000), and ASCE/SEI 41 (2009) are respectively 2.22, 2.89, 2.20, and 2.81%,

- According to evaluation of capacity curves obtained from analytical studies, estimated drift ratios for each performance level have average values of 0.51, 2.53, and 3.37%,

- When standard deviations are compared, it is seen that FEMA 356 provides closer and smaller standard deviation values for all performance levels compared to other seismic provisions.

Table 3.4 Statistical Analysis Results Obtained According to Different Seismic Guidelines

		Drift Ratio (%)		
Procedure	**Stat.**	**IO**	**LS**	**CP**
TEC 2007	μ	1.03	1.77	2.22
	σ	0.25	0.40	0.68
	cov	0.24	0.23	0.31
FEMA 356	μ	0.88	1.81	2.20
	σ	0.12	0.14	0.19
	cov	0.14	0.08	0.09
EC 8	μ	0.66	2.17	2.89
	σ	0.52	0.57	0.76
	cov	0.78	0.26	0.26
ASCE/SEI 41 Update	μ	0.91	2.22	2.81
	σ	0.12	0.42	0.59
	cov	0.14	0.19	0.21
ESTIMATED	μ	0.51	2.53	3.37
	σ	0.14	1.09	1.45
	cov	0.27	0.43	0.43

Table 3.5 Statistical Analysis Results Obtained for the Comparison of Different Seismic Guidelines

		Drift Ratio (%)		
Procedure	**Stat.**	**IO**	**LS**	**CP**
TEC 2007	μ	2.17	0.80	0.72
	σ	0.83	0.28	0.19
	cov	0.38	0.35	0.26
FEMA 356	μ	1.81	0.87	0.78
	σ	0.36	0.43	0.37
	cov	0.20	0.49	0.47
EC 8	μ	1.24	0.97	0.97
	σ	0.20	0.34	0.34
	cov	0.16	0.35	0.35
ASCE/SEI 41 Update	μ	1.86	1.01	0.95
	σ	0.36	0.37	0.34
	cov	0.19	0.37	0.36
ESTIMATED	μ	1.00	1.00	1.00
	σ	0.00	0.00	0.00
	cov	0.00	0.00	0.00

Plastic rotation capacities corresponding to each performance level are investigated. In this investigation, some variables are used such as axial load ratio, concrete compressive strength, yielding strength of reinforcement, and transverse reinforcement ratio etc.

- Figure 3.8 shows the effect of $V/(b_w)d\sqrt{f_c}$ ratio on plastic rotation capacities according to different seismic provisions.

- Figure 3.9 shows the effect of axial load ratio on plastic rotation capacities according to different seismic provisions.

- Figure 3.10 shows the effect of concrete compressive strength on plastic rotation capacities according to different seismic provisions.

- Figure 3.11 shows the effect of yielding strength of reinforcement on plastic rotation capacities according to different seismic provisions.

- Figure 3.12 shows the effect of transverse reinforcement ratio on plastic rotation capacities according to different seismic provisions.

- Figure 3.13 shows the effect of column dimensions on plastic rotation capacities according to different seismic provisions.

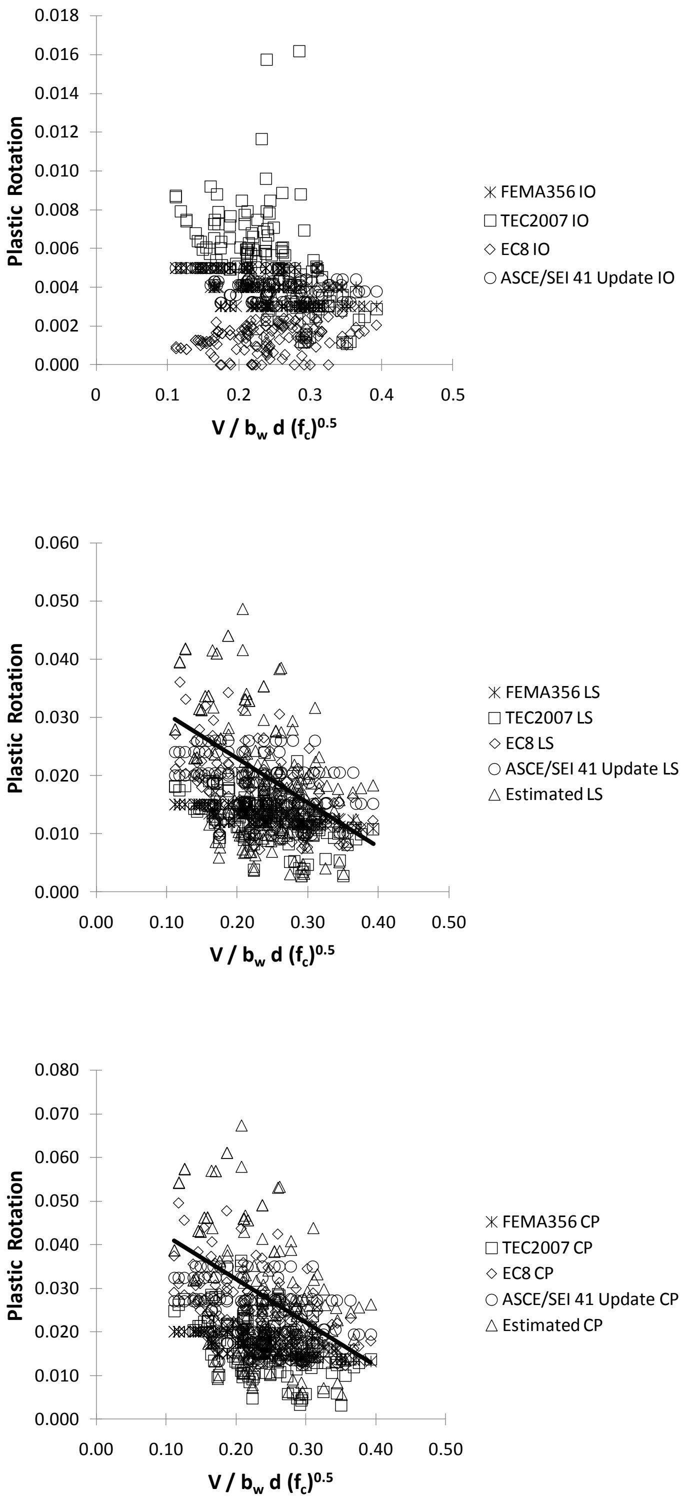


Figure 3.8 Effect of $V/b_wd(f_c)^{0.5}$ Ratio on Plastic Rotation According to Different Seismic Guidelines

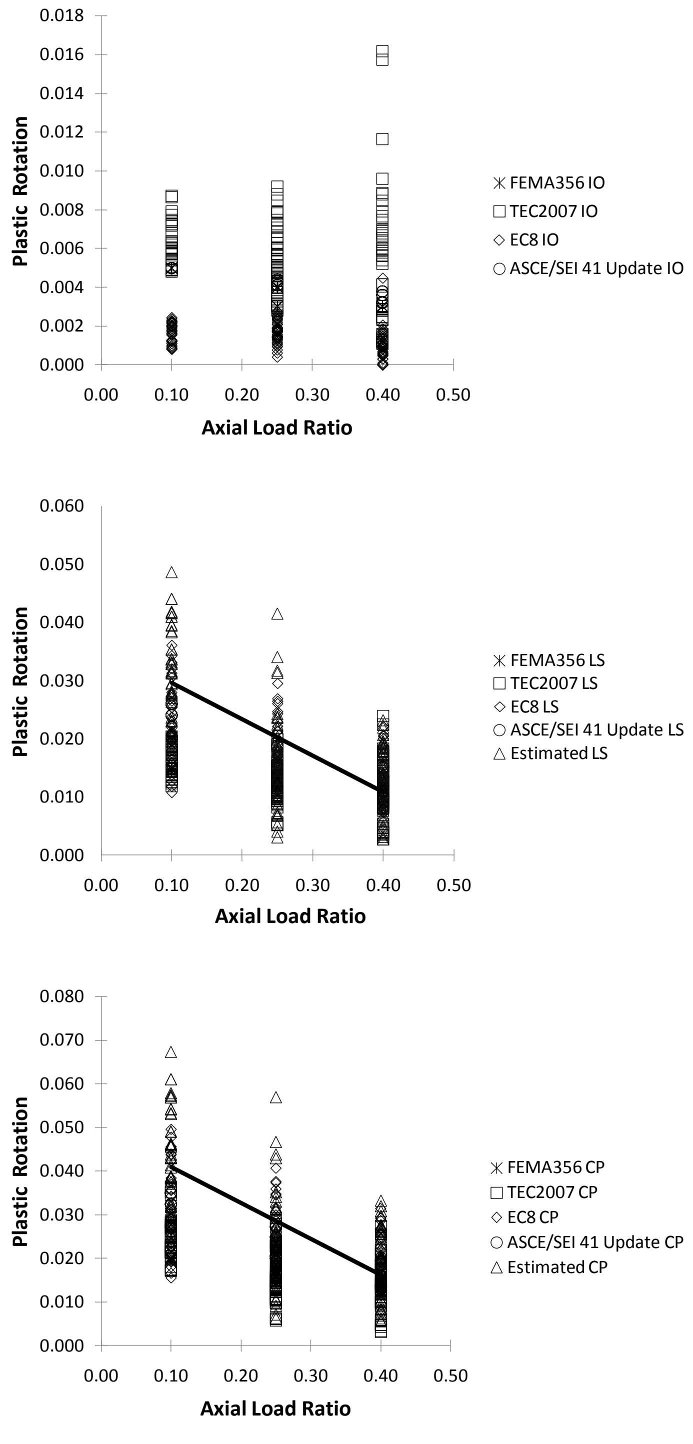
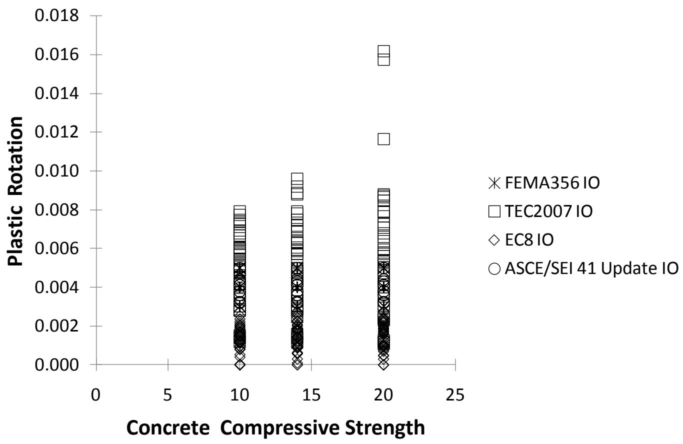
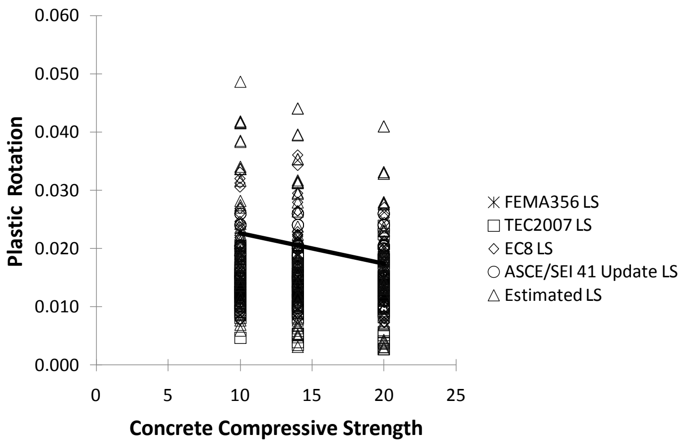


Figure 3.9 Effect of Axial Load Ratio on Plastic Rotation According to Different Seismic Guidelines





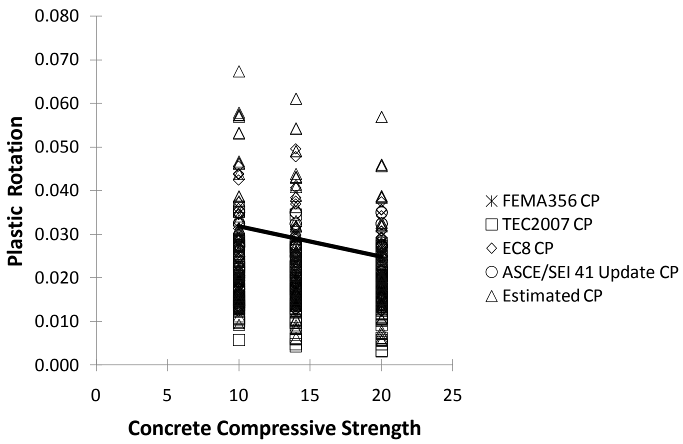


Figure 3.10 Effect of Concrete Compressive Strength on Plastic Rotation According to Different Seismic Guidelines

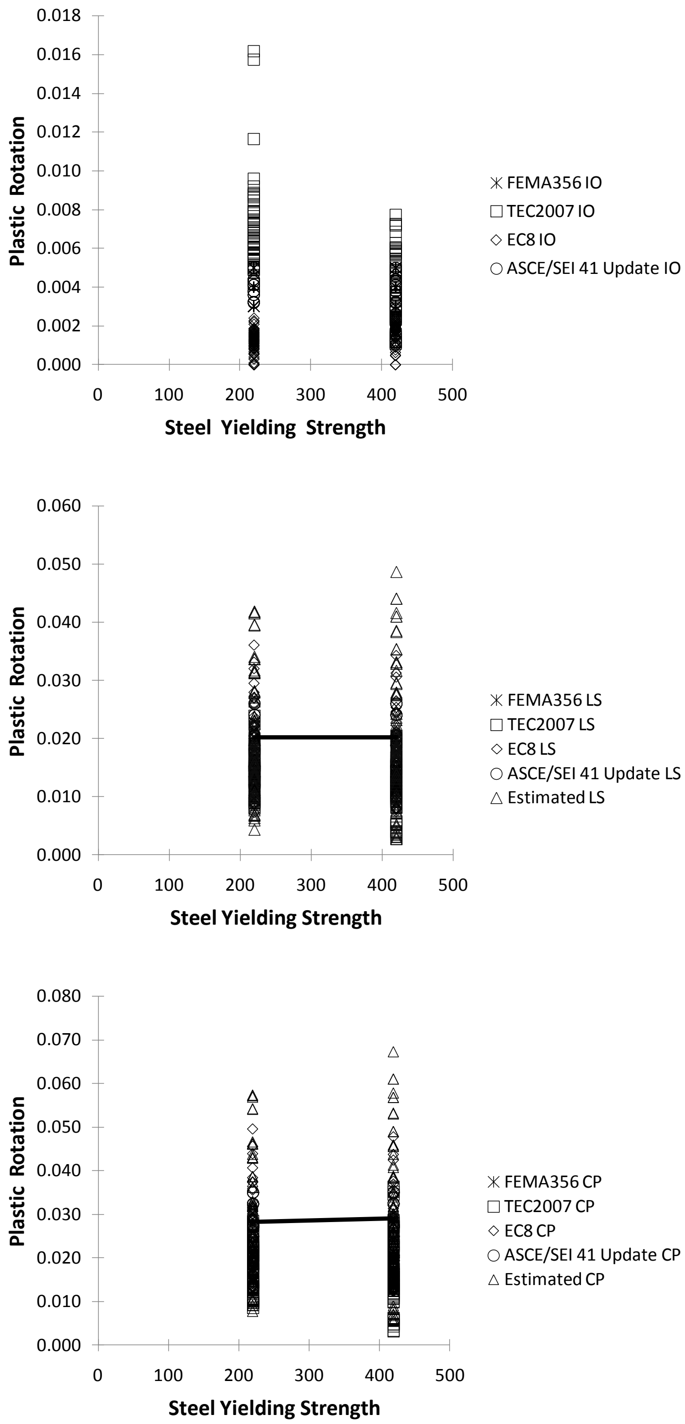


Figure 3.11 Effect of Steel Yielding Strength on Plastic Rotation According to Different Seismic Guidelines

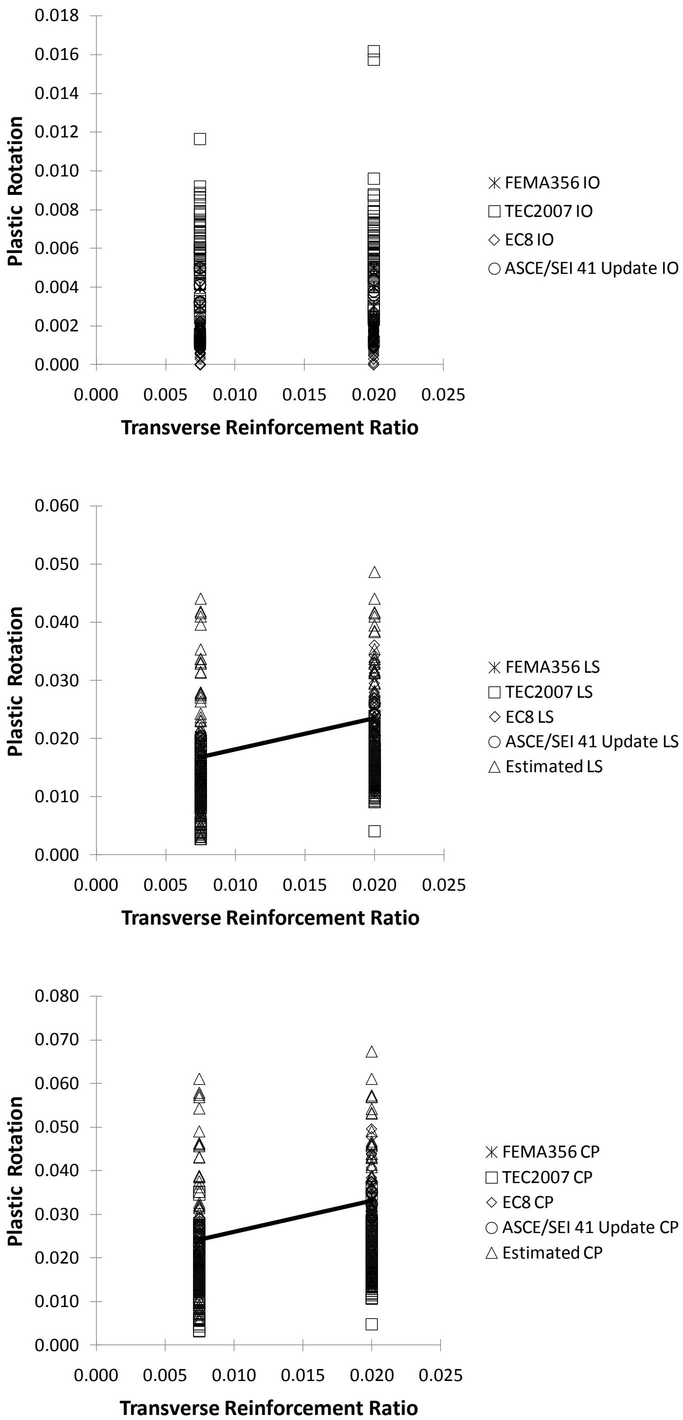
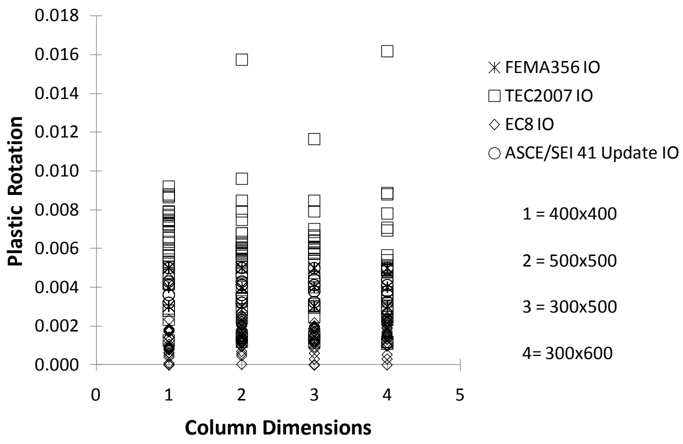
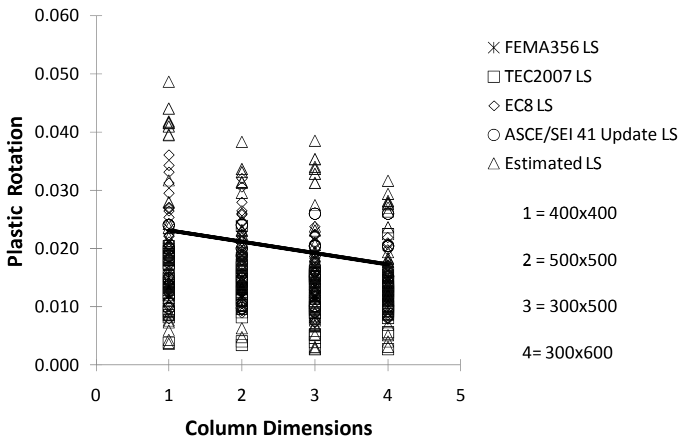


Figure 3.12 Effect of Transverse Reinforcement Ratio on Plastic Rotation According to Different Seismic Guidelines





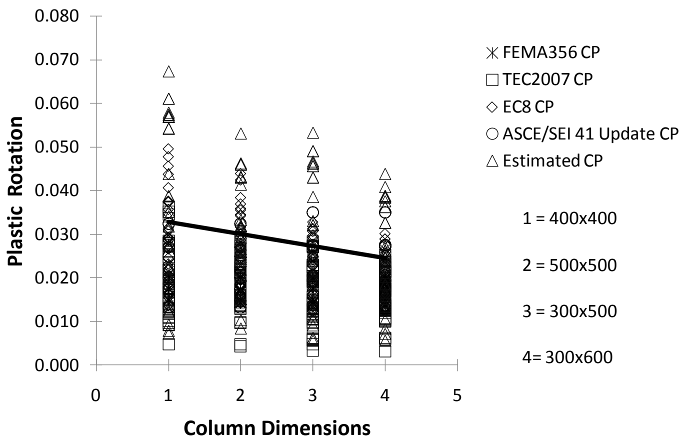


Figure 3.13 Effect of Column Dimensions on Plastic Rotation According to Different Seismic Guidelines

Examination of these figures leads to the following interpretations:

- Figure 3.8 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns decrease with an increase in $V/b_w d(f_c)^{0.5}$ ratio,

- Figure 3.9 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns significantly decrease with an increase in axial load ratio,

- Figure 3.10 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns decrease with an increase in concrete compressive strength,

- Figure 3.11 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns are not affected from a change in yielding strength of longitudinal reinforcement,

- Figure 3.12 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns significantly increase with an increase transverse reinforcement ratio,

- Figure 3.13 shows that plastic rotation capabilities of the flexure critical reinforced concrete columns are affected with a change in column dimensions,

- For all cases, variation of plastic rotation obtained from analytical results is consistent with the seismic provisions.

3.9. Proposed Equations for Performance Levels

According to the evaluation of seismic provisions, main parameters which affect plastic rotation capacities of assessed columns are presented in Figures 3.8, 3.9, 3.10, 3.11, 3.12, and 3.13. In order to generate appropriate equations for immediate occupancy, life safety, and collapse prevention performance levels, these parameters are considered. Nonlinear regression analyses are performed and Equations 3.14, 3.15, and 3.16 are obtained with R^2 values of 0.738, 0.738, and 0.822, respectively.

Drift ratio (%) at collapse prevention performance level can be calculated by Equation 3.14;

$$(DR)_{CP} = -1.42 + 70.212\rho_s + 5.324(0.01)^{N/N_0} + 0.0074\left(\frac{V}{b_w d\sqrt{f_c}}\right)^{-0.818} + 0.00142 f_{yk} + 0.822\left(L/H\right) - 0.077 f_c \qquad \text{Eq. 3.14}$$

Drift ratio (%) at life safety performance level can be calculated by Equation 3.15;

$$(DR)_{LS} = 0.75(DR)_{CP} \qquad \text{Eq. 3.15}$$

Drift ratio (%) at immediate occupancy performance level can be calculated by Equation 3.16;

$$(DR)_{IO} = -0.30 + 0.001 f_{yk} + 0.16\left(L/H\right) \qquad \text{Eq. 3.16}$$

Where:

ρ_s: Volumetric ratio of transverse reinforcement

N/N_o: Axial load ratio

V: Shear force at the critical section

b_w : Width of the web reinforcement

d: Flexural depth of the section

f_c: Concrete compressive strength

f_{yk}: Yielding strength of longitudinal reinforcement

L/H: Slenderness ratio

Derived equations are utilized on flexure critical columns used in evaluation of PEER Database (2005) and parametric study. Statistical analyses which are performed on ratios of the calculated drift ratio to the estimated drift ratio for each performance level are illustrated separately for the database and parametric study columns in Table 3.6.

Table 3.6 Statistical Analysis Results of Equations 3.14, 3.15, and 3.16 for PEER Database Columns and Parametric Study Columns

		Equation 3.12	Equation 3.13	Equation 3.14
		IO	LS	CP
PEER Database (2005) (30 Columns)	Mean	0.91	0.62	0.62
	Standart Deviation	0.26	0.17	0.17
	Coefficient of Variation	0.29	0.27	0.27
Parametric Study (144 Columns)	Mean	1.01	1.06	1.06
	Standart Deviation	0.12	0.27	0.27
	Coefficient of Variation	0.12	0.26	0.26

Estimated versus calculated drift ratios are plotted in Figure 3.14 for both PEER database (2005) and parametric study columns for immediate occupancy, life safety, and collapse prevention performance levels. Calculated values indicate the ones computed from the proposed equations.

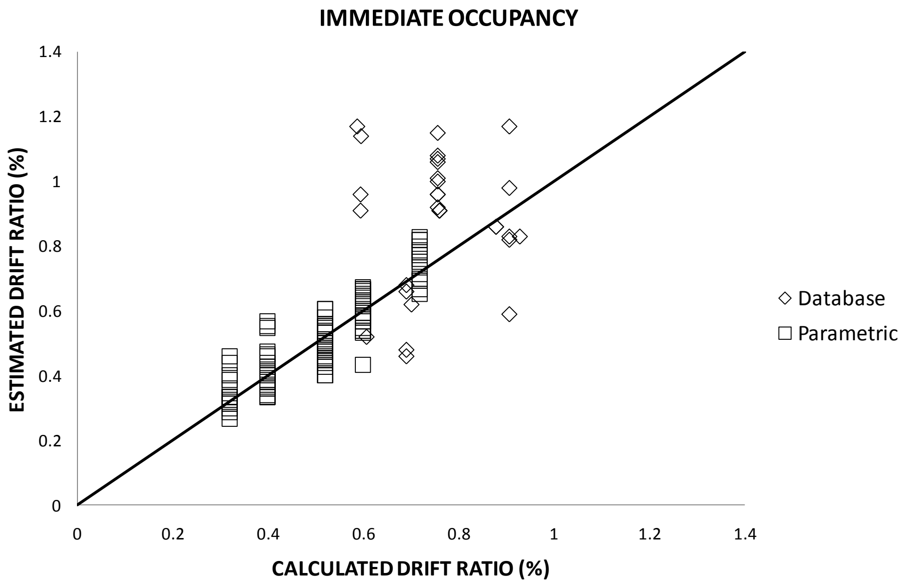
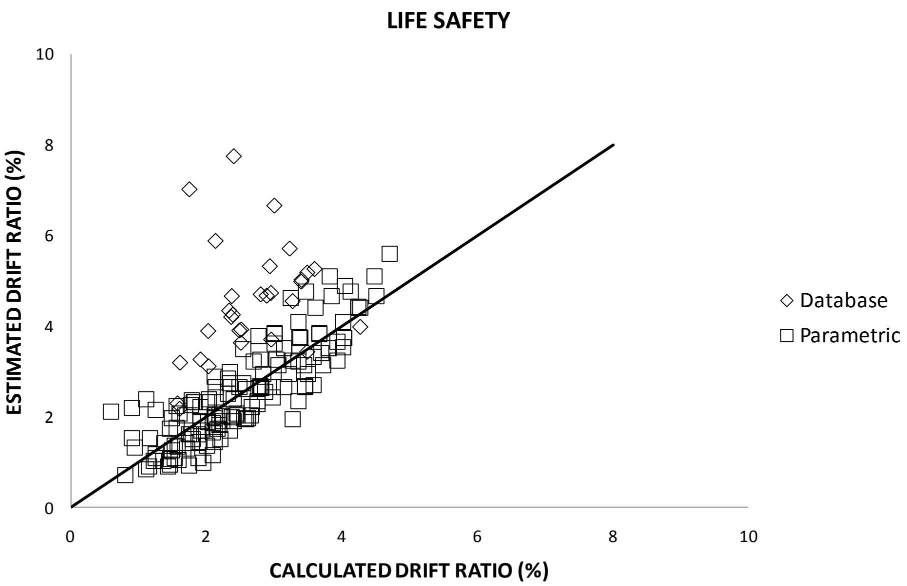


Figure 3.14 Comparison of Estimated and Calculated Drift Ratios Proposed by Equations 3.14, 3.15, and 3.16 for PEER Database (2005) and Parametric Study Columns



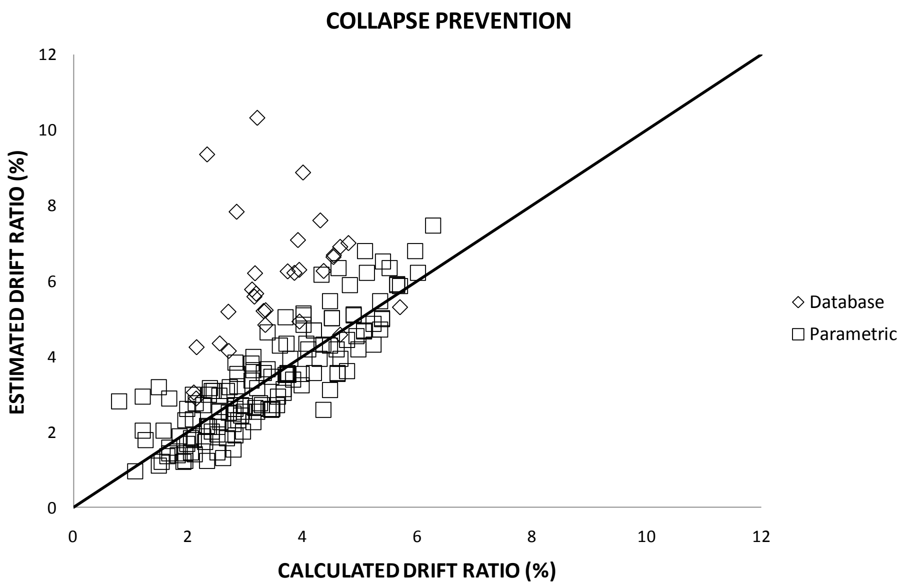


Figure 3.14 (cont'd) Comparison of Estimated and Calculated Drift Ratios Proposed by Equations 3.14, 3.15, and 3.16 for PEER Database (2005) and Parametric Study Columns

As it is shown in Table 3.6 and Figure 3.14, as expected proposed equations are more accurate for parametric study columns than PEER database (2005) columns. When immediate occupancy performance level is considered, ratios of the calculated drift ratio to the estimated drift ratio have the mean values of 0.91 and 1.01 for the database and parametric study columns, respectively. In addition, when life safety and collapse prevention performance levels are considered, it is seen that Equations 3.15 and 3.16 provide more conservative mean values for PEER database (2005) columns than parametric study columns. The reason of this can be explained as follows;

- Range of used parameters in Equations 3.15 and 3.16, which affect the drift ratios at life safety and collapse prevention performance levels significantly vary when PEER Database (2005) and parametric study columns are evaluated,

- Different seismic provisions and parametric studies show that plastic rotation capabilities of the flexure critical reinforced concrete columns decrease with an increase in $V/b_w d(f_c)^{0.5}$ ratio. On the other hand, this variation is not accurately provided when PEER database (2005) columns are considered. Figure 3.15 shows the different tendencies of the variation of $V/b_w d(f_c)^{0.5}$ ratio for PEER database (2005) and parametric study columns.

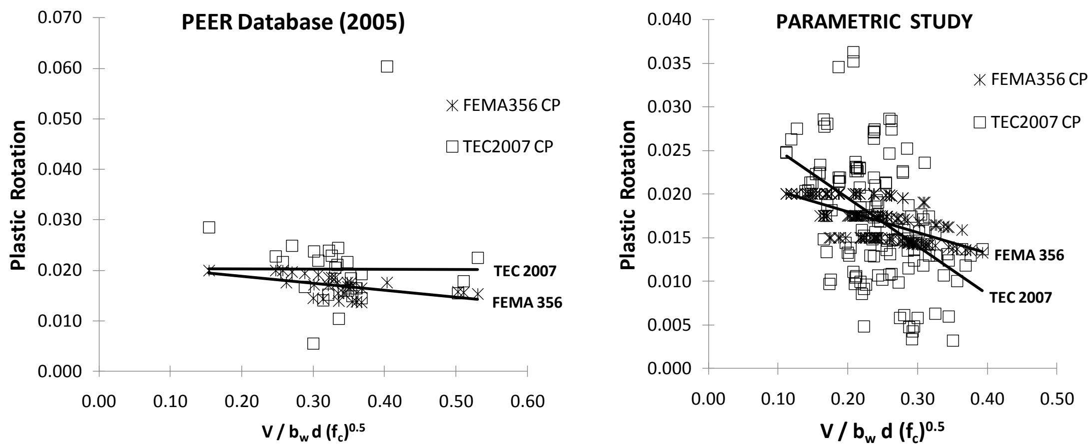


Figure 3.15 Different Tendencies of the Variation of $V/b_w d(f_c)^{0.5}$ Ratio for PEER Database (2005) and Parametric Study Columns

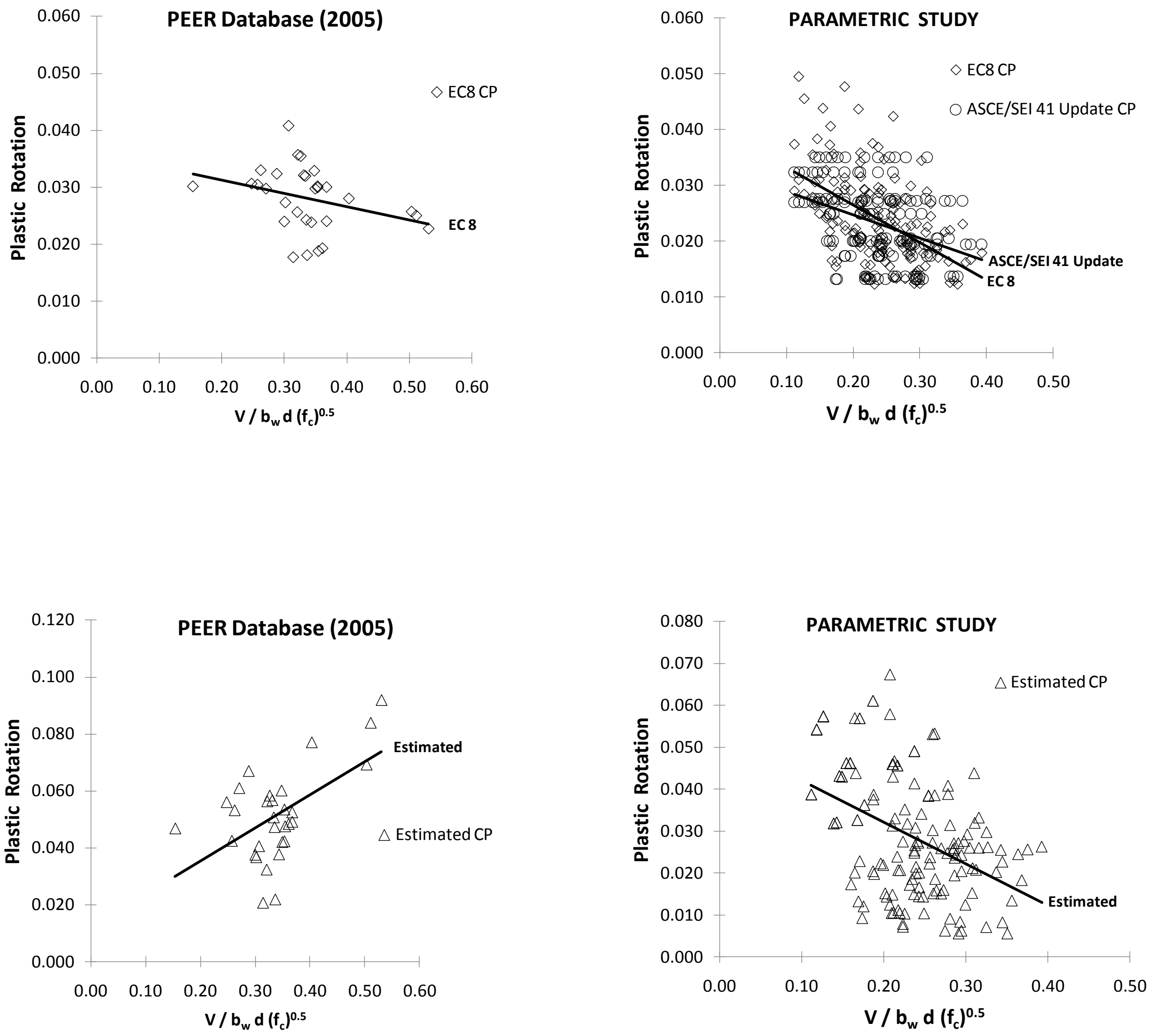


Figure 3.15 (cont'd) Different Tendencies of the Variation of $V/b_wd(f_c)^{0.5}$ Ratio for PEER Database (2005) and Parametric Study Columns

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

4.1. Summary

In this study, seismic behavior of reinforced concrete columns, whose failure modes were flexural, was evaluated analytically with a finite element analysis program OpenSees (2005). The main objectives of this study were to evaluate performance based displacement limits for each performance levels, compare these limits with the limits obtained from different seismic provisions, and investigate the effects of key parameters, such as concrete strength, axial load ratio, yielding strength of longitudinal reinforcement, and transverse reinforcement ratio, on capacity curves and performance based displacement limits. New relationships that take into account the influential parameters are proposed to improve the code recommended performance based displacements limits.

For these purposes, firstly different seismic provisions were examined. TEC (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009) were clarified to find out the deficiencies of each provision while assessing and deciding the performance level of an existing member. Secondly, analytical studies were conducted to find an appropriate model which predicts the seismic behavior accurately. In this part of the study, a total number of 30 columns with flexural failure mode were extracted from Pacific Earthquake Engineering Research Center's Structural Performance Database (2005). The selected columns were subjected to monotonic loading and obtained capacity curves were compared with the results obtained from experimental studies. Finally, parametric studies were carried out by using the most trustworthy analytical model to estimate performance limits for each performance level. A total number of 144 columns were loaded monotonically and their seismic performances were evaluated. Estimated performance limits derived from these analytical studies were compared statistically with the limits achieved by seismic assessment guidelines TEC (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009). In addition, effects of key parameters on capacity curves and performance based displacement limits were illustrated.

4.2. Conclusions

Conclusions obtained from this study can be stated as;

- Main parameters affecting the deformation capacity of a flexure critical reinforced concrete column are axial load ratio, amount of transverse reinforcement, and yielding strength of longitudinal reinforcement,

- Axial load ratio and amount of transverse reinforcement significantly affect the ultimate drift ratio; on the other hand have no considerable effect on the drift ratio at the yielding point,

- Yielding strength of longitudinal reinforcement significantly affects the drift ratio at the yielding point; on the other hand has no significant effect on the ultimate drift ratio,

- Concrete strength does not remarkably affect the deformation capacities; on the other hand lateral load capacities are significantly affected from a change in concrete strength,

- For most of the flexure critical columns, TEC (2007), FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009) provide underestimated seismic performance. When these columns reach performance level of collapse prevention according to these seismic assessment guidelines, all of them do not even reach performance level of life safety according to experimental and analytical test results,

- Eurocode 8 (2003) estimates performance limits corresponding to the performance level of immediate occupancy more accurate than TEC (2007), FEMA 356 (2000), and ASCE/SEI 41 Update (2009). TEC (2007), FEMA 356 (2000), and ASCE/SEI 41 Update (2009) provide overestimated drift ratios compared to Eurocode 8 (2003),

- TEC (2007) , FEMA 356 (2000), Eurocode 8 (2003), and ASCE/SEI 41 Update (2009) are very conservative while considering rotation limits of life safety and collapse prevention performance levels. Eurocode 8 (2003) and ASCE/SEI 41 Update (2009) provide closer performance limits compared to TEC (2007) and FEMA 356 (2000),

- For low levels of axial load, ASCE/SEI 41 Update (2009) and TEC (2007) provides closer flexural rigidities than FEMA 356 (2000) and EC 2 (2004). On the other hand, with increasing levels of axial load ASCE/SEI 41 Update (2009) estimates more accurately than other seismic provisions. In addition to this, FEMA 356 (2000) and EC 2 (2004) estimate flexural rigidities closer than TEC (2007) for high levels of axial load.

4.3. Recommendations

- Performance limits should be produced separately for each failure mode while making assessment of a reinforced concrete column,

- Effects of axial load ratio, transverse reinforcement ratio, and confinement detailing should be included in the determination of the performance level of a reinforced concrete column,

- The column database used in the parametric study should be expanded in order to generalize the equations proposed for more reliable limits.

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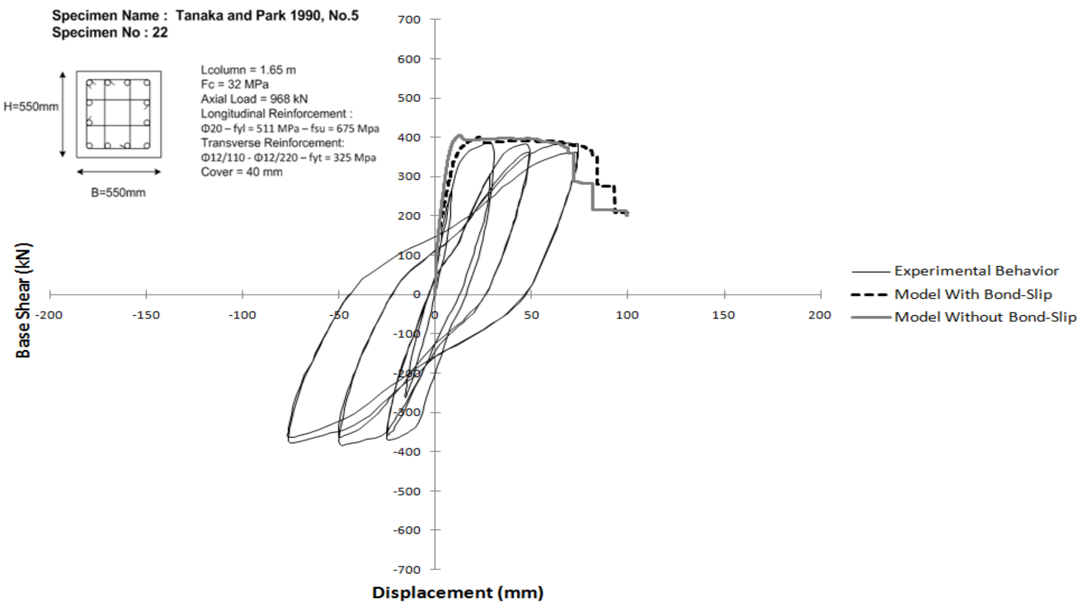
APPENDIX A



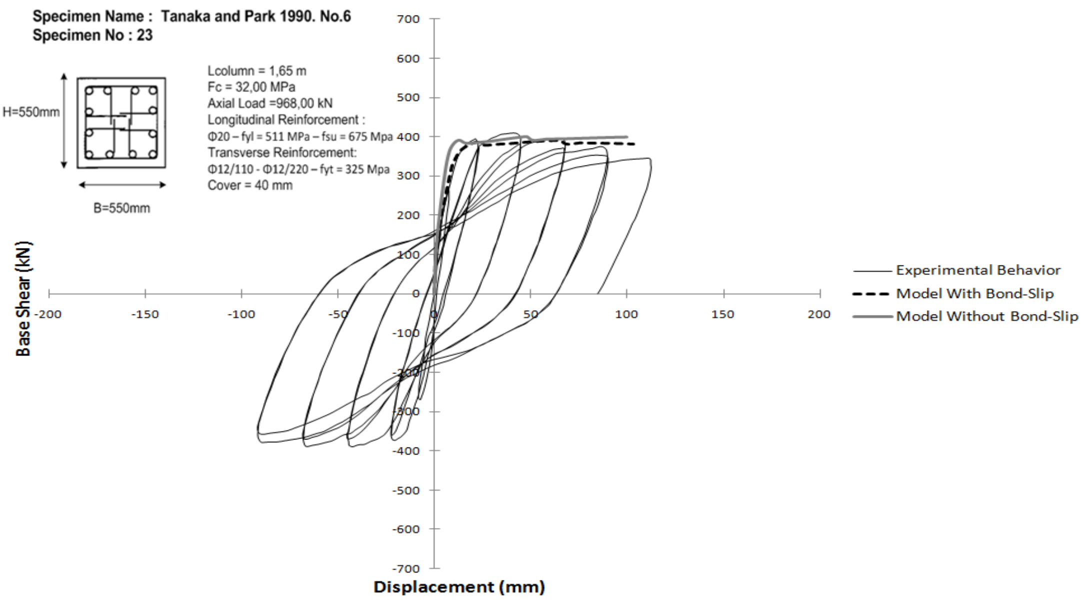
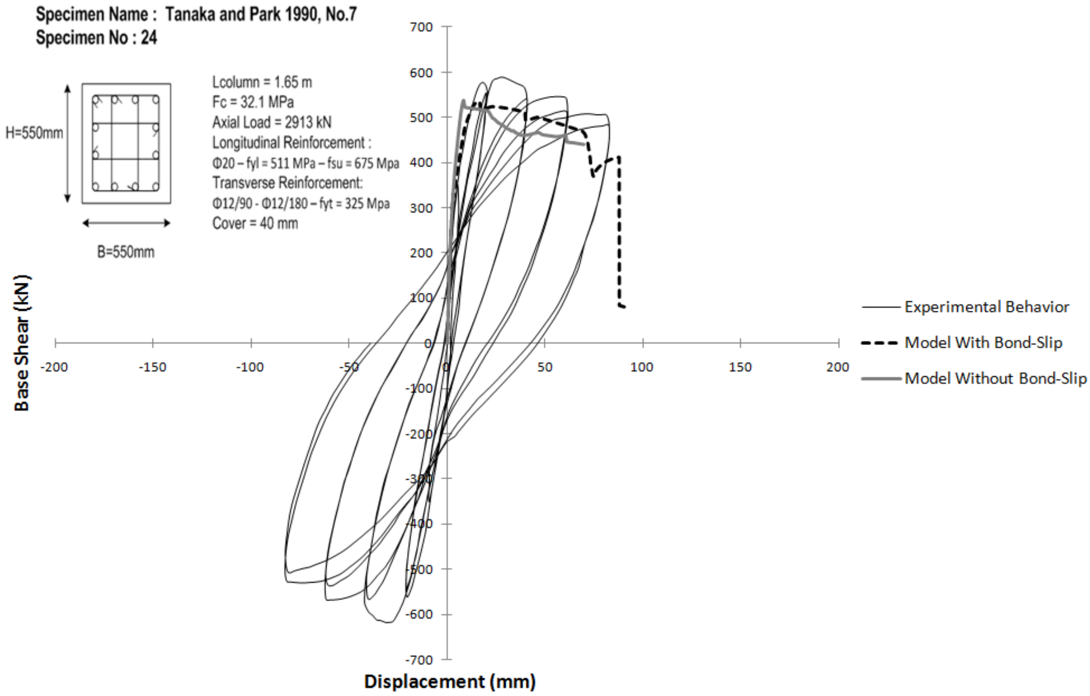
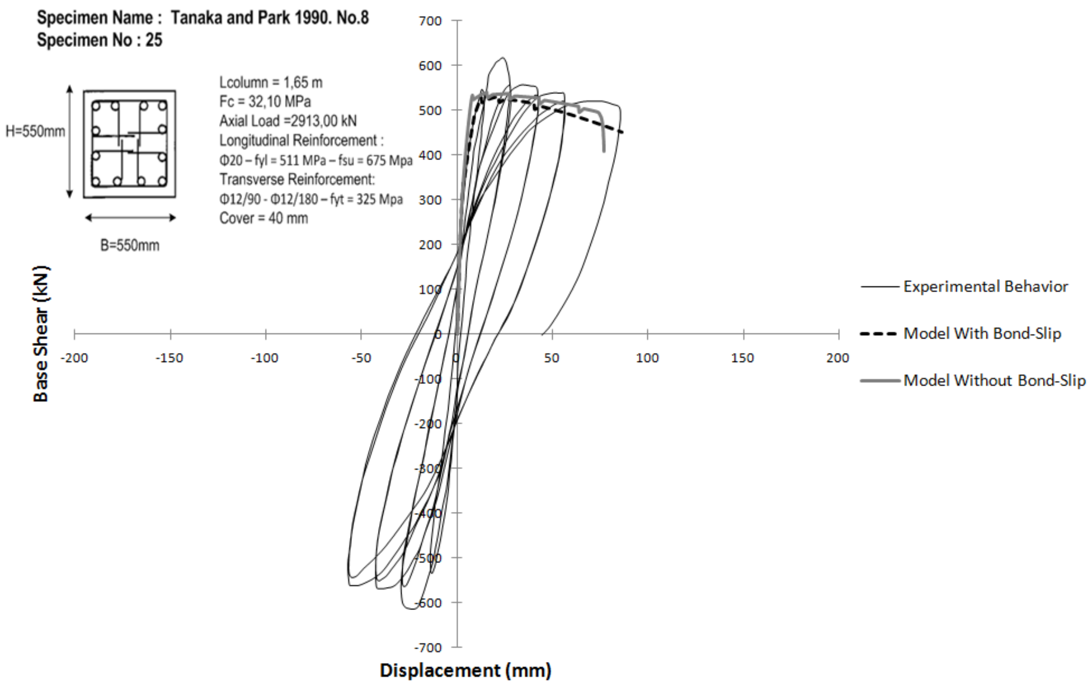


Figure A.1 Comparison of Experimental and Analytical Behavior of Flexure Critical Columns Selected from PEER Database (2005)





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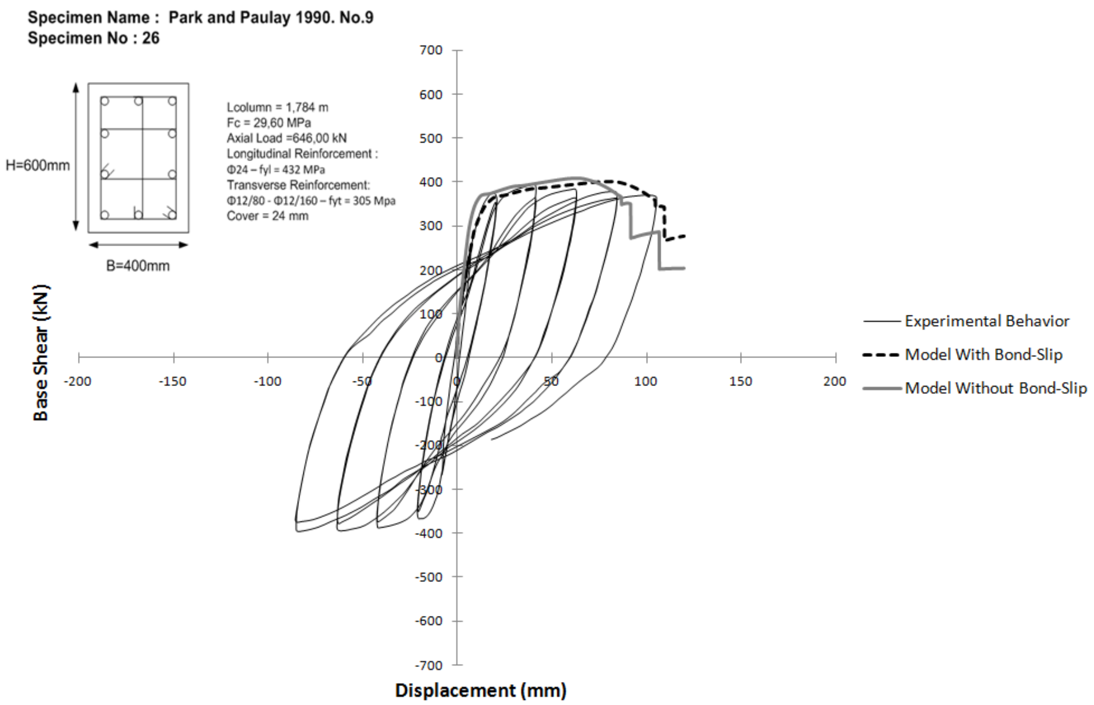

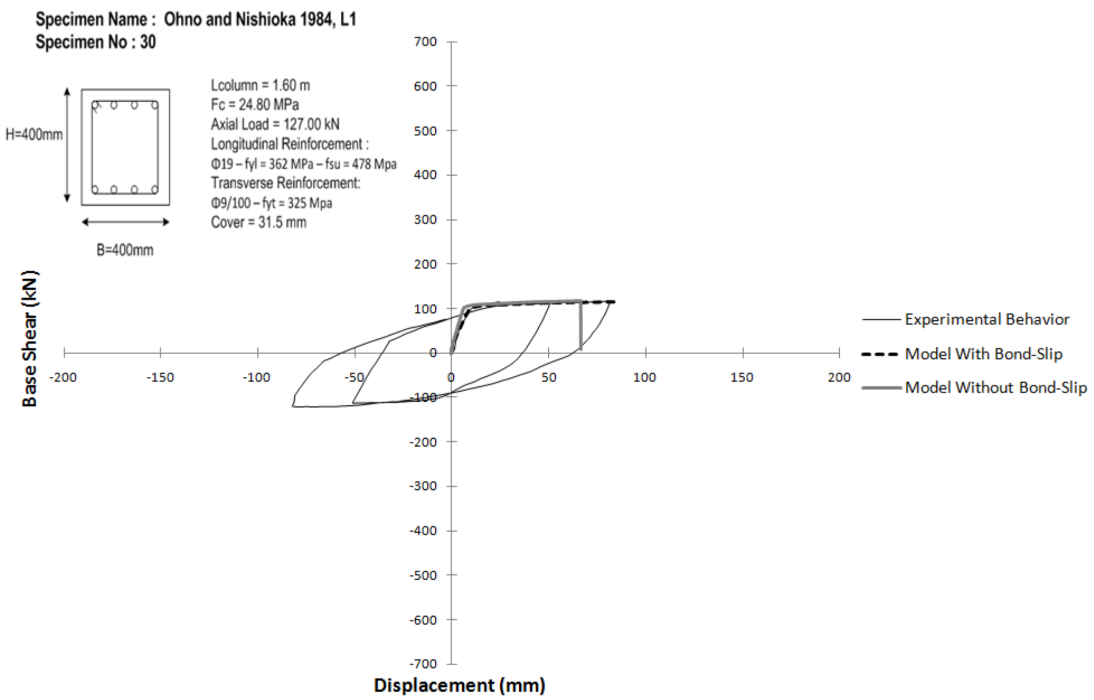

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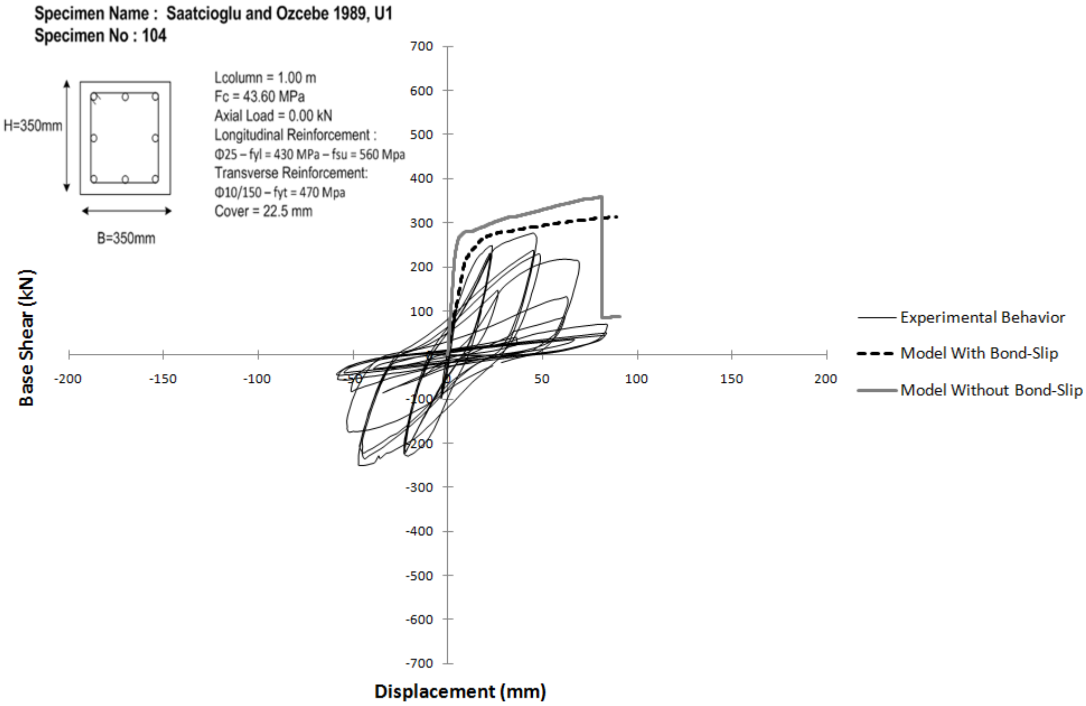

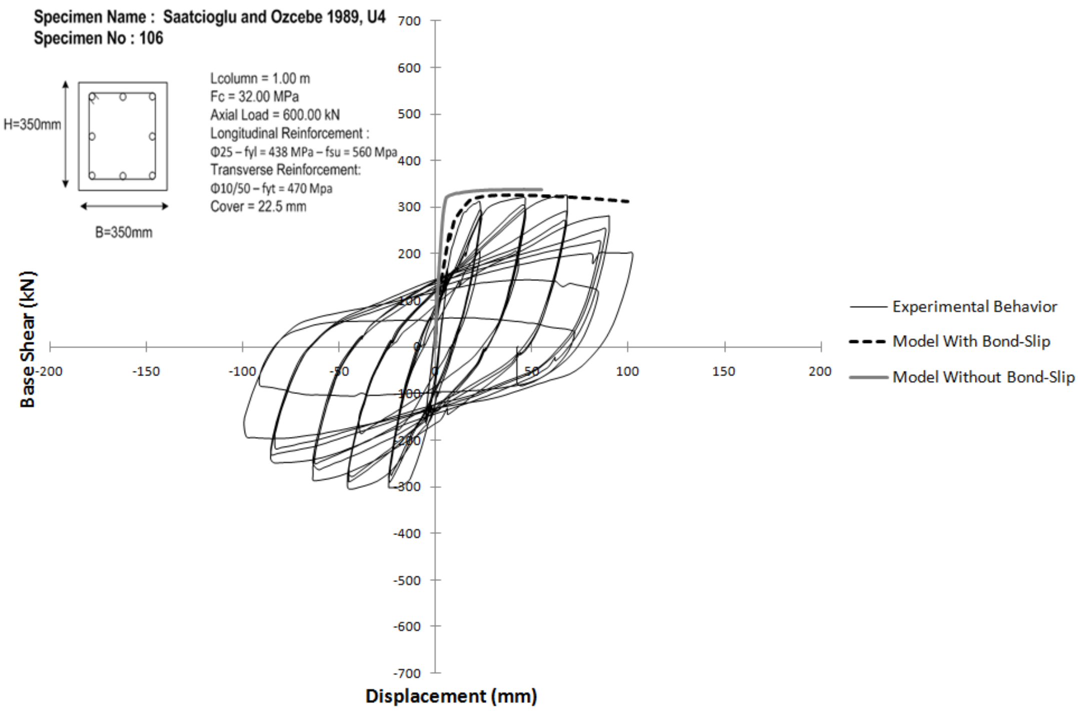

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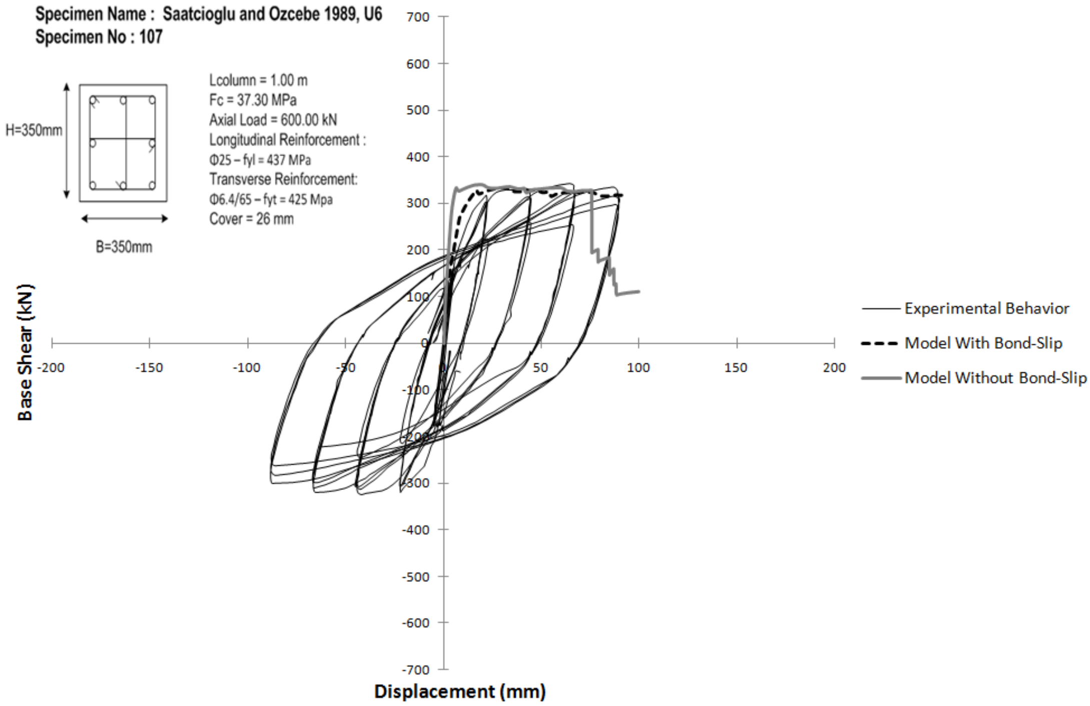

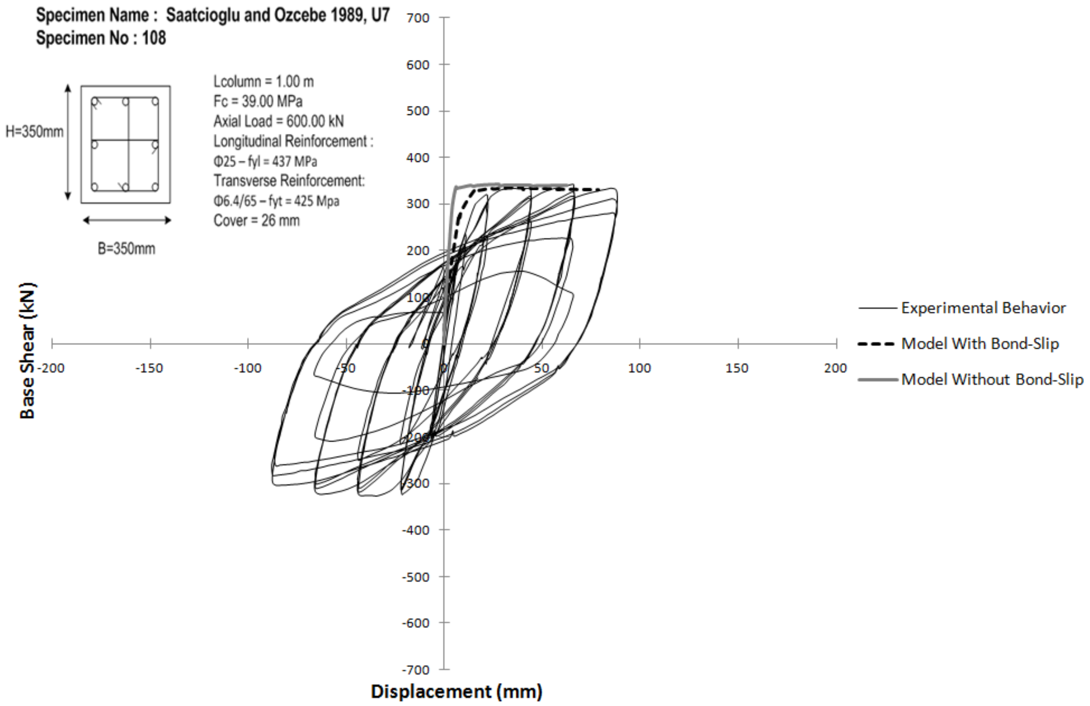

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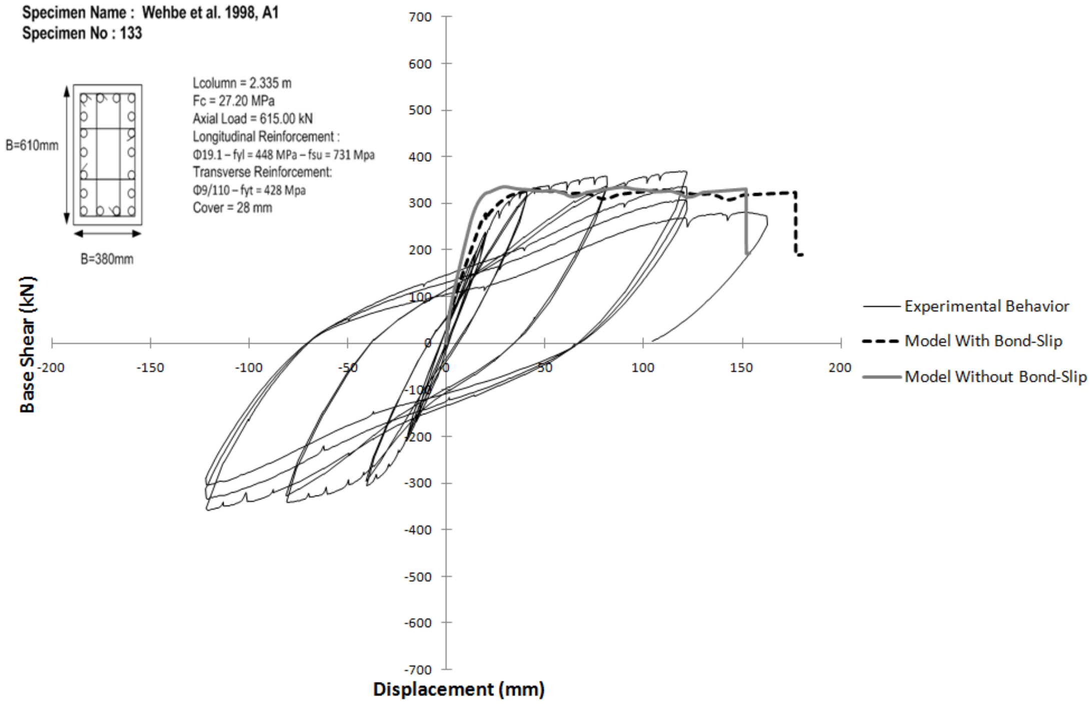

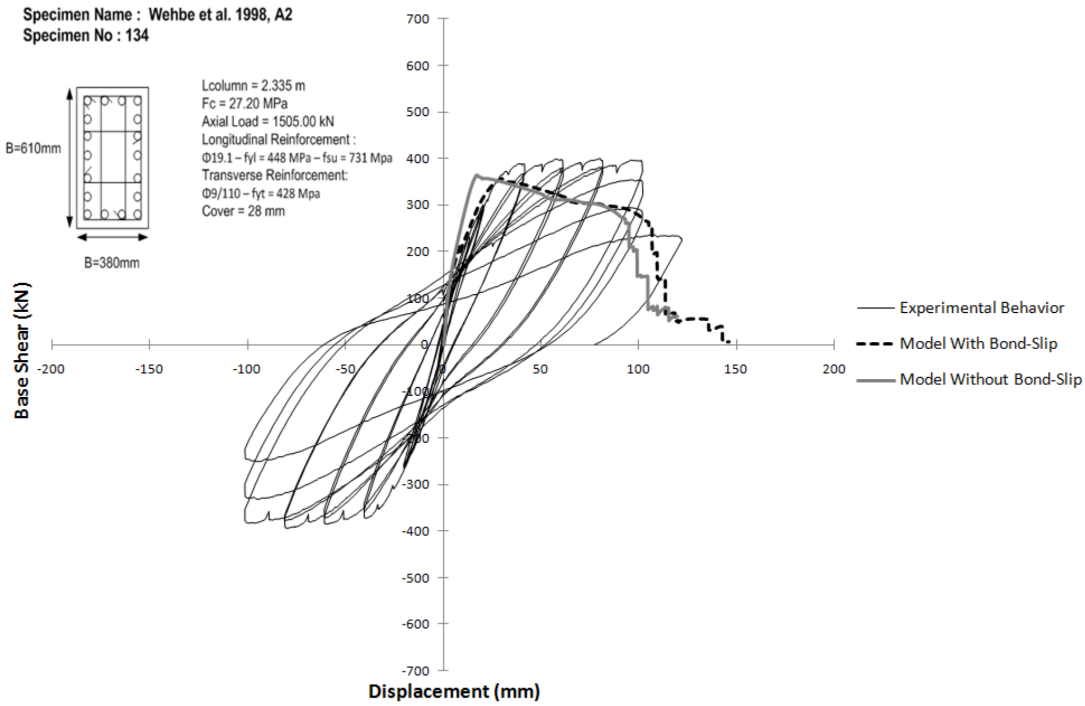

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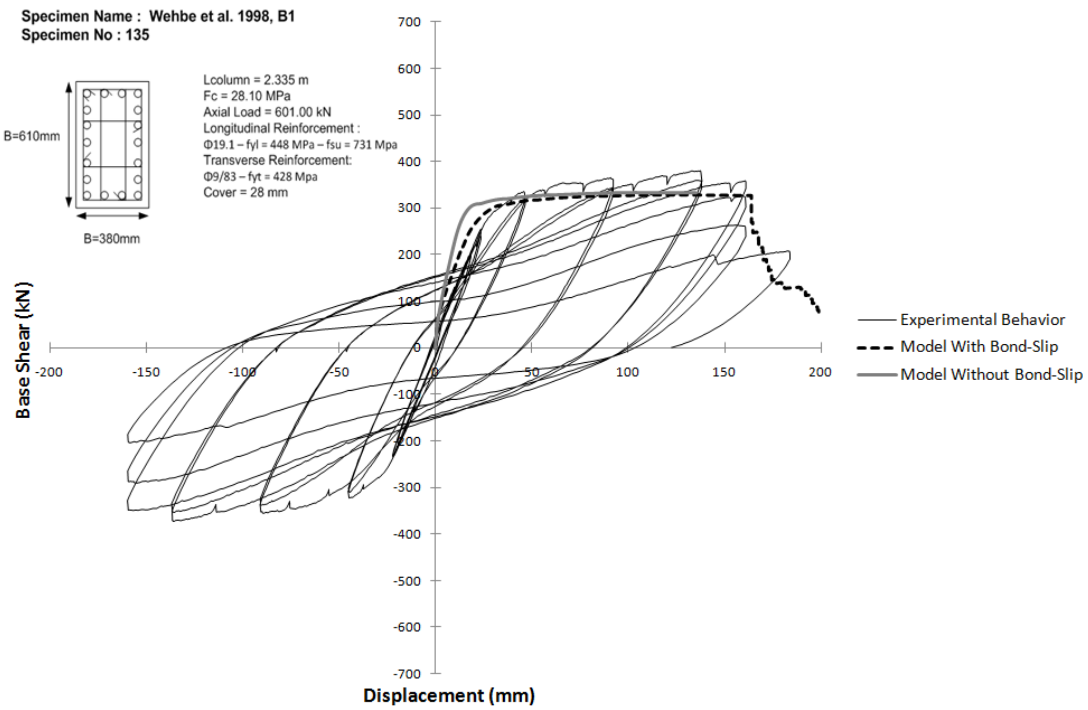

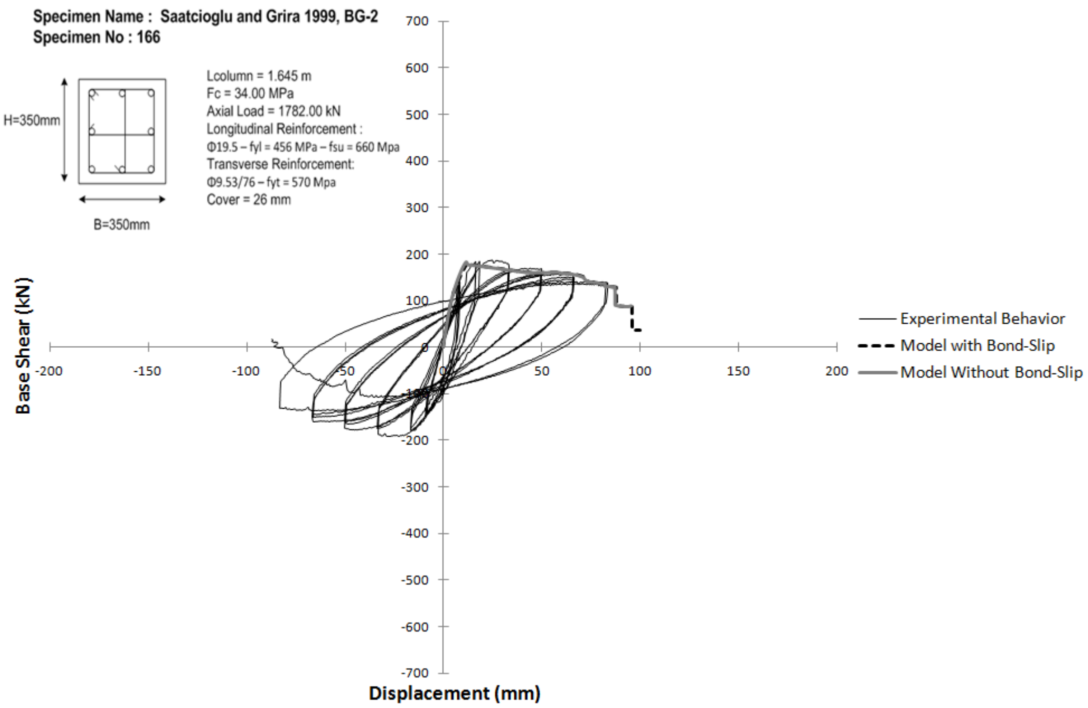

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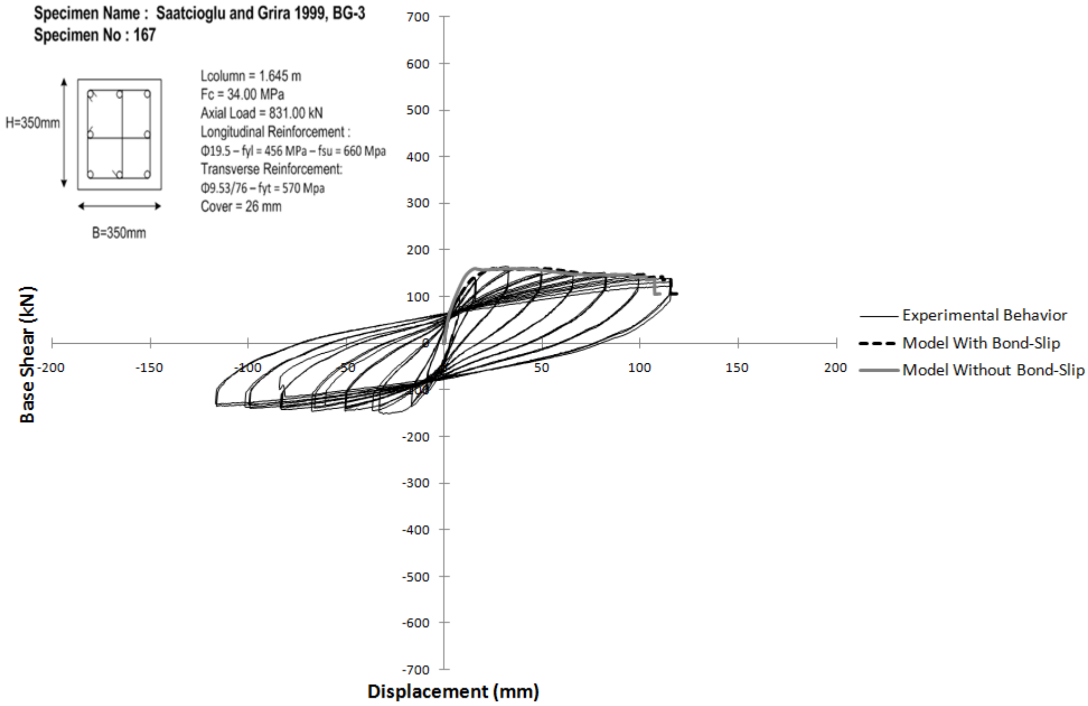

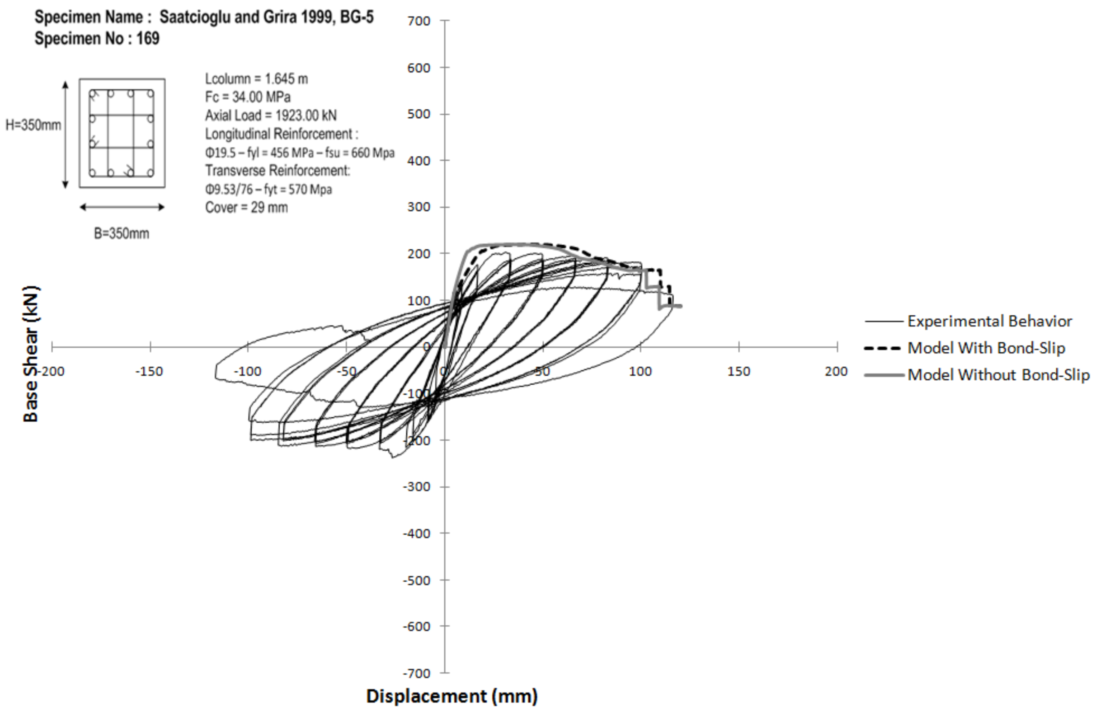

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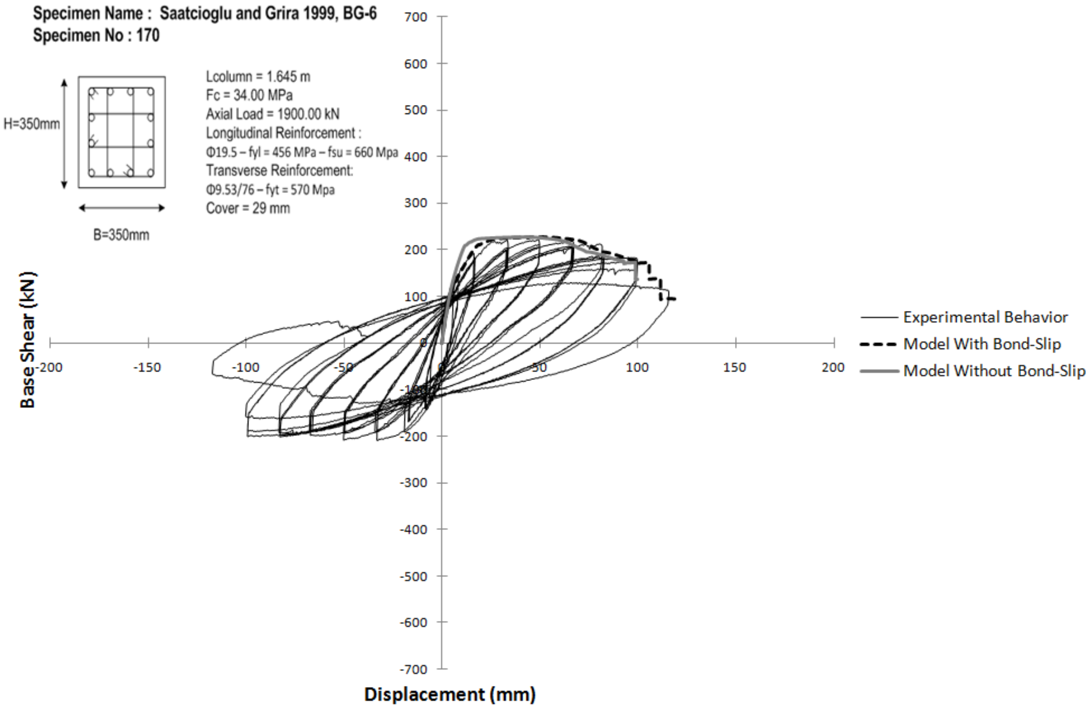

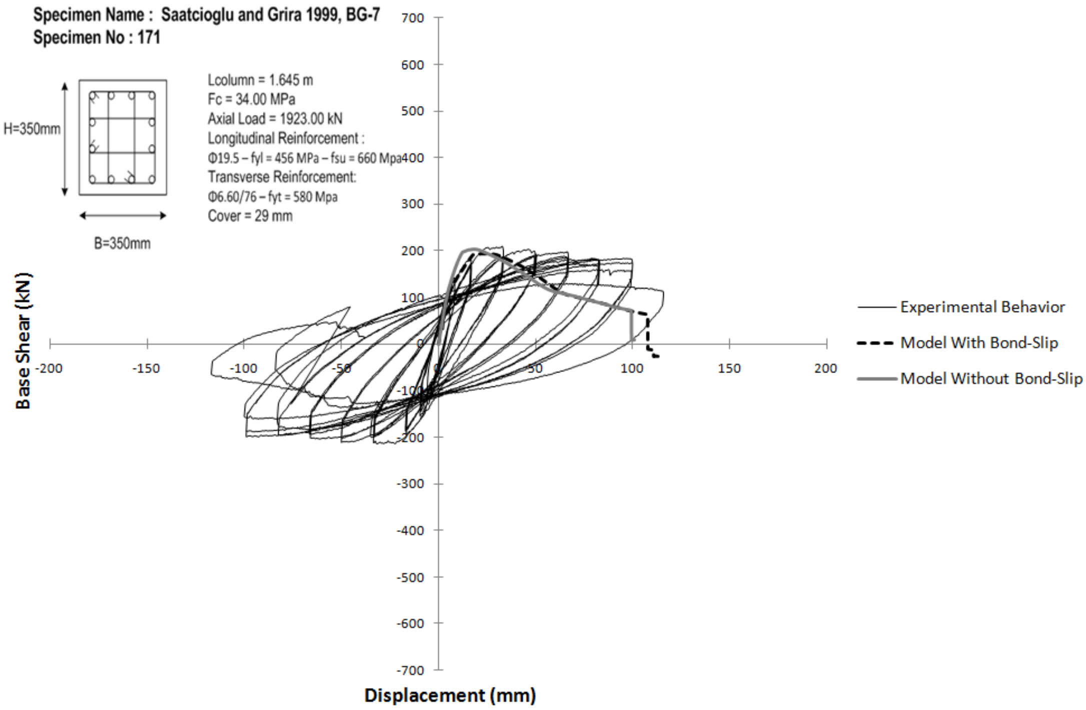

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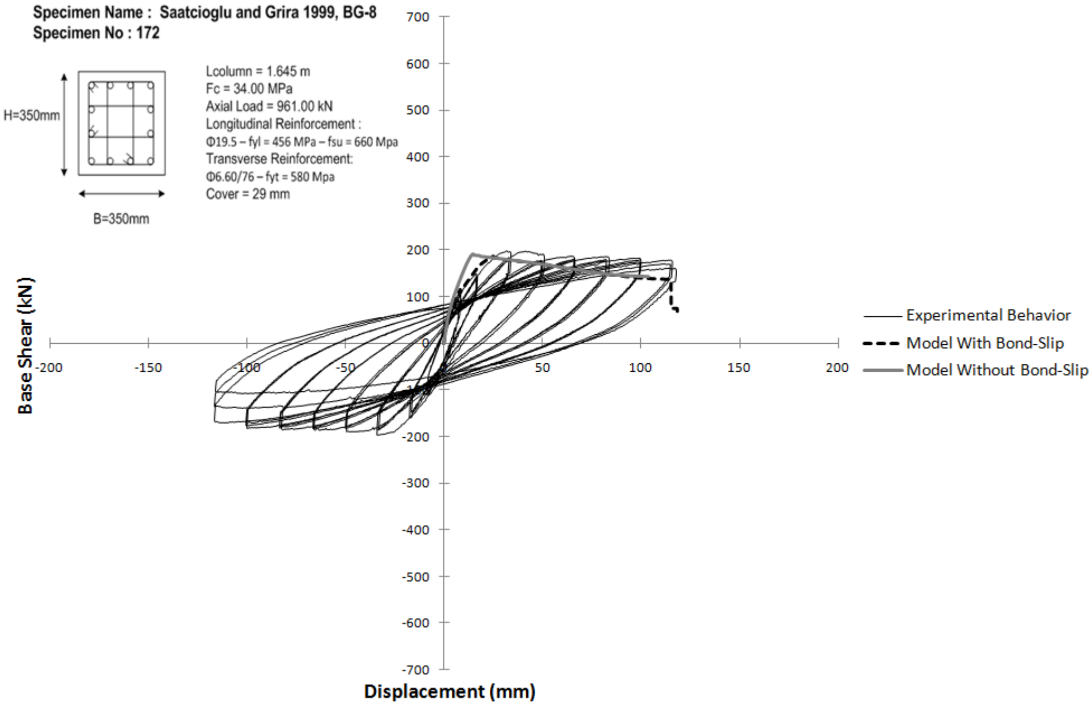

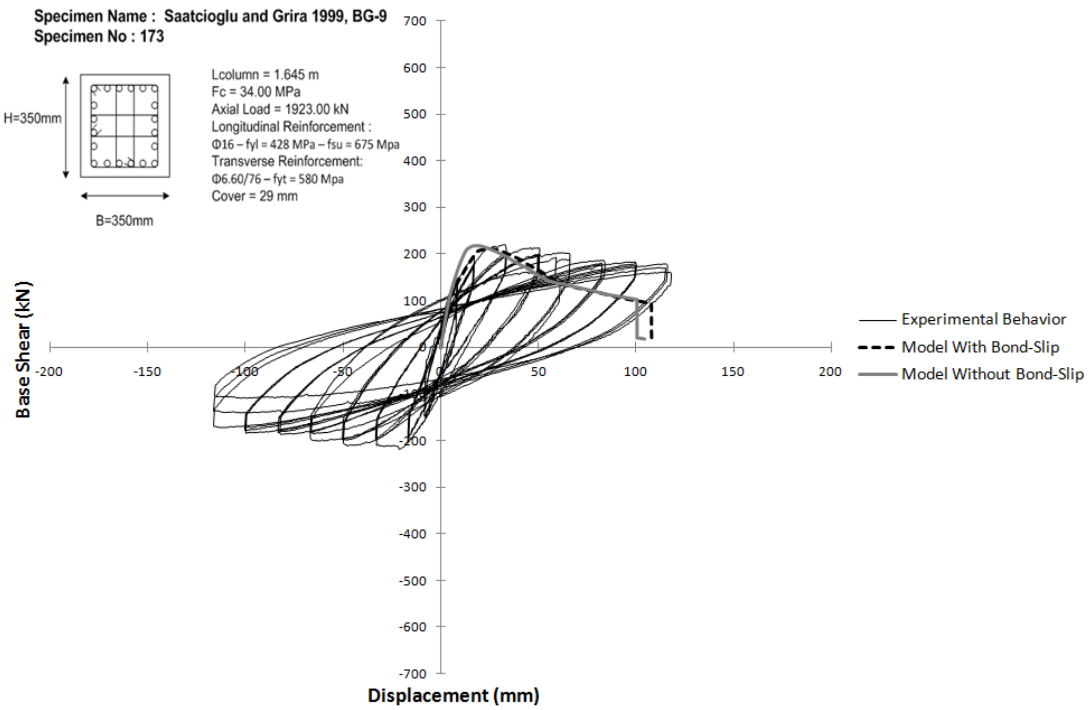

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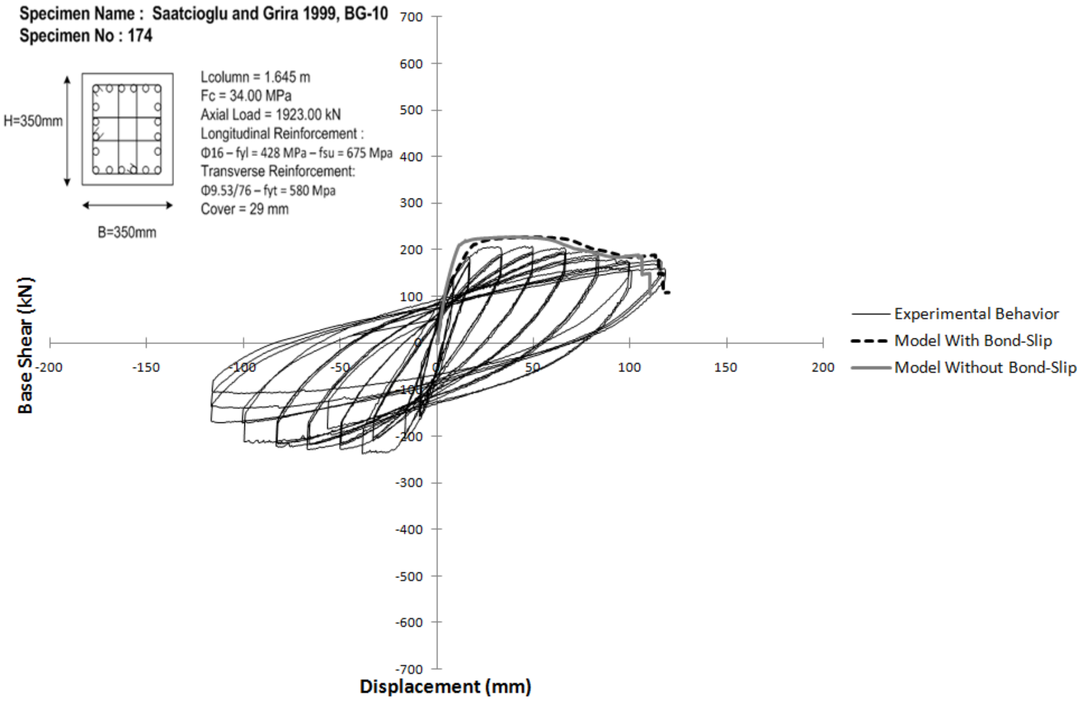

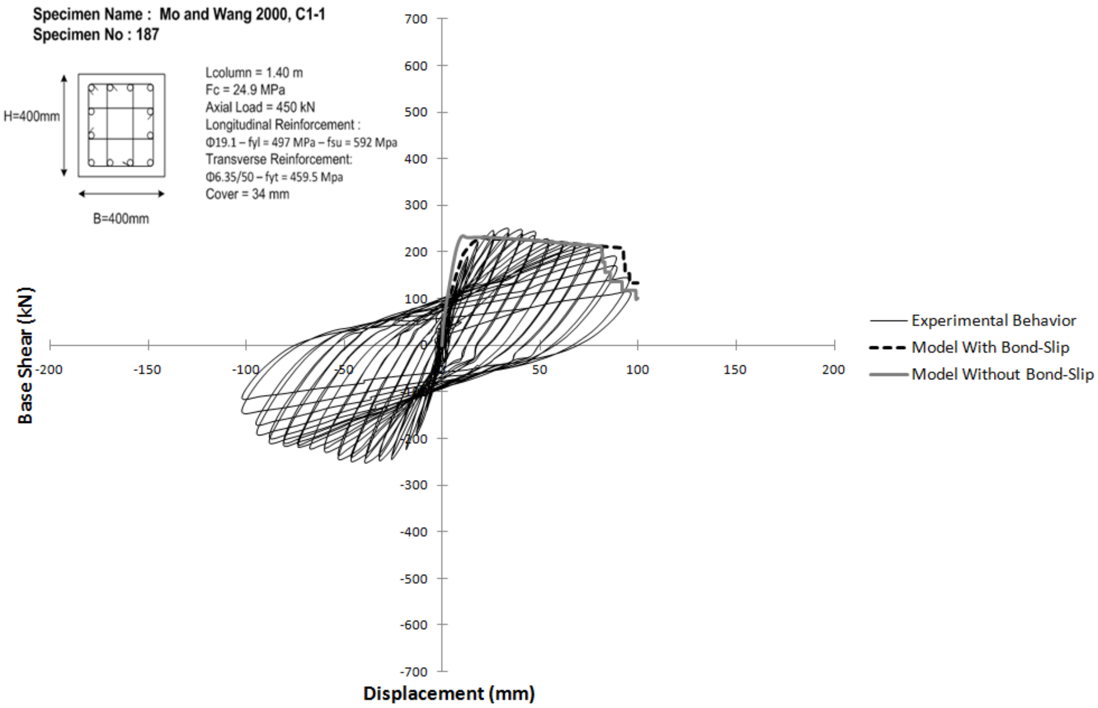

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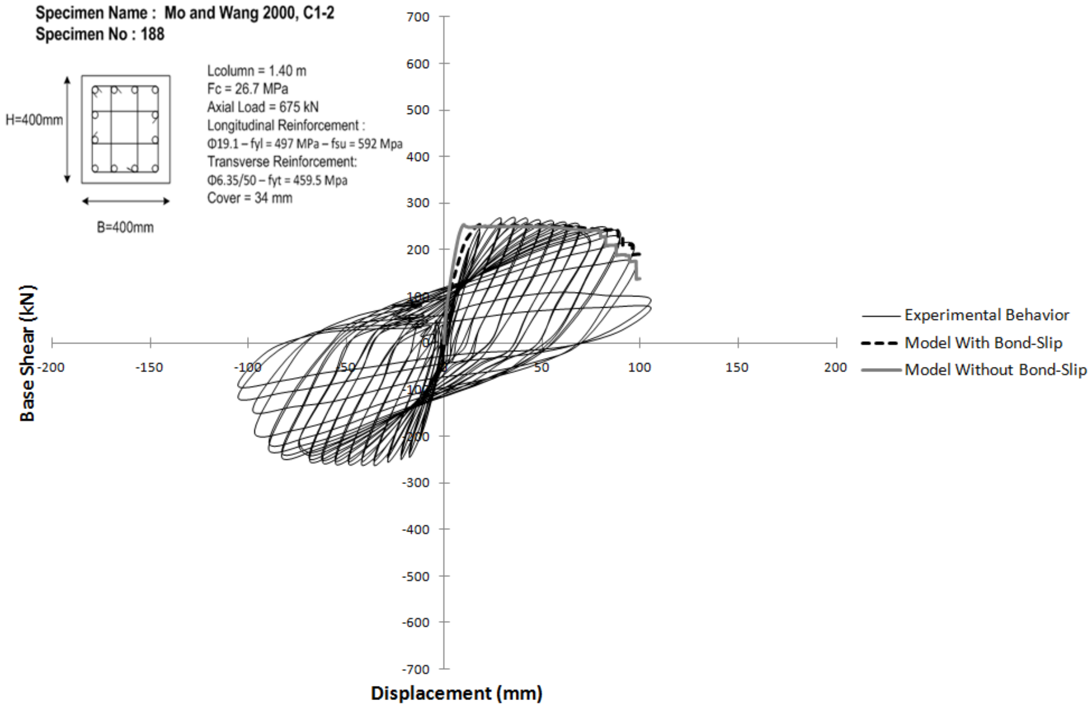

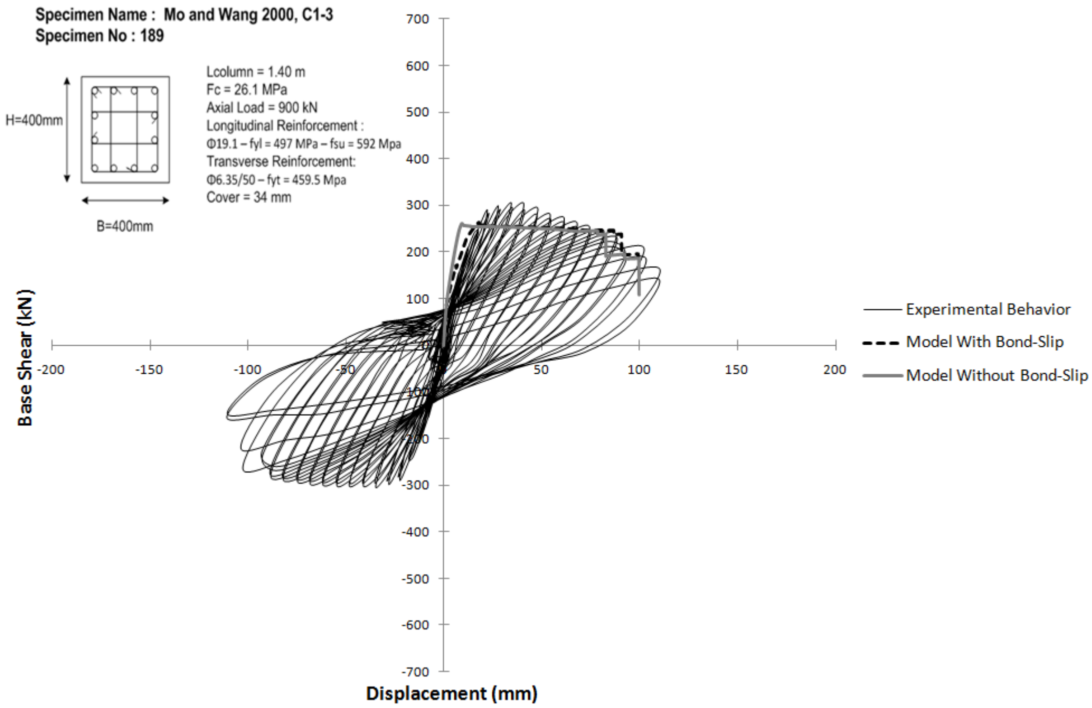

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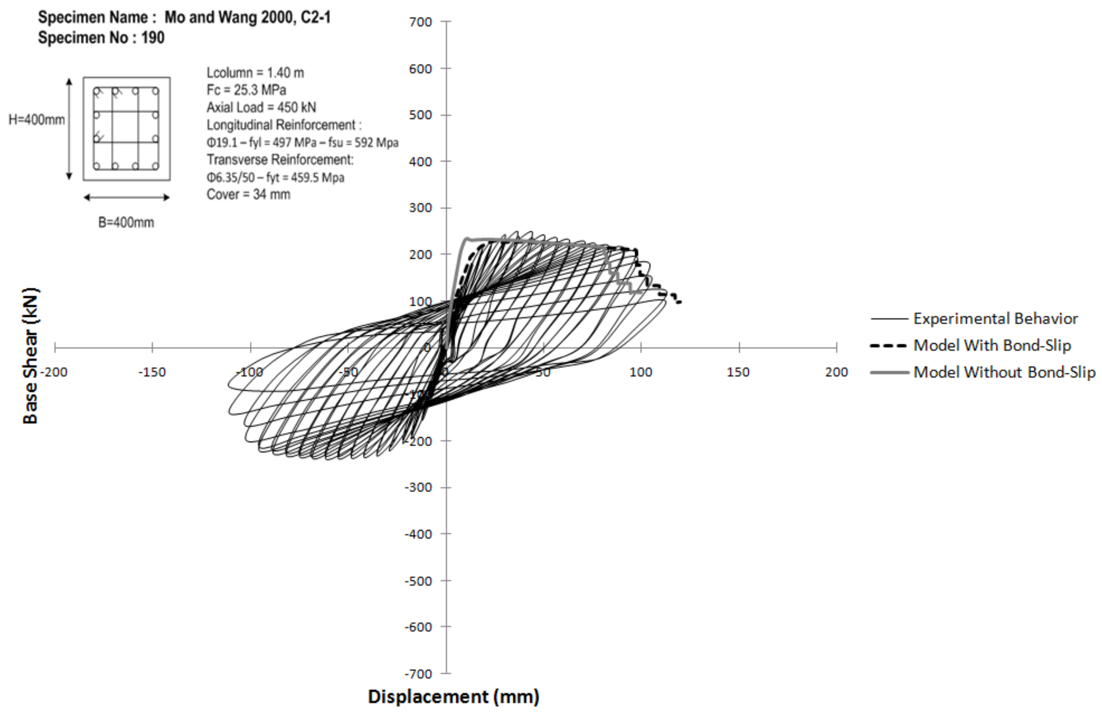

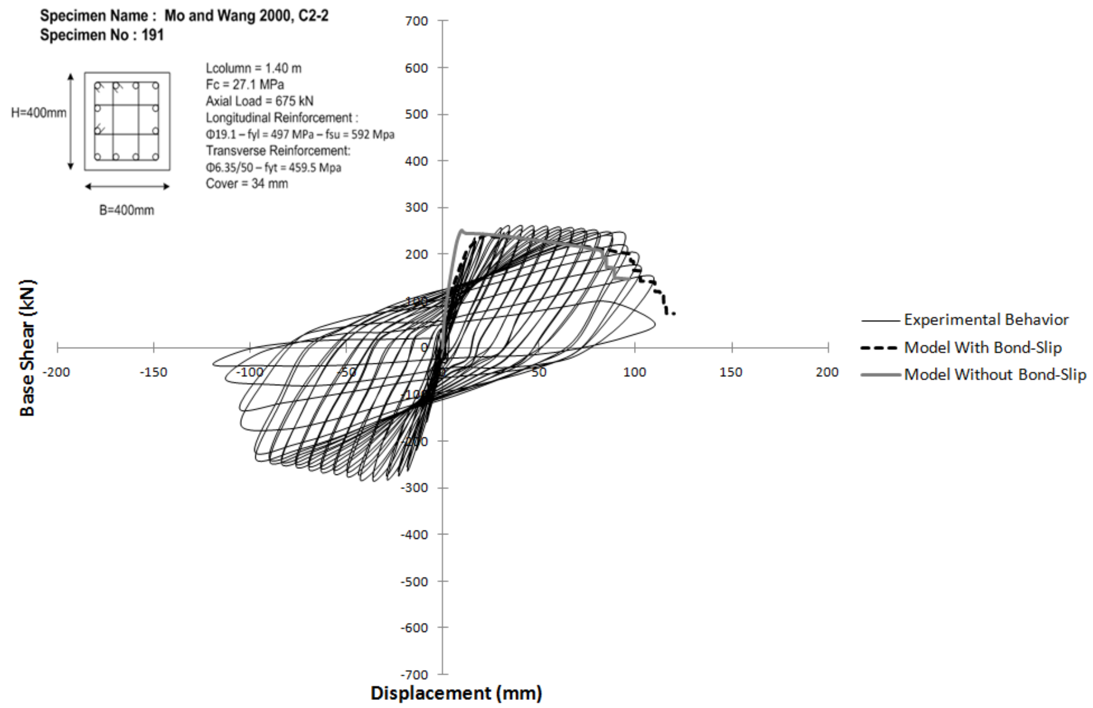

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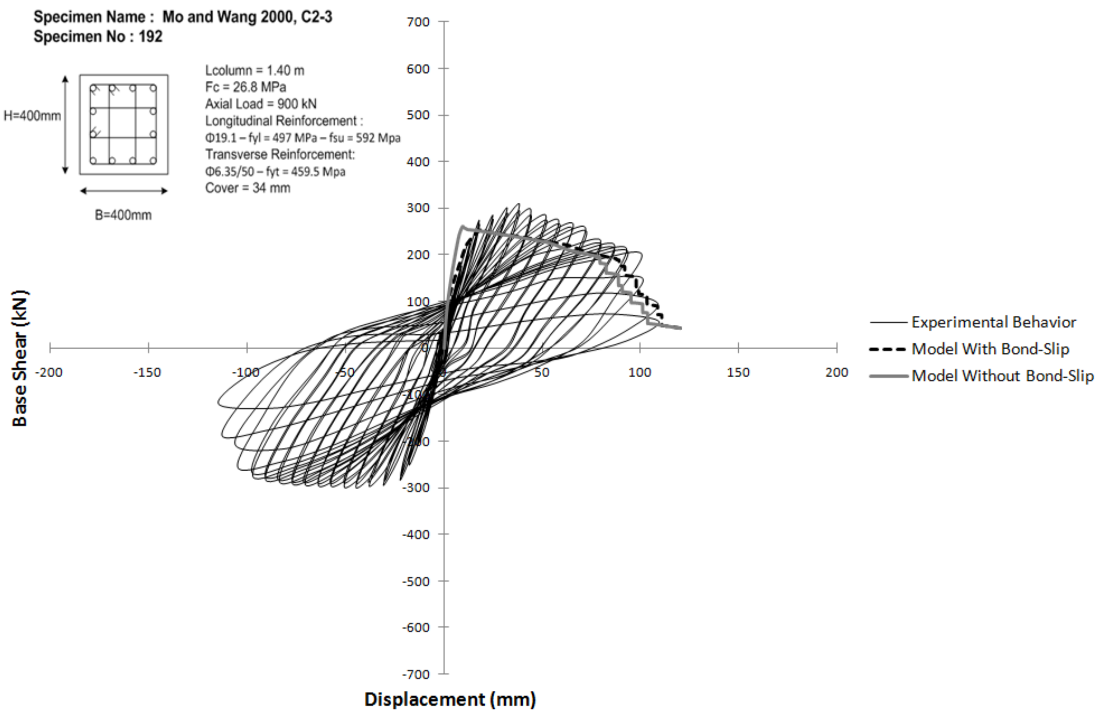

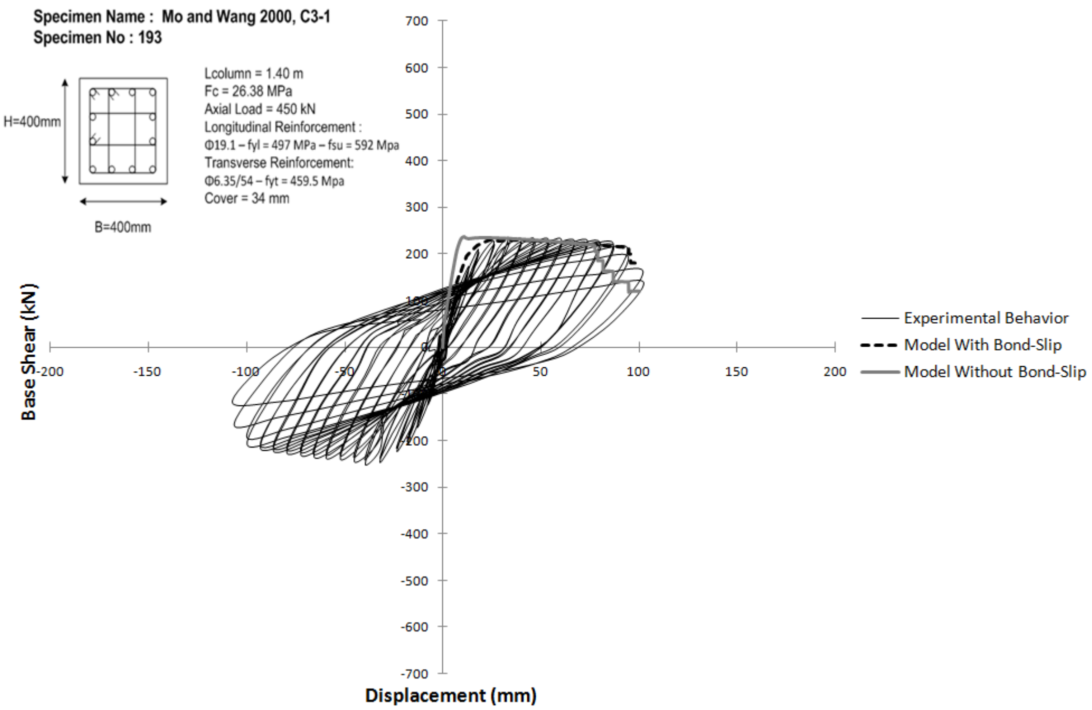

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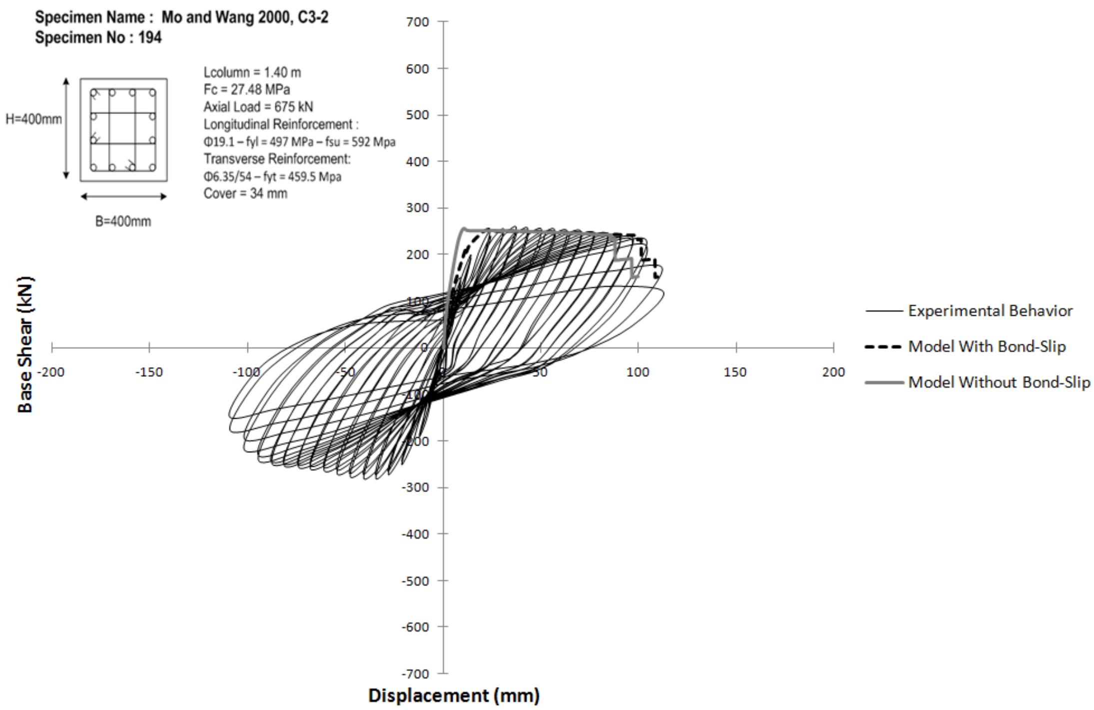

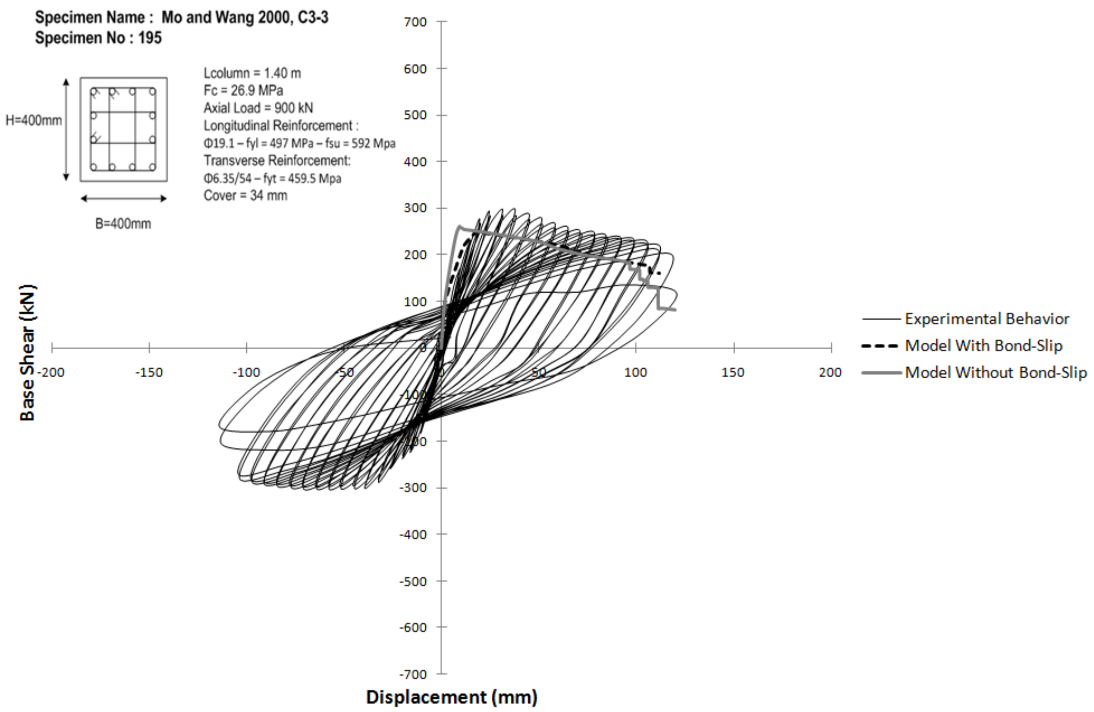

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APPENDIX B

Table B.1 Estimated Performance Limits for Performance Level of Immediate Occupancy

Specimen No	Estimated Immediate Occupancy			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	637.00	0.0068	400.02	11.06
23	614.11	0.0066	385.21	10.76
24	902.87	0.0048	534.89	7.68
25	871.97	0.0046	522.16	7.42
26	595.00	0.0052	350.00	9.26
30	163.20	0.0062	107.24	9.89
104	251.63	0.0117	279.51	11.70
106	310.04	0.0114	315.10	11.20
107	320.97	0.0096	327.55	9.51
108	322.75	0.0091	329.97	9.01
133	735.08	0.0091	319.56	21.10
134	839.34	0.0091	355.90	20.89
135	702.59	0.0091	305.43	20.96
166	283.71	0.0059	183.63	9.66
167	248.13	0.0098	160.60	16.14
169	335.00	0.0083	217.00	13.73
170	340.00	0.0083	221.00	13.56
171	332.40	0.0082	192.32	12.99
172	308.97	0.0117	184.71	18.91
173	354.05	0.0086	205.94	13.68
174	347.00	0.0086	225.00	14.11
187	310.33	0.0096	231.32	13.30
188	332.07	0.0092	255.44	12.83
189	341.56	0.0096	262.74	13.41
190	309.71	0.0107	229.76	14.74
191	332.27	0.0115	243.22	15.81
192	349.90	0.0100	255.97	13.77
193	312.18	0.0106	231.33	14.57
194	331.89	0.0108	255.30	15.06
195	347.13	0.0101	253.65	13.90

Table B.2 Estimated Performance Limits for Performance Level of Life Safety

Specimen No	Estimated Life Safety			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	639.85	0.0370	389.32	61.05
23	663.30	0.0455	382.16	77.63
24	929.54	0.0319	484.62	52.65
25	946.77	0.0389	470.45	64.20
26	686.40	0.0343	386.56	61.28
30	177.32	0.0398	112.77	63.68
104	273.14	0.0666	303.27	66.60
106	342.05	0.0775	311.41	77.48
107	346.38	0.0702	319.78	70.20
108	349.00	0.0588	329.88	58.80
133	803.83	0.0571	322.51	133.35
134	808.83	0.0311	307.40	72.75
135	790.24	0.0526	320.40	122.78
166	245.52	0.0326	159.72	53.55
167	234.29	0.0473	151.65	77.78
169	323.40	0.0420	208.50	69.00
170	338.27	0.0425	217.93	70.37
171	328.08	0.0217	165.00	35.63
172	305.00	0.0363	161.00	59.78
173	355.00	0.0229	177.50	35.58
174	336.29	0.0434	217.97	71.25
187	310.48	0.0498	214.80	69.68
188	320.80	0.0470	246.77	65.78
189	326.51	0.0466	251.17	65.18
190	314.42	0.0518	216.76	72.53
191	328.32	0.0467	217.89	65.26
192	340.03	0.0392	220.54	54.90
193	317.05	0.0502	219.43	70.28
194	319.40	0.0532	245.69	74.48
195	335.00	0.0390	208.28	54.75

Table B.3 Estimated Performance Limits for Performance Level of Collapse Prevention

Specimen No	Estimated Collapse Prevention			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	641.02	0.0493	385.00	81.40
23	682.64	0.0627	380.98	103.50
24	940.00	0.0425	465.00	70.20
25	975.00	0.0519	450.96	85.60
26	722.53	0.0458	400.92	81.70
30	182.89	0.0531	114.94	84.90
104	281.84	0.0888	312.88	88.80
106	354.55	0.1033	309.98	103.30
107	355.90	0.0936	316.82	93.60
108	359.36	0.0784	329.85	78.40
133	831.13	0.0761	323.68	177.80
134	795.00	0.0415	284.72	97.00
135	825.51	0.0701	326.03	163.70
166	230.00	0.0435	150.00	71.40
167	228.48	0.0630	147.88	103.70
169	279.60	0.0559	173.60	92.00
170	289.00	0.0567	187.50	93.82
171	324.99	0.0289	153.86	47.50
172	307.00	0.0484	147.77	79.70
173	355.60	0.0305	164.75	50.10
174	296.62	0.0578	191.25	95.00
187	310.54	0.0664	208.00	92.90
188	316.14	0.0626	243.18	87.70
189	320.22	0.0621	246.32	86.90
190	316.40	0.0691	211.32	96.70
191	325.68	0.0622	206.74	87.02
192	328.00	0.0523	204.77	73.20
193	319.11	0.0669	214.43	93.70
194	314.18	0.0709	241.68	99.30
195	328.00	0.0521	202.92	73.00

Table B.4 Estimated Drift Ratios

Specimen No	Estimated Immediate Occupancy Drift Ratio (%)	Estimated Life Safety Drift Ratio (%)	Estimated Collapse Prevention Drift Ratio (%)
22	0.68	3.70	4.93
23	0.66	4.55	6.27
24	0.48	3.19	4.25
25	0.46	3.89	5.19
26	0.52	3.43	4.58
30	0.62	3.98	5.31
104	1.17	6.66	8.88
106	1.14	7.75	10.33
107	0.96	7.02	9.36
108	0.91	5.88	7.84
133	0.91	5.71	7.61
134	0.91	3.11	4.15
135	0.91	5.26	7.01
166	0.59	3.26	4.35
167	0.98	4.73	6.30
169	0.83	4.20	5.59
170	0.83	4.25	5.67
171	0.82	2.17	2.89
172	1.17	3.63	4.84
173	0.86	2.29	3.05
174	0.86	4.34	5.78
187	0.96	4.98	6.64
188	0.92	4.70	6.26
189	0.96	4.66	6.21
190	1.07	5.18	6.91
191	1.15	4.67	6.22
192	1.00	3.92	5.23
193	1.06	5.02	6.69
194	1.08	5.32	7.09
195	1.01	3.90	5.21

Table B.5 Performance Limits Obtained by TEC (2007) for Performance Level of Immediate Occupancy

Specimen No	TEC2007 Immediate Occupancy			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	632.79	0.0128	398.13	21.10
23	608.60	0.0122	382.96	20.20
24	895.79	0.0084	533.31	13.80
25	871.97	0.0071	522.16	11.70
26	557.08	0.0071	328.01	12.70
30	161.00	0.0099	106.04	15.80
104	245.78	0.0235	273.01	23.50
106	309.68	0.0183	314.85	18.30
107	319.77	0.0165	326.53	16.50
108	322.75	0.0160	329.97	16.00
133	732.46	0.0143	318.69	33.50
134	838.86	0.0126	355.94	29.40
135	699.00	0.0139	304.21	32.40
166	281.56	0.0077	182.24	12.70
167	246.64	0.0146	159.64	24.00
169	320.04	0.0116	207.15	19.10
170	325.89	0.0114	210.93	18.80
171	330.85	0.0111	192.04	18.20
172	311.92	0.0153	186.74	25.10
173	349.16	0.0112	203.61	18.40
174	327.52	0.0116	211.99	19.10
187	310.89	0.0157	231.86	22.00
188	332.71	0.0137	255.93	19.20
189	342.01	0.0129	263.09	18.00
190	310.84	0.0181	230.76	25.30
191	334.36	0.0177	244.93	24.80
192	350.07	0.0141	256.23	19.70
193	313.62	0.0188	232.57	26.30
194	333.37	0.0174	256.44	24.40
195	348.09	0.0143	254.52	20.00

Table B.6 Performance Limits Obtained by TEC (2007) for Performance Level of Life Safety

Specimen No	TEC2007 Life Safety			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	632.24	0.0212	389.36	35.00
23	617.81	0.0209	380.28	34.50
24	913.86	0.0161	521.75	26.60
25	921.68	0.0175	522.33	28.90
26	639.64	0.0153	371.88	27.30
30	169.22	0.0219	109.94	35.00
104	261.20	0.0451	290.09	45.10
106	320.07	0.0247	321.87	24.70
107	323.99	0.0228	327.10	22.80
108	325.93	0.0205	330.56	20.50
133	761.89	0.0220	327.07	51.30
134	821.51	0.0197	337.25	46.00
135	755.13	0.0275	320.96	64.10
166	271.07	0.0112	175.45	18.40
167	247.04	0.0248	159.90	40.80
169	339.82	0.0229	219.95	37.70
170	348.93	0.0233	225.84	38.30
171	343.47	0.0229	177.08	37.60
172	307.11	0.0289	170.14	47.50
173	374.98	0.0192	204.56	31.60
174	348.11	0.0220	225.31	36.20
187	310.25	0.0253	226.91	35.40
188	326.49	0.0228	251.14	31.90
189	331.19	0.0238	254.76	33.30
190	313.35	0.0284	227.87	39.80
191	330.91	0.0272	235.64	38.10
192	343.74	0.0224	243.65	31.30
193	316.24	0.0293	229.71	41.00
194	325.95	0.0260	250.73	36.40
195	341.57	0.0224	241.99	31.30

Table B.7 Performance Limits Obtained by TEC (2007) for Performance Level of Collapse Prevention

Specimen No	TEC2007 Collapse Prevention			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	643.59	0.0272	390.80	44.80
23	635.82	0.0282	384.71	46.50
24	928.44	0.0217	514.51	35.80
25	946.95	0.0298	501.92	49.10
26	674.58	0.0251	386.18	44.80
30	175.91	0.0341	112.79	54.60
104	274.86	0.0692	305.19	69.20
106	326.58	0.0317	324.42	31.70
107	328.00	0.0253	329.80	25.30
108	328.77	0.0228	332.14	22.80
133	760.02	0.0233	325.38	54.50
134	812.59	0.0225	328.98	52.50
135	766.39	0.0317	323.34	74.10
166	268.57	0.0128	173.83	21.00
167	247.60	0.0273	160.26	44.90
169	340.88	0.0263	220.63	43.20
170	350.50	0.0275	226.86	45.30
171	339.10	0.0248	170.45	40.80
172	307.03	0.0341	164.91	56.10
173	372.51	0.0209	199.62	34.40
174	350.47	0.0258	226.84	42.40
187	311.04	0.0286	225.99	40.00
188	326.76	0.0262	251.36	36.70
189	330.49	0.0282	254.22	39.50
190	314.39	0.0319	227.05	44.70
191	331.64	0.0311	233.50	43.50
192	343.93	0.0257	240.67	36.00
193	317.26	0.0327	228.90	45.80
194	325.68	0.0307	250.52	43.00
195	341.74	0.0258	238.93	36.10

Table B.8 Drift Ratios Obtained by TEC (2007)

Specimen No	TEC2007 Immediate Occupancy	TEC2007 Life Safety	TEC2007 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
22	1.28	2.12	2.72
23	1.22	2.09	2.82
24	0.84	1.61	2.17
25	0.71	1.75	2.98
26	0.71	1.53	2.51
30	0.99	2.19	3.41
104	2.35	4.51	6.92
106	1.83	2.47	3.17
107	1.65	2.28	2.53
108	1.60	2.05	2.28
133	1.43	2.20	2.33
134	1.26	1.97	2.25
135	1.39	2.75	3.17
166	0.77	1.12	1.28
167	1.46	2.48	2.73
169	1.16	2.29	2.63
170	1.14	2.33	2.75
171	1.11	2.29	2.48
172	1.53	2.89	3.41
173	1.12	1.92	2.09
174	1.16	2.20	2.58
187	1.57	2.53	2.86
188	1.37	2.28	2.62
189	1.29	2.38	2.82
190	1.81	2.84	3.19
191	1.77	2.72	3.11
192	1.41	2.24	2.57
193	1.88	2.93	3.27
194	1.74	2.60	3.07
195	1.43	2.24	2.58

Table B.9 Performance Limits Obtained by FEMA 356 (2000) for Performance Level of Immediate Occupancy

Specimen No	FEMA356 Immediate Occupancy			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	621.90	0.0113	392.56	18.60
23	594.79	0.0104	366.47	14.30
24	903.19	0.0094	534.92	15.50
25	882.86	0.0090	523.40	14.80
26	585.87	0.0083	344.43	14.80
30	161.84	0.0106	106.51	16.90
104	218.58	0.0138	242.82	13.80
106	288.61	0.0140	295.27	14.00
107	294.67	0.0123	302.66	12.30
108	300.25	0.0121	308.65	12.10
133	748.86	0.0166	324.63	38.70
134	814.51	0.0113	347.07	26.30
135	673.96	0.0119	294.25	27.70
166	272.23	0.0104	176.20	17.10
167	238.21	0.0126	154.18	20.70
169	330.09	0.0144	213.65	23.70
170	336.54	0.0141	217.82	23.20
171	340.77	0.0138	193.10	22.70
172	306.87	0.0145	184.25	23.80
173	364.66	0.0135	209.10	22.20
174	337.53	0.0143	218.47	23.50
187	301.79	0.0131	226.07	18.30
188	327.68	0.0125	252.06	17.50
189	337.54	0.0132	259.65	18.50
190	297.70	0.0140	222.51	19.60
191	323.14	0.0146	238.40	20.50
192	347.68	0.0136	254.85	19.00
193	297.29	0.0138	222.30	19.30
194	320.12	0.0138	246.25	19.30
195	347.19	0.0141	254.02	19.70

Table B.10 Performance Limits Obtained by FEMA 356 (2000) for Performance Level of Life Safety

Specimen No	FEMA356 Life Safety			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	630.88	0.0206	389.08	34.00
23	616.70	0.0204	378.91	30.80
24	921.48	0.0187	518.86	30.90
25	924.21	0.0183	521.59	30.20
26	653.51	0.0183	378.15	32.70
30	168.34	0.0206	109.52	33.00
104	246.16	0.0238	273.44	23.80
106	318.83	0.0238	321.12	23.80
107	322.97	0.0222	326.40	22.20
108	327.77	0.0220	331.57	22.00
133	762.85	0.0216	327.71	50.50
134	817.99	0.0208	333.97	48.60
135	736.91	0.0219	316.25	51.10
166	259.15	0.0194	167.73	31.90
167	245.99	0.0223	159.22	36.70
169	339.93	0.0234	220.02	38.50
170	348.86	0.0231	225.80	38.00
171	343.59	0.0228	177.28	37.50
172	306.64	0.0240	174.66	39.50
173	369.84	0.0225	194.80	37.00
174	349.00	0.0233	225.89	38.40
187	309.40	0.0230	227.32	32.20
188	326.42	0.0223	251.09	31.20
189	331.29	0.0228	254.84	31.90
190	311.14	0.0240	228.23	33.60
191	329.92	0.0244	236.88	34.10
192	343.83	0.0232	242.92	32.50
193	313.13	0.0238	229.87	33.30
194	325.75	0.0235	250.57	32.90
195	341.69	0.0237	240.82	33.20

Table B.11 Performance Limits Obtained by FEMA 356 (2000) for Performance Level of Collapse Prevention

Specimen No	FEMA356 Collapse Prevention			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	641.18	0.0256	390.74	42.30
23	628.43	0.0254	381.60	39.20
24	929.91	0.0224	513.30	37.00
25	934.76	0.0220	517.27	36.30
26	671.22	0.0233	385.39	41.60
30	171.66	0.0256	111.08	41.00
104	251.72	0.0288	279.60	28.80
106	323.86	0.0285	323.52	28.50
107	330.45	0.0270	331.33	27.00
108	331.11	0.0269	332.08	26.90
133	758.32	0.0266	322.56	62.20
134	804.66	0.0248	321.81	58.00
135	753.54	0.0269	320.56	62.90
166	254.32	0.0224	164.61	36.90
167	247.59	0.0266	160.25	43.80
169	340.92	0.0264	220.66	43.50
170	350.14	0.0261	226.63	43.00
171	336.50	0.0258	166.74	42.50
172	307.08	0.0282	170.78	46.40
173	362.77	0.0255	184.27	42.00
174	350.62	0.0263	226.94	43.30
187	310.90	0.0279	226.18	39.10
188	326.76	0.0269	251.35	37.70
189	330.70	0.0271	254.38	38.00
190	313.51	0.0289	227.76	40.50
191	331.34	0.0291	234.62	40.80
192	343.89	0.0275	238.98	38.50
193	316.04	0.0287	229.82	40.20
194	326.02	0.0282	250.79	39.50
195	341.70	0.0280	236.83	39.20

Table B.12 Drift Ratios Obtained by FEMA 356 (2000)

Specimen No	FEMA356 Immediate Occupancy	FEMA356 Life Safety	FEMA356 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
22	1.13	2.06	2.56
23	1.04	2.04	2.54
24	0.94	1.87	2.24
25	0.90	1.83	2.20
26	0.83	1.83	2.33
30	1.06	2.06	2.56
104	1.38	2.38	2.88
106	1.40	2.38	2.85
107	1.23	2.22	2.70
108	1.21	2.20	2.69
133	1.66	2.16	2.66
134	1.13	2.08	2.48
135	1.19	2.19	2.69
166	1.04	1.94	2.24
167	1.26	2.23	2.66
169	1.44	2.34	2.64
170	1.41	2.31	2.61
171	1.38	2.28	2.58
172	1.45	2.40	2.82
173	1.35	2.25	2.55
174	1.43	2.33	2.63
187	1.31	2.30	2.79
188	1.25	2.23	2.69
189	1.32	2.28	2.71
190	1.40	2.40	2.89
191	1.46	2.44	2.91
192	1.36	2.32	2.75
193	1.38	2.38	2.87
194	1.38	2.35	2.82
195	1.41	2.37	2.80

Table B.13 Performance Limits Obtained by Eurocode 8 (2003) for Performance Level of Damage Limitation

Specimen No	Eurocode8 Damage Limitation			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	600.84	0.0091	381.04	15.00
23	575.52	0.0085	365.20	14.00
24	876.37	0.0099	516.54	16.40
25	891.06	0.0099	525.84	16.30
26	531.22	0.0063	313.13	11.20
30	157.78	0.0080	104.14	12.80
104	168.79	0.0078	187.52	7.80
106	249.03	0.0090	256.64	9.00
107	269.78	0.0091	278.40	9.10
108	276.26	0.0090	285.28	9.00
133	629.98	0.0085	276.51	19.80
134	749.59	0.0090	321.43	21.10
135	608.16	0.0089	266.64	20.70
166	266.34	0.0144	172.39	23.70
167	234.13	0.0118	151.54	19.40
169	327.60	0.0135	212.04	22.20
170	334.71	0.0134	216.64	22.00
171	339.20	0.0134	192.92	22.00
172	281.20	0.0116	170.50	19.00
173	358.26	0.0123	207.35	20.20
174	331.11	0.0126	214.31	20.70
187	287.65	0.0107	216.27	15.00
188	317.10	0.0109	243.93	15.30
189	323.60	0.0107	248.92	15.00
190	276.33	0.0106	207.61	14.90
191	295.87	0.0108	220.08	15.10
192	331.02	0.0112	244.20	15.70
193	275.83	0.0105	207.29	14.70
194	293.37	0.0103	225.67	14.40
195	327.50	0.0113	241.43	15.80

Table B.14 Performance Limits Obtained by Eurocode 8 (2003) for Performance Level of Significant Damage

Specimen No	Eurocode8 Significant Damage			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	643.32	0.0270	390.81	44.50
23	632.63	0.0270	383.85	44.50
24	929.19	0.0221	513.91	36.40
25	934.92	0.0221	517.19	36.40
26	694.71	0.0330	392.93	58.80
30	172.34	0.0268	111.38	42.90
104	250.59	0.0276	278.35	27.60
106	319.12	0.0240	321.30	24.00
107	326.77	0.0245	328.99	24.50
108	329.58	0.0248	331.76	24.80
133	761.63	0.0293	322.33	68.30
134	805.25	0.0247	322.34	57.60
135	755.13	0.0275	320.96	64.10
166	252.75	0.0235	163.59	38.70
167	247.68	0.0309	160.31	50.90
169	339.71	0.0225	219.88	37.00
170	348.59	0.0225	225.63	37.00
171	346.44	0.0213	181.97	35.10
172	307.07	0.0281	170.90	46.20
173	371.86	0.0213	198.37	35.10
174	350.65	0.0265	226.96	43.60
187	311.33	0.0301	225.48	42.20
188	326.71	0.0284	251.31	39.80
189	330.27	0.0293	254.05	41.00
190	314.79	0.0334	226.66	46.80
191	331.68	0.0314	233.29	44.00
192	343.80	0.0294	237.18	41.10
193	317.46	0.0334	228.72	46.80
194	325.57	0.0315	250.44	44.10
195	341.62	0.0297	235.18	41.60

Table B.15 Performance Limits Obtained by Eurocode 8 (2003) for Performance Level of Near Collapse

Specimen No	Eurocode8 Near Collapse			
	Moment (kNm)	Chord Rotation (rad)	Base Shear (kN)	Displacement (mm)
22	655.64	0.0360	389.77	59.40
23	653.96	0.0360	388.70	59.40
24	935.63	0.0295	495.79	48.70
25	946.55	0.0295	502.38	48.70
26	720.00	0.0440	400.62	78.50
30	176.45	0.0357	112.95	57.10
104	255.61	0.0368	283.90	36.80
106	326.80	0.0320	324.48	32.00
107	333.37	0.0325	331.05	32.50
108	336.29	0.0330	333.78	33.00
133	772.93	0.0390	321.32	91.00
134	789.77	0.0329	302.85	76.80
135	775.87	0.0366	324.56	85.50
166	248.22	0.0313	160.66	51.50
167	234.97	0.0412	152.08	67.80
169	340.42	0.0302	220.34	49.70
170	350.99	0.0303	227.18	49.90
171	327.17	0.0284	155.56	46.80
172	306.43	0.0376	161.04	61.90
173	352.39	0.0285	171.68	46.90
174	349.67	0.0353	226.33	58.10
187	311.60	0.0402	221.00	56.30
188	325.57	0.0380	250.44	53.20
189	327.23	0.0390	251.71	54.60
190	316.22	0.0445	222.61	62.30
191	331.62	0.0419	225.91	58.70
192	342.71	0.0392	227.15	54.90
193	319.27	0.0445	224.97	62.30
194	322.98	0.0420	248.45	58.80
195	340.63	0.0395	225.30	55.30

Table B.16 Drift Ratios Obtained by Eurocode 8 (2003)

Specimen No	EC8 Damage Limitation	EC8 Significant Damage	EC8 Near Collapse
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
22	0.91	2.70	3.60
23	0.85	2.70	3.60
24	0.99	2.21	2.95
25	0.99	2.21	2.95
26	0.63	3.30	4.40
30	0.80	2.68	3.57
104	0.78	2.76	3.68
106	0.90	2.40	3.20
107	0.91	2.45	3.25
108	0.90	2.48	3.30
133	0.85	2.93	3.90
134	0.90	2.47	3.29
135	0.89	2.75	3.66
166	1.44	2.35	3.13
167	1.18	3.09	4.12
169	1.35	2.25	3.02
170	1.34	2.25	3.03
171	1.34	2.13	2.84
172	1.16	2.81	3.76
173	1.23	2.13	2.85
174	1.26	2.65	3.53
187	1.07	3.01	4.02
188	1.09	2.84	3.80
189	1.07	2.93	3.90
190	1.06	3.34	4.45
191	1.08	3.14	4.19
192	1.12	2.94	3.92
193	1.05	3.34	4.45
194	1.03	3.15	4.20
195	1.13	2.97	3.95

APPENDIX C

Table C.1 Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
1	400x400	10	0.10	0.01	220	0.0075	420	400	375	160.00	160000	115.47	82.76	100	130.34	222.72	56.00	3.98	Flexure
2	400x400	10	0.10	0.01	220	0.0200	420	400	375	160.00	160000	115.47	220.69	100	347.59	439.96	56.00	7.86	Flexure
3	400x400	10	0.10	0.01	420	0.0075	420	400	375	160.00	160000	115.47	82.76	100	130.34	222.72	92.00	2.42	Flexure
4	400x400	10	0.10	0.01	420	0.0200	420	400	375	160.00	160000	115.47	220.69	100	347.59	439.96	92.00	4.78	Flexure
5	400x400	10	0.25	0.01	220	0.0075	420	400	375	400.00	160000	126.80	82.76	100	130.34	231.78	73.00	3.18	Flexure
6	400x400	10	0.25	0.01	220	0.0200	420	400	375	400.00	160000	126.80	220.69	100	347.59	449.02	73.00	6.15	Flexure
7	400x400	10	0.25	0.01	420	0.0075	420	400	375	400.00	160000	126.80	82.76	100	130.34	231.78	100.00	2.32	Flexure
8	400x400	10	0.25	0.01	420	0.0200	420	400	375	400.00	160000	126.80	220.69	100	347.59	449.02	109.00	4.12	Flexure
9	400x400	10	0.40	0.01	220	0.0075	420	400	375	640.00	160000	138.13	82.76	100	130.34	240.85	77.00	3.13	Flexure
10	400x400	10	0.40	0.01	220	0.0200	420	400	375	640.00	160000	138.13	220.69	100	347.59	458.09	87.00	5.27	Flexure
11	400x400	10	0.40	0.01	420	0.0075	420	400	375	640.00	160000	138.13	82.76	100	130.34	240.85	105.00	2.29	Flexure
12	400x400	10	0.40	0.01	420	0.0200	420	400	375	640.00	160000	138.13	220.69	100	347.59	458.09	115.00	3.98	Flexure
13	400x400	14	0.10	0.01	220	0.0075	420	400	375	224.00	160000	140.20	82.76	100	130.34	242.50	62.00	3.91	Flexure
14	400x400	14	0.10	0.01	220	0.0200	420	400	375	224.00	160000	140.20	220.69	100	347.59	459.74	62.00	7.42	Flexure
15	400x400	14	0.10	0.01	420	0.0075	420	400	375	224.00	160000	140.20	82.76	100	130.34	242.50	98.00	2.47	Flexure
16	400x400	14	0.10	0.01	420	0.0200	420	400	375	224.00	160000	140.20	220.69	100	347.59	459.74	98.00	4.69	Flexure
17	400x400	14	0.25	0.01	220	0.0075	420	400	375	560.00	160000	158.97	82.76	100	130.34	257.52	84.00	3.07	Flexure
18	400x400	14	0.25	0.01	220	0.0200	420	400	375	560.00	160000	158.97	220.69	100	347.59	474.76	87.00	5.46	Flexure
19	400x400	14	0.25	0.01	420	0.0075	420	400	375	560.00	160000	158.97	82.76	100	130.34	257.52	123.00	2.09	Flexure
20	400x400	14	0.25	0.01	420	0.0200	420	400	375	560.00	160000	158.97	220.69	100	347.59	474.76	120.00	3.96	Flexure
21	400x400	14	0.40	0.01	220	0.0075	420	400	375	896.00	160000	177.74	82.76	100	130.34	272.53	92.00	2.96	Flexure
22	400x400	14	0.40	0.01	220	0.0200	420	400	375	896.00	160000	177.74	220.69	100	347.59	489.78	98.00	5.00	Flexure
23	400x400	14	0.40	0.01	420	0.0075	420	400	375	896.00	160000	177.74	82.76	100	130.34	272.53	130.00	2.10	Flexure
24	400x400	14	0.40	0.01	420	0.0200	420	400	375	896.00	160000	177.74	220.69	100	347.59	489.78	127.00	3.86	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.1 (cont'd) Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
25	400x400	20	0.10	0.01	220	0.0075	420	400	375	320.00	160000	173.98	82.76	100	130.34	269.53	70.00	3.85	Flexure
26	400x400	20	0.10	0.01	220	0.0200	420	400	375	320.00	160000	173.98	220.69	100	347.59	486.77	70.00	6.95	Flexure
27	400x400	20	0.10	0.01	420	0.0075	420	400	375	320.00	160000	173.98	82.76	100	130.34	269.53	107.00	2.52	Flexure
28	400x400	20	0.10	0.01	420	0.0200	420	400	375	320.00	160000	173.98	220.69	100	347.59	486.77	107.00	4.55	Flexure
29	400x400	20	0.25	0.01	220	0.0075	420	400	375	800.00	160000	206.03	82.76	100	130.34	295.17	106.00	2.78	Flexure
30	400x400	20	0.25	0.01	220	0.0200	420	400	375	800.00	160000	206.03	220.69	100	347.59	512.41	107.00	4.79	Flexure
31	400x400	20	0.25	0.01	420	0.0075	420	400	375	800.00	160000	206.03	82.76	100	130.34	295.17	130.00	2.27	Flexure
32	400x400	20	0.25	0.01	420	0.0200	420	400	375	800.00	160000	206.03	220.69	100	347.59	512.41	140.00	3.66	Flexure
33	400x400	20	0.40	0.01	220	0.0075	420	400	375	1,280.00	160000	238.07	82.76	100	130.34	320.80	140.00	2.29	Flexure
34	400x400	20	0.40	0.01	220	0.0200	420	400	375	1,280.00	160000	238.07	220.69	100	347.59	538.05	118.00	4.56	Flexure
35	400x400	20	0.40	0.01	420	0.0075	420	400	375	1,280.00	160000	238.07	82.76	100	130.34	320.80	140.00	2.29	Flexure
36	400x400	20	0.40	0.01	420	0.0200	420	400	375	1,280.00	160000	238.07	220.69	100	347.59	538.05	150.00	3.59	Flexure
37	500x500	10	0.10	0.01	220	0.0075	420	500	475	250.00	250000	182.82	101.35	100	202.20	348.45	110.00	3.17	Flexure
38	500x500	10	0.10	0.01	220	0.0200	420	500	475	250.00	250000	182.82	270.27	100	539.19	685.45	110.00	6.23	Flexure
39	500x500	10	0.10	0.01	420	0.0075	420	500	475	250.00	250000	182.82	101.35	100	202.20	348.45	185.00	1.88	Flexure
40	500x500	10	0.10	0.01	420	0.0200	420	500	475	250.00	250000	182.82	270.27	100	539.19	685.45	185.00	3.71	Flexure
41	500x500	10	0.25	0.01	220	0.0075	420	500	475	625.00	250000	200.76	101.35	100	202.20	362.81	142.00	2.55	Flexure
42	500x500	10	0.25	0.01	220	0.0200	420	500	475	625.00	250000	200.76	270.27	100	539.19	699.80	150.00	4.67	Flexure
43	500x500	10	0.25	0.01	420	0.0075	420	500	475	625.00	250000	200.76	101.35	100	202.20	362.81	200.00	1.81	Flexure
44	500x500	10	0.25	0.01	420	0.0200	420	500	475	625.00	250000	200.76	270.27	100	539.19	699.80	215.00	3.25	Flexure
45	500x500	10	0.40	0.01	220	0.0075	420	500	475	1,000.00	250000	218.70	101.35	100	202.20	377.16	155.00	2.43	Flexure
46	500x500	10	0.40	0.01	220	0.0200	420	500	475	1,000.00	250000	218.70	270.27	100	539.19	714.15	170.00	4.20	Flexure
47	500x500	10	0.40	0.01	420	0.0075	420	500	475	1,000.00	250000	218.70	101.35	100	202.20	377.16	210.00	1.80	Flexure
48	500x500	10	0.40	0.01	420	0.0200	420	500	475	1,000.00	250000	218.70	270.27	100	539.19	714.15	225.00	3.17	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.1 (cont'd) Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
49	500x500	14	0.10	0.01	220	0.0075	420	500	475	350.00	250000	221.98	101.35	100	202.20	379.78	123.00	3.09	Flexure
50	500x500	14	0.10	0.01	220	0.0200	420	500	475	350.00	250000	221.98	270.27	100	539.19	716.77	123.00	5.83	Flexure
51	500x500	14	0.10	0.01	420	0.0075	420	500	475	350.00	250000	221.98	101.35	100	202.20	379.78	200.00	1.90	Flexure
52	500x500	14	0.10	0.01	420	0.0200	420	500	475	350.00	250000	221.98	270.27	100	539.19	716.77	200.00	3.58	Flexure
53	500x500	14	0.25	0.01	220	0.0075	420	500	475	875.00	250000	251.70	101.35	100	202.20	403.55	170.00	2.37	Flexure
54	500x500	14	0.25	0.01	220	0.0200	420	500	475	875.00	250000	251.70	270.27	100	539.19	740.55	178.00	4.16	Flexure
55	500x500	14	0.25	0.01	420	0.0075	420	500	475	875.00	250000	251.70	101.35	100	202.20	403.55	230.00	1.75	Flexure
56	500x500	14	0.25	0.01	420	0.0200	420	500	475	875.00	250000	251.70	270.27	100	539.19	740.55	241.00	3.07	Flexure
57	500x500	14	0.40	0.01	220	0.0075	420	500	475	1,400.00	250000	281.42	101.35	100	202.20	427.33	190.00	2.25	Flexure
58	500x500	14	0.40	0.01	220	0.0200	420	500	475	1,400.00	250000	281.42	270.27	100	539.19	764.32	200.00	3.82	Flexure
59	500x500	14	0.40	0.01	420	0.0075	420	500	475	1,400.00	250000	281.42	101.35	100	202.20	427.33	247.00	1.73	Flexure
60	500x500	14	0.40	0.01	420	0.0200	420	500	475	1,400.00	250000	281.42	270.27	100	539.19	764.32	262.00	2.92	Flexure
61	500x500	20	0.10	0.01	220	0.0075	420	500	475	500.00	250000	275.46	101.35	100	202.20	422.57	140.00	3.02	Flexure
62	500x500	20	0.10	0.01	220	0.0200	420	500	475	500.00	250000	275.46	270.27	100	539.19	759.56	140.00	5.43	Flexure
63	500x500	20	0.10	0.01	420	0.0075	420	500	475	500.00	250000	275.46	101.35	100	202.20	422.57	213.00	1.98	Flexure
64	500x500	20	0.10	0.01	420	0.0200	420	500	475	500.00	250000	275.46	270.27	100	539.19	759.56	212.00	3.58	Flexure
65	500x500	20	0.25	0.01	220	0.0075	420	500	475	1,250.00	250000	326.21	101.35	100	202.20	463.16	205.00	2.26	Flexure
66	500x500	20	0.25	0.01	220	0.0200	420	500	475	1,250.00	250000	326.21	270.27	100	539.19	800.16	218.00	3.67	Flexure
67	500x500	20	0.25	0.01	420	0.0075	420	500	475	1,250.00	250000	326.21	101.35	100	202.20	463.16	272.00	1.70	Flexure
68	500x500	20	0.25	0.01	420	0.0200	420	500	475	1,250.00	250000	326.21	270.27	100	539.19	800.16	272.00	2.94	Flexure
69	500x500	20	0.40	0.01	220	0.0075	420	500	475	2,000.00	250000	376.95	101.35	100	202.20	503.76	307.00	1.64	Flexure
70	500x500	20	0.40	0.01	220	0.0200	420	500	475	2,000.00	250000	376.95	270.27	100	539.19	840.75	240.00	3.50	Flexure
71	500x500	20	0.40	0.01	420	0.0075	420	500	475	2,000.00	250000	376.95	101.35	100	202.20	503.76	300.00	1.68	Flexure
72	500x500	20	0.40	0.01	420	0.0200	420	500	475	2,000.00	250000	376.95	270.27	100	539.19	840.75	290.00	2.90	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.1 (cont'd) Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	$ρ_s$	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
73	300x500	10	0.10	0.01	220	0.0075	420	300	475	150.00	150000	109.69	77.59	100	154.78	242.54	68.00	3.57	Flexure
74	300x500	10	0.10	0.01	220	0.0200	420	300	475	150.00	150000	109.69	206.90	100	412.76	500.51	68.00	7.36	Flexure
75	300x500	10	0.10	0.01	420	0.0075	420	300	475	150.00	150000	109.69	77.59	100	154.78	242.54	112.00	2.17	Flexure
76	300x500	10	0.10	0.01	420	0.0200	420	300	475	150.00	150000	109.69	206.90	100	412.76	500.51	112.00	4.47	Flexure
77	300x500	10	0.25	0.01	220	0.0075	420	300	475	375.00	150000	120.46	77.59	100	154.78	251.15	90.00	2.79	Flexure
78	300x500	10	0.25	0.01	220	0.0200	420	300	475	375.00	150000	120.46	206.90	100	412.76	509.12	91.00	5.59	Flexure
79	300x500	10	0.25	0.01	420	0.0075	420	300	475	375.00	150000	120.46	77.59	100	154.78	251.15	122.00	2.06	Flexure
80	300x500	10	0.25	0.01	420	0.0200	420	300	475	375.00	150000	120.46	206.90	100	412.76	509.12	135.00	3.77	Flexure
81	300x500	10	0.40	0.01	220	0.0075	420	300	475	600.00	150000	131.22	77.59	100	154.78	259.76	93.00	2.79	Flexure
82	300x500	10	0.40	0.01	220	0.0200	420	300	475	600.00	150000	131.22	206.90	100	412.76	517.74	103.00	5.03	Flexure
83	300x500	10	0.40	0.01	420	0.0075	420	300	475	600.00	150000	131.22	77.59	100	154.78	259.76	128.00	2.03	Flexure
84	300x500	10	0.40	0.01	420	0.0200	420	300	475	600.00	150000	131.22	206.90	100	412.76	517.74	139.00	3.72	Flexure
85	300x500	14	0.10	0.01	220	0.0075	420	300	475	210.00	150000	133.19	77.59	100	154.78	261.33	75.40	3.47	Flexure
86	300x500	14	0.10	0.01	220	0.0200	420	300	475	210.00	150000	133.19	206.90	100	412.76	519.31	75.40	6.89	Flexure
87	300x500	14	0.10	0.01	420	0.0075	420	300	475	210.00	150000	133.19	77.59	100	154.78	261.33	120.00	2.18	Flexure
88	300x500	14	0.10	0.01	420	0.0200	420	300	475	210.00	150000	133.19	206.90	100	412.76	519.31	120.00	4.33	Flexure
89	300x500	14	0.25	0.01	220	0.0075	420	300	475	525.00	150000	151.02	77.59	100	154.78	275.60	106.00	2.60	Flexure
90	300x500	14	0.25	0.01	220	0.0200	420	300	475	525.00	150000	151.02	206.90	100	412.76	533.57	108.00	4.94	Flexure
91	300x500	14	0.25	0.01	420	0.0075	420	300	475	525.00	150000	151.02	77.59	100	154.78	275.60	142.00	1.94	Flexure
92	300x500	14	0.25	0.01	420	0.0200	420	300	475	525.00	150000	151.02	206.90	100	412.76	533.57	149.00	3.58	Flexure
93	300x500	14	0.40	0.01	220	0.0075	420	300	475	840.00	150000	168.85	77.59	100	154.78	289.86	111.00	2.61	Flexure
94	300x500	14	0.40	0.01	220	0.0200	420	300	475	840.00	150000	168.85	206.90	100	412.76	547.84	121.00	4.53	Flexure
95	300x500	14	0.40	0.01	420	0.0075	420	300	475	840.00	150000	168.85	77.59	100	154.78	289.86	149.00	1.95	Flexure
96	300x500	14	0.40	0.01	420	0.0200	420	300	475	840.00	150000	168.85	206.90	100	412.76	547.84	158.00	3.47	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.1 (cont'd) Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
97	300x500	20	0.10	0.01	220	0.0075	420	300	475	300.00	150000	165.28	77.59	100	154.78	287.01	86.20	3.33	Flexure
98	300x500	20	0.10	0.01	220	0.0200	420	300	475	300.00	150000	165.28	206.90	100	412.76	544.98	86.20	6.32	Flexure
99	300x500	20	0.10	0.01	420	0.0075	420	300	475	300.00	150000	165.28	77.59	100	154.78	287.01	131.00	2.19	Flexure
100	300x500	20	0.10	0.01	420	0.0200	420	300	475	300.00	150000	165.28	206.90	100	412.76	544.98	131.00	4.16	Flexure
101	300x500	20	0.25	0.01	220	0.0075	420	300	475	750.00	150000	195.72	77.59	100	154.78	311.36	128.00	2.43	Flexure
102	300x500	20	0.25	0.01	220	0.0200	420	300	475	750.00	150000	195.72	206.90	100	412.76	569.34	133.00	4.28	Flexure
103	300x500	20	0.25	0.01	420	0.0075	420	300	475	750.00	150000	195.72	77.59	100	154.78	311.36	166.00	1.88	Flexure
104	300x500	20	0.25	0.01	420	0.0200	420	300	475	750.00	150000	195.72	206.90	100	412.76	569.34	173.00	3.29	Flexure
105	300x500	20	0.40	0.01	220	0.0075	420	300	475	1,200.00	150000	226.17	77.59	100	154.78	335.72	140.00	2.40	Flexure
106	300x500	20	0.40	0.01	220	0.0200	420	300	475	1,200.00	150000	226.17	206.90	100	412.76	593.69	147.00	4.04	Flexure
107	300x500	20	0.40	0.01	420	0.0075	420	300	475	1,200.00	150000	226.17	77.59	100	154.78	335.72	176.00	1.91	Flexure
108	300x500	20	0.40	0.01	420	0.0200	420	300	475	1,200.00	150000	226.17	206.90	100	412.76	593.69	186.00	3.19	Flexure
109	300x600	10	0.10	0.01	220	0.0075	420	300	575	180.00	180000	132.79	81.82	100	197.59	303.82	97.90	3.10	Flexure
110	300x600	10	0.10	0.01	220	0.0200	420	300	575	180.00	180000	132.79	218.18	100	526.91	633.14	98.00	6.46	Flexure
111	300x600	10	0.10	0.01	420	0.0075	420	300	575	180.00	180000	132.79	81.82	100	197.59	303.82	161.00	1.89	Flexure
112	300x600	10	0.10	0.01	420	0.0200	420	300	575	180.00	180000	132.79	218.18	100	526.91	633.14	162.00	3.91	Flexure
113	300x600	10	0.25	0.01	220	0.0075	420	300	575	450.00	180000	145.82	81.82	100	197.59	314.24	127.00	2.47	Flexure
114	300x600	10	0.25	0.01	220	0.0200	420	300	575	450.00	180000	145.82	218.18	100	526.91	643.56	134.00	4.80	Flexure
115	300x600	10	0.25	0.01	420	0.0075	420	300	575	450.00	180000	145.82	81.82	100	197.59	314.24	179.00	1.76	Flexure
116	300x600	10	0.25	0.01	420	0.0200	420	300	575	450.00	180000	145.82	218.18	100	526.91	643.56	190.00	3.39	Flexure
117	300x600	10	0.40	0.01	220	0.0075	420	300	575	720.00	180000	158.85	81.82	100	197.59	324.67	138.00	2.35	Flexure
118	300x600	10	0.40	0.01	220	0.0200	420	300	575	720.00	180000	158.85	218.18	100	526.91	653.99	152.00	4.30	Flexure
119	300x600	10	0.40	0.01	420	0.0075	420	300	575	720.00	180000	158.85	81.82	100	197.59	324.67	186.00	1.75	Flexure
120	300x600	10	0.40	0.01	420	0.0200	420	300	575	720.00	180000	158.85	218.18	100	526.91	653.99	205.00	3.19	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.1 (cont'd) Properties of the Flexure Critical Columns Analyzed in Parametric Study

Specimen Number	Dimension (mm)	f_{ck} (MPa)	N/N_o	ρ	f_{yk} (MPa)	ρ_s	f_{ywk} (MPa)	b_w (mm)	d (mm)	Axial Load (kN)	A_g (mm^2)	V_{cr} (kN)	A_{sw} (mm^2)	s (mm)	V_w (kN)	$V_n = 0.8V_{cr} + V_w$ (kN)	$V_{flexure}$ (kN)	$V_n / V_{flexure}$	Failure Type
121	300x600	14	0.10	0.01	220	0.0075	420	300	575	252.00	180000	161.23	81.82	100	197.59	326.57	109.00	3.00	Flexure
122	300x600	14	0.10	0.01	220	0.0200	420	300	575	252.00	180000	161.23	218.18	100	526.91	655.89	109.00	6.02	Flexure
123	300x600	14	0.10	0.01	420	0.0075	420	300	575	252.00	180000	161.23	81.82	100	197.59	326.57	172.00	1.90	Flexure
124	300x600	14	0.10	0.01	420	0.0200	420	300	575	252.00	180000	161.23	218.18	100	526.91	655.89	172.00	3.81	Flexure
125	300x600	14	0.25	0.01	220	0.0075	420	300	575	630.00	180000	182.81	81.82	100	197.59	343.84	150.00	2.29	Flexure
126	300x600	14	0.25	0.01	220	0.0200	420	300	575	630.00	180000	182.81	218.18	100	526.91	673.16	158.00	4.26	Flexure
127	300x600	14	0.25	0.01	420	0.0075	420	300	575	630.00	180000	182.81	81.82	100	197.59	343.84	202.00	1.70	Flexure
128	300x600	14	0.25	0.01	420	0.0200	420	300	575	630.00	180000	182.81	218.18	100	526.91	673.16	213.00	3.16	Flexure
129	300x600	14	0.40	0.01	220	0.0075	420	300	575	1,008.00	180000	204.40	81.82	100	197.59	361.11	161.00	2.24	Flexure
130	300x600	14	0.40	0.01	220	0.0200	420	300	575	1,008.00	180000	204.40	218.18	100	526.91	690.43	177.00	3.90	Flexure
131	300x600	14	0.40	0.01	420	0.0075	420	300	575	1,008.00	180000	204.40	81.82	100	197.59	361.11	213.00	1.70	Flexure
132	300x600	14	0.40	0.01	420	0.0200	420	300	575	1,008.00	180000	204.40	218.18	100	526.91	690.43	232.00	2.98	Flexure
133	300x600	20	0.10	0.01	220	0.0075	420	300	575	360.00	180000	200.07	81.82	100	197.59	357.65	124.00	2.88	Flexure
134	300x600	20	0.10	0.01	220	0.0200	420	300	575	360.00	180000	200.07	218.18	100	526.91	686.97	124.00	5.54	Flexure
135	300x600	20	0.10	0.01	420	0.0075	420	300	575	360.00	180000	200.07	81.82	100	197.59	357.65	188.00	1.90	Flexure
136	300x600	20	0.10	0.01	420	0.0200	420	300	575	360.00	180000	200.07	218.18	100	526.91	686.97	188.00	3.65	Flexure
137	300x600	20	0.25	0.01	220	0.0075	420	300	575	900.00	180000	236.93	81.82	100	197.59	387.13	184.00	2.10	Flexure
138	300x600	20	0.25	0.01	220	0.0200	420	300	575	900.00	180000	236.93	218.18	100	526.91	716.45	194.00	3.69	Flexure
139	300x600	20	0.25	0.01	420	0.0075	420	300	575	900.00	180000	236.93	81.82	100	197.59	387.13	240.00	1.61	Flexure
140	300x600	20	0.25	0.01	420	0.0200	420	300	575	900.00	180000	236.93	218.18	100	526.91	716.45	249.00	2.88	Flexure
141	300x600	20	0.40	0.01	220	0.0075	420	300	575	1,440.00	180000	273.79	81.82	100	197.59	416.62	205.00	2.03	Flexure
142	300x600	20	0.40	0.01	220	0.0200	420	300	575	1,440.00	180000	273.79	218.18	100	526.91	745.94	210.00	3.55	Flexure
143	300x600	20	0.40	0.01	420	0.0075	420	300	575	1,440.00	180000	273.79	81.82	100	197.59	416.62	259.00	1.61	Flexure
144	300x600	20	0.40	0.01	420	0.0200	420	300	575	1,440.00	180000	273.79	218.18	100	526.91	745.94	272.00	2.74	Flexure

Notation: f_{ck}: concrete compressive strength, N/N_0: axial load ratio, ρ: longitudinal reinforcement ratio, f_{yk}: yielding strength of longitudinal reinforcement, b_w: width of the section, d: effective depth of the section, A_g: cross sectional area of the specimen, V_{cr}: diagonal cracking strength of the section, A_{sw}: cross sectional area of the transverse reinforcement, s: spacing of the transverse reinforcement, V_w: transverse reinforcement contribution to the shear strength of the section, V_n: Shear strength of the section, $V_{flexure}$: lateral load that causes the column to reach its moment capacity

Table C.2 Estimated Drift Ratios

Specimen No	Estimated Immediate Occupancy	Estimated Life Safety	Estimated Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
1	0.48	4.67	6.22
2	0.49	4.66	6.21
3	0.73	4.89	6.52
4	0.73	5.60	7.47
5	0.58	1.94	2.59
6	0.47	4.63	6.17
7	0.83	3.25	4.34
8	0.79	3.15	4.19
9	0.40	0.99	1.32
10	0.40	1.97	2.63
11	0.82	1.74	2.31
12	0.80	2.64	3.52
13	0.46	4.42	5.89
14	0.46	4.41	5.87
15	0.70	5.11	6.81
16	0.70	5.11	6.81
17	0.53	1.69	2.26
18	0.45	3.63	4.83
19	0.76	1.96	2.61
20	0.77	2.96	3.95
21	0.53	1.30	1.73
22	0.61	1.99	2.65
23	0.82	1.69	2.25
24	0.75	2.61	3.47
25	0.45	3.24	4.31
26	0.44	3.24	4.31
27	0.67	4.77	6.35
28	0.67	4.77	6.35
29	0.51	1.37	1.83
30	0.43	2.03	2.71
31	0.78	1.51	2.02
32	0.65	2.55	3.40
33	0.61	1.04	1.39
34	0.53	1.88	2.51
35	0.69	1.06	1.41
36	0.69	2.01	2.68

Table C.2 (cont'd) Estimated Drift Ratios

Specimen No	Estimated Immediate Occupancy	Estimated Life Safety	Estimated Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
37	0.39	3.75	5.01
38	0.39	3.75	5.01
39	0.59	2.71	3.61
40	0.59	4.42	5.89
41	0.43	1.96	2.61
42	0.40	2.65	3.53
43	0.67	2.85	3.81
44	0.62	2.65	3.54
45	0.55	1.96	2.61
46	0.46	2.65	3.54
47	0.67	2.03	2.71
48	0.67	2.99	3.99
49	0.37	3.52	4.69
50	0.37	3.52	4.69
51	0.59	2.34	3.12
52	0.58	3.54	4.71
53	0.41	1.45	1.93
54	0.36	3.49	4.65
55	0.63	1.67	2.22
56	0.55	2.35	3.14
57	0.55	1.19	1.58
58	0.47	2.22	2.95
59	0.59	1.07	1.43
60	0.64	2.88	3.83
61	0.36	2.66	3.54
62	0.36	2.66	3.54
63	0.54	3.85	5.13
64	0.53	3.85	5.13
65	0.40	1.37	1.83
66	0.34	2.05	2.73
67	0.65	1.61	2.15
68	0.59	2.38	3.17
69	0.33	2.20	2.93
70	0.33	2.25	2.99
71	0.43	2.39	3.19
72	0.57	2.25	3.00

Table C.2 (cont'd) Estimated Drift Ratios

Specimen No	Estimated Immediate Occupancy	Estimated Life Safety	Estimated Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
73	0.39	3.76	5.01
74	0.39	3.75	5.00
75	0.59	3.33	4.44
76	0.59	4.44	5.91
77	0.44	1.44	1.92
78	0.38	3.79	5.05
79	0.65	2.52	3.36
80	0.65	2.43	3.25
81	0.57	1.26	1.68
82	0.47	2.42	3.23
83	0.66	1.43	1.90
84	0.67	2.73	3.64
85	0.38	3.51	4.68
86	0.38	3.51	4.67
87	0.57	4.10	5.47
88	0.57	4.11	5.47
89	0.43	1.10	1.47
90	0.37	2.75	3.67
91	0.63	1.15	1.54
92	0.62	2.29	3.05
93	0.40	1.09	1.45
94	0.40	1.91	2.55
95	0.63	0.94	1.25
96	0.63	2.03	2.71
97	0.36	2.67	3.57
98	0.36	2.67	3.57
99	0.54	3.83	5.10
100	0.54	3.83	5.10
101	0.41	1.09	1.46
102	0.38	1.83	2.45
103	0.63	0.93	1.25
104	0.59	1.90	2.53
105	0.33	1.53	2.05
106	0.33	1.75	2.34
107	0.57	0.84	1.12
108	0.62	1.61	2.14

Table C.2 (cont'd) Estimated Drift Ratios

Specimen No	Estimated Immediate Occupancy	Estimated Life Safety	Estimated Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
109	0.44	3.15	4.19
110	0.33	3.15	4.19
111	0.49	1.95	2.60
112	0.49	3.65	4.87
113	0.36	1.51	2.01
114	0.33	2.03	2.71
115	0.55	2.33	3.10
116	0.50	2.21	2.95
117	0.46	1.53	2.04
118	0.39	2.33	3.10
119	0.56	1.43	1.90
120	0.55	2.39	3.18
121	0.31	2.95	3.93
122	0.31	2.95	3.93
123	0.47	3.27	4.35
124	0.47	3.41	4.55
125	0.36	1.35	1.80
126	0.32	1.91	2.54
127	0.55	2.37	3.16
128	0.49	2.07	2.76
129	0.27	1.33	1.78
130	0.40	2.07	2.76
131	0.40	0.91	1.22
132	0.54	2.33	3.10
133	0.30	2.67	3.56
134	0.30	2.67	3.56
135	0.45	3.22	4.29
136	0.45	3.21	4.29
137	0.33	1.03	1.37
138	0.29	1.61	2.14
139	0.50	0.91	1.21
140	0.48	1.87	2.50
141	0.33	2.11	2.81
142	0.33	2.17	2.89
143	0.40	0.71	0.95
144	0.48	1.73	2.31

Table C.3 Drift Ratios Obtained by TEC (2007)

Specimen No	TEC2007 Immediate Occupancy	TEC2007 Life Safety	TEC2007 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
1	1.14	2.23	3.15
2	1.15	2.23	3.15
3	1.36	2.55	4.11
4	1.31	2.63	4.22
5	1.17	1.81	2.01
6	1.13	2.31	3.27
7	1.16	2.28	2.73
8	1.23	2.03	2.35
9	1.31	1.57	1.68
10	1.05	1.77	1.98
11	1.05	1.61	1.75
12	1.05	1.68	1.84
13	1.19	2.15	3.02
14	1.19	2.15	3.02
15	1.29	2.51	4.03
16	1.29	2.51	4.03
17	1.39	2.39	2.81
18	1.14	2.26	3.17
19	1.35	1.91	2.15
20	1.17	2.18	2.46
21	1.43	1.73	1.82
22	1.24	2.33	2.77
23	1.22	2.10	2.22
24	1.08	2.13	2.57
25	1.26	2.21	2.87
26	1.26	2.21	2.87
27	1.29	2.41	3.37
28	1.29	2.41	3.37
29	1.36	1.73	1.82
30	1.16	2.13	2.25
31	1.22	1.73	1.87
32	1.12	1.83	2.11
33	1.09	1.35	1.44
34	1.45	2.47	2.87
35	1.09	1.35	1.44
36	1.09	2.07	2.43

Table C.3 (cont'd) Drift Ratios Obtained by TEC (2007)

Specimen No	TEC2007 Immediate Occupancy	TEC2007 Life Safety	TEC2007 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
37	0.93	1.81	2.55
38	0.93	1.81	2.55
39	1.07	2.15	2.93
40	1.05	2.15	3.33
41	0.89	1.49	1.71
42	0.93	1.97	2.71
43	0.93	1.81	2.17
44	0.96	1.80	2.05
45	1.21	2.05	2.38
46	1.21	2.13	2.51
47	0.81	1.69	2.02
48	0.95	1.95	2.34
49	0.95	1.77	2.45
50	0.95	1.77	2.45
51	1.07	2.01	2.21
52	1.09	2.14	3.11
53	0.98	1.50	1.67
54	0.88	1.85	2.57
55	0.89	1.39	1.55
56	0.94	1.60	1.83
57	1.29	1.45	1.51
58	1.41	2.28	2.64
59	0.84	1.05	1.13
60	0.92	1.87	2.23
61	0.99	1.74	2.35
62	0.99	1.74	2.35
63	1.03	1.98	2.77
64	1.04	1.98	2.76
65	1.21	1.65	1.75
66	0.85	1.83	2.37
67	1.06	1.85	2.19
68	0.93	1.74	2.01
69	0.92	1.79	2.15
70	2.08	2.90	3.25
71	0.92	1.79	2.15
72	0.87	1.17	1.23

Table C.3 (cont'd) Drift Ratios Obtained by TEC (2007)

Specimen No	TEC2007 Immediate Occupancy	TEC2007 Life Safety	TEC2007 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
73	0.89	1.80	2.55
74	0.89	1.80	2.57
75	1.08	2.03	3.22
76	1.05	2.09	3.31
77	0.90	1.33	1.43
78	0.92	1.87	2.62
79	0.89	1.75	2.09
80	1.00	1.61	1.85
81	0.97	1.46	1.55
82	1.09	2.00	2.35
83	0.81	1.15	1.25
84	0.91	1.83	2.18
85	0.91	1.75	2.45
86	0.91	1.75	2.45
87	1.03	2.03	3.17
88	1.03	2.03	3.18
89	0.97	1.27	1.35
90	0.94	1.84	2.58
91	0.87	1.11	1.19
92	0.97	1.55	1.78
93	1.20	1.41	1.47
94	1.16	1.99	2.32
95	0.85	1.09	1.17
96	0.91	1.71	2.03
97	0.95	1.70	2.36
98	0.95	1.70	2.36
99	1.03	1.96	2.75
100	1.03	1.96	2.76
101	1.17	1.38	1.43
102	0.99	1.71	1.92
103	0.89	1.10	1.16
104	0.93	1.53	1.68
105	1.99	2.08	2.12
106	1.38	2.14	2.44
107	0.93	1.09	1.15
108	0.95	1.67	1.88

Table C.3 (cont'd) Drift Ratios Obtained by TEC (2007)

Specimen No	TEC2007 Immediate Occupancy	TEC2007 Life Safety	TEC2007 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
109	0.76	1.53	2.41
110	0.76	1.53	2.41
111	0.89	1.73	2.10
112	0.87	1.78	2.75
113	0.73	1.19	1.38
114	0.77	1.56	1.75
115	0.77	1.49	1.80
116	0.80	1.53	1.79
117	1.01	1.67	1.91
118	1.03	1.78	2.08
119	0.67	1.35	1.55
120	0.78	1.57	1.87
121	0.77	1.49	2.08
122	0.77	1.49	2.08
123	0.86	1.73	2.63
124	0.86	1.73	2.64
125	1.09	1.73	2.01
126	0.77	1.41	1.63
127	0.81	1.50	1.78
128	0.79	1.45	1.67
129	1.37	1.75	1.79
130	1.25	1.95	2.25
131	0.68	1.11	1.16
132	0.77	1.52	1.82
133	0.80	1.45	2.01
134	0.80	1.45	2.01
135	0.85	1.67	2.50
136	0.86	1.67	2.50
137	1.01	1.28	1.33
138	0.73	1.17	1.33
139	0.76	1.02	1.08
140	0.78	1.35	1.49
141	0.00	0.00	0.00
142	2.04	2.67	2.94
143	0.73	0.90	0.95
144	0.79	1.47	1.74

Table C.4 Drift Ratios Obtained by FEMA 356 (2000)

Specimen No	FEMA356 Immediate Occupancy	FEMA356 Life Safety	FEMA356 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
1	0.90	1.90	2.40
2	0.90	1.90	2.40
3	1.09	2.09	2.59
4	1.09	2.09	2.59
5	0.92	1.87	2.27
6	0.81	1.76	2.16
7	1.15	2.10	2.50
8	1.07	2.02	2.42
9	1.01	1.91	2.21
10	0.83	1.73	2.03
11	0.76	1.66	1.96
12	1.07	1.96	2.25
13	0.89	1.89	2.39
14	0.89	1.89	2.39
15	1.07	2.07	2.57
16	1.07	2.07	2.57
17	0.87	1.82	2.22
18	0.79	1.74	2.14
19	1.07	2.02	2.42
20	1.10	2.05	2.45
21	1.10	2.00	2.30
22	0.89	1.79	2.09
23	1.11	2.01	2.31
24	1.10	2.00	2.30
25	0.89	1.89	2.39
26	0.89	1.89	2.39
27	1.06	2.06	2.56
28	1.06	2.06	2.56
29	0.88	1.83	2.23
30	0.77	1.72	2.12
31	1.15	2.10	2.50
32	0.99	1.94	2.34
33	0.83	1.73	2.03
34	0.98	1.88	2.18
35	1.26	2.16	2.46
36	1.16	2.06	2.36

Table C.4 (cont'd) Drift Ratios Obtained by FEMA 356 (2000)

Specimen No	FEMA356 Immediate Occupancy	FEMA356 Life Safety	FEMA356 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
37	0.82	1.82	2.32
38	0.82	1.82	2.32
39	0.97	1.95	2.45
40	0.97	1.95	2.45
41	0.78	1.73	2.13
42	0.74	1.69	2.09
43	0.99	1.91	2.29
44	0.88	1.78	2.16
45	0.83	1.73	2.03
46	0.71	1.61	1.91
47	0.96	1.82	2.11
48	0.90	1.75	2.02
49	0.82	1.82	2.32
50	0.82	1.82	2.32
51	0.98	1.98	2.48
52	0.97	1.97	2.47
53	0.77	1.72	2.12
54	0.71	1.66	2.06
55	0.97	1.90	2.28
56	0.87	1.79	2.17
57	0.84	1.74	2.04
58	0.75	1.65	1.95
59	1.00	1.86	2.15
60	0.93	1.78	2.06
61	0.81	1.81	2.31
62	0.81	1.81	2.31
63	0.95	1.95	2.45
64	0.95	1.95	2.45
65	0.77	1.72	2.12
66	0.69	1.64	2.04
67	0.99	1.92	2.30
68	0.93	1.86	2.25
69	0.68	1.53	1.81
70	0.81	1.71	2.01
71	0.98	1.84	2.13
72	1.05	1.92	2.20

Table C.4 (cont'd) Drift Ratios Obtained by FEMA 356 (2000)

Specimen No	FEMA356 Immediate Occupancy	FEMA356 Life Safety	FEMA356 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
73	0.82	1.82	2.32
74	0.82	1.82	2.32
75	0.97	1.96	2.45
76	0.97	1.95	2.45
77	0.79	1.74	2.14
78	0.72	1.67	2.07
79	0.89	1.76	2.04
80	0.85	1.69	1.97
81	0.85	1.75	2.05
82	0.73	1.63	1.93
83	0.97	1.82	2.10
84	0.91	1.75	2.02
85	0.82	1.82	2.32
86	0.82	1.82	2.32
87	0.96	1.96	2.46
88	0.96	1.96	2.46
89	0.78	1.73	2.13
90	0.71	1.66	2.06
91	0.88	1.74	2.03
92	0.84	1.70	1.99
93	0.91	1.81	2.11
94	0.76	1.66	1.96
95	0.99	1.83	2.12
96	0.91	1.75	2.03
97	0.81	1.81	2.31
98	0.81	1.81	2.31
99	0.95	1.95	2.45
100	0.95	1.95	2.45
101	0.77	1.72	2.12
102	0.73	1.68	2.08
103	0.88	1.74	2.04
104	0.83	1.70	1.98
105	1.13	2.03	2.33
106	0.83	1.73	2.03
107	1.11	1.96	2.24
108	1.00	1.85	2.12

Table C.4 (cont'd) Drift Ratios Obtained by FEMA 356 (2000)

Specimen No	FEMA356 Immediate Occupancy	FEMA356 Life Safety	FEMA356 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
109	0.77	1.77	2.27
110	0.77	1.77	2.27
111	0.89	1.81	2.29
112	0.89	1.81	2.29
113	0.71	1.66	2.06
114	0.68	1.62	2.02
115	0.89	1.74	2.11
116	0.83	1.66	2.02
117	0.74	1.63	1.92
118	0.64	1.51	1.79
119	0.85	1.66	1.92
120	0.79	1.58	1.82
121	0.76	1.76	2.26
122	0.76	1.76	2.26
123	0.88	1.85	2.33
124	0.88	1.85	2.33
125	0.71	1.66	2.06
126	0.67	1.62	2.02
127	0.89	1.76	2.13
128	0.83	1.68	2.04
129	0.78	1.67	1.97
130	0.67	1.54	1.83
131	0.87	1.69	1.96
132	0.83	1.63	1.88
133	0.76	1.76	2.26
134	0.76	1.76	2.26
135	0.87	1.86	2.36
136	0.87	1.86	2.36
137	0.71	1.66	2.06
138	0.64	1.58	1.97
139	0.85	1.73	2.10
140	0.83	1.69	2.06
141	0.89	1.76	2.05
142	0.72	1.59	1.88
143	0.93	1.75	2.00
144	0.85	1.66	1.91

Table C.5 Drift Ratios Obtained by EC 8 (2003)

Specimen No	EC 8 Immediate Occupancy	EC 8 Life Safety	EC 8 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
1	0.48	2.44	3.25
2	0.48	3.72	4.96
3	0.77	2.44	3.25
4	0.77	3.72	4.96
5	0.56	2.03	2.70
6	0.53	3.10	4.14
7	0.84	2.03	2.70
8	0.84	3.10	4.14
9	0.63	1.70	2.26
10	0.61	2.60	3.45
11	0.91	1.70	2.26
12	0.95	2.60	3.45
13	0.48	2.63	3.50
14	0.48	4.01	5.35
15	0.75	2.63	3.50
16	0.75	4.01	5.35
17	0.53	2.19	2.93
18	0.53	3.35	4.46
19	0.81	2.19	2.93
20	0.88	3.35	4.46
21	0.63	1.83	2.44
22	0.60	2.80	3.73
23	0.87	1.83	2.44
24	0.89	2.80	3.73
25	0.48	2.51	3.30
26	0.48	3.10	4.13
27	0.73	2.51	3.30
28	0.73	3.10	4.13
29	0.59	2.10	2.80
30	0.54	2.59	3.45
31	0.83	2.10	2.80
32	0.82	2.59	3.45
33	0.62	1.75	2.33
34	0.62	2.16	2.88
35	0.93	1.75	2.33
36	0.91	2.16	2.88

Table C.5 (cont'd) Drift Ratios Obtained by EC 8 (2003)

Specimen No	EC 8 Immediate Occupancy	EC 8 Life Safety	EC 8 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
37	0.44	2.28	3.04
38	0.43	3.53	4.71
39	0.68	2.28	3.04
40	0.67	3.53	4.71
41	0.51	1.90	2.53
42	0.51	2.95	3.93
43	0.73	1.90	2.53
44	0.73	2.95	3.93
45	0.53	1.59	2.12
46	0.53	2.46	3.28
47	0.79	1.59	2.12
48	0.77	2.46	3.28
49	0.45	2.28	3.04
50	0.42	3.12	4.16
51	0.70	2.28	3.04
52	0.71	3.12	4.16
53	0.52	1.90	2.53
54	0.49	2.60	3.47
55	0.77	1.90	2.53
56	0.73	2.60	3.47
57	0.60	1.59	2.12
58	0.54	2.17	2.90
59	0.86	1.59	2.12
60	0.78	2.17	2.90
61	0.44	2.33	3.11
62	0.44	2.90	3.87
63	0.65	2.33	3.11
64	0.65	2.90	3.87
65	0.55	1.95	2.60
66	0.52	2.43	3.23
67	0.73	1.95	2.60
68	0.77	2.43	3.23
69	0.57	1.63	2.17
70	0.58	2.02	2.70
71	0.80	1.63	2.17
72	0.80	2.02	2.70

Table C.5 (cont'd) Drift Ratios Obtained by EC 8 (2003)

Specimen No	EC 8 Immediate Occupancy	EC 8 Life Safety	EC 8 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
73	0.44	2.06	2.74
74	0.44	2.70	3.60
75	0.67	2.06	2.74
76	0.66	2.70	3.60
77	0.50	1.72	2.29
78	0.47	2.25	3.00
79	0.74	1.72	2.29
80	0.72	2.25	3.00
81	0.53	1.44	1.92
82	0.51	1.88	2.50
83	0.57	1.44	1.92
84	0.56	1.88	2.50
85	0.44	2.12	2.82
86	0.43	2.57	3.43
87	0.66	2.12	2.82
88	0.66	2.57	3.43
89	0.52	1.77	2.36
90	0.49	2.15	2.86
91	0.77	1.77	2.36
92	0.73	2.15	2.86
93	0.55	1.48	1.97
94	0.52	1.79	2.39
95	0.80	1.48	1.97
96	0.78	1.79	2.39
97	0.44	2.22	2.96
98	0.44	2.54	3.38
99	0.65	2.22	2.96
100	0.65	2.54	3.38
101	0.53	1.85	2.47
102	0.52	2.12	2.82
103	0.77	1.85	2.47
104	0.75	2.12	2.82
105	0.61	1.55	2.06
106	0.56	1.77	2.36
107	0.81	1.55	2.06
108	0.79	1.77	2.26

Table C.5 (cont'd) Drift Ratios Obtained by EC 8 (2003)

Specimen No	EC 8 Immediate Occupancy	EC 8 Life Safety	EC 8 Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
109	0.42	1.91	2.55
110	0.42	2.46	3.28
111	0.62	1.91	2.55
112	0.61	2.46	3.28
113	0.41	1.60	2.13
114	0.41	2.05	2.74
115	0.60	1.60	2.13
116	0.62	2.05	2.74
117	0.49	1.33	1.78
118	0.49	1.72	2.29
119	0.71	1.33	1.78
120	0.70	1.72	2.29
121	0.42	1.97	2.63
122	0.42	2.36	3.15
123	0.61	1.97	2.63
124	0.61	2.36	3.15
125	0.46	1.65	2.20
126	0.48	1.97	2.63
127	6.60	1.65	2.20
128	0.69	1.97	2.63
129	0.51	1.37	1.83
130	0.51	1.65	2.20
131	0.71	1.37	1.83
132	0.70	1.65	2.20
133	0.48	1.44	1.92
134	0.43	1.64	2.18
135	0.59	1.44	1.92
136	0.59	1.64	2.18
137	0.49	1.73	2.30
138	0.48	1.96	2.60
139	0.70	1.73	2.30
140	0.70	1.96	2.60
141	0.54	1.44	1.92
142	0.52	1.64	2.18
143	0.73	1.44	1.92
144	0.71	1.64	2.18

Table C.6 Drift Ratios Obtained by ASCE/SEI 41 Update (2009)

Specimen No	ASCE/SEI 41 Update Immediate Occupancy	ASCE/SEI 41 Update Life Safety	ASCE/SEI 41 Update Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
1	0.90	2.40	3.10
2	0.90	2.81	3.64
3	1.09	2.59	3.29
4	1.09	3.00	3.83
5	0.93	2.01	2.53
6	0.84	2.29	2.90
7	1.16	2.24	2.76
8	1.10	2.55	3.16
9	1.03	1.69	2.03
10	0.89	1.88	2.27
11	0.78	1.44	1.78
12	1.13	2.12	2.51
13	0.89	2.39	3.09
14	0.89	2.80	3.63
15	1.07	2.57	3.27
16	1.07	2.98	3.81
17	0.88	1.96	2.48
18	0.82	2.27	2.88
19	1.08	2.16	2.68
20	1.13	2.58	3.19
21	1.12	1.78	2.12
22	0.95	1.94	2.33
23	1.13	1.79	2.13
24	1.16	2.15	2.54
25	0.89	2.39	3.09
26	0.89	2.80	3.63
27	1.06	2.56	3.26
28	1.06	2.97	3.80
29	0.89	1.97	2.49
30	0.80	2.25	2.86
31	1.16	2.24	2.76
32	1.02	2.47	3.08
33	0.85	1.51	1.85
34	1.04	2.03	2.42
35	1.28	1.94	2.28
36	1.22	2.21	2.60

Table C.6 (cont'd) Drift Ratios Obtained by ASCE/SEI 41 Update (2009)

Specimen No	ASCE/SEI 41 Update Immediate Occupancy	ASCE/SEI 41 Update Life Safety	ASCE/SEI 41 Update Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
37	0.82	2.32	3.02
38	0.82	2.73	3.56
39	0.97	2.47	3.17
40	0.97	2.88	3.71
41	0.79	1.87	2.39
42	0.77	2.22	2.83
43	1.00	2.08	2.60
44	0.91	2.36	2.97
45	0.85	1.51	1.85
46	0.77	1.76	2.15
47	0.98	1.64	1.98
48	0.96	1.95	2.34
49	0.82	2.32	3.02
50	0.82	2.73	3.56
51	0.98	2.48	3.18
52	0.97	2.88	3.71
53	0.78	1.86	2.38
54	0.74	2.19	2.80
55	0.98	2.06	2.58
56	0.90	2.35	2.96
57	0.86	1.52	1.86
58	0.81	1.80	2.19
59	1.02	1.68	2.02
60	0.99	1.98	2.37
61	0.81	2.31	3.01
62	0.81	2.72	3.55
63	0.95	2.45	3.15
64	0.95	2.86	3.69
65	0.78	1.86	2.38
66	0.72	2.17	2.78
67	1.00	2.08	2.60
68	0.96	2.41	3.02
69	0.70	1.36	1.70
70	0.87	1.86	2.25
71	1.00	1.66	2.00
72	1.11	2.10	2.49

Table C.6 (cont'd) Drift Ratios Obtained by ASCE/SEI 41 Update (2009)

Specimen No	ASCE/SEI 41 Update Immediate Occupancy	ASCE/SEI 41 Update Life Safety	ASCE/SEI 41 Update Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
73	0.82	2.37	3.08
74	0.82	2.92	3.82
75	0.97	2.52	3.23
76	0.97	3.07	3.97
77	0.80	1.92	2.45
78	0.76	2.38	3.04
79	1.01	2.12	2.65
80	0.99	2.61	3.27
81	0.88	1.57	1.92
82	0.81	1.95	2.37
83	1.00	1.69	2.04
84	0.99	2.13	2.55
85	0.82	2.37	3.08
86	0.82	2.92	3.82
87	0.96	2.51	3.22
88	0.96	3.06	3.96
89	0.79	1.91	2.44
90	0.75	2.37	3.03
91	0.99	2.11	2.64
92	0.98	2.60	3.26
93	0.93	1.63	1.98
94	0.84	1.98	2.40
95	1.01	1.71	2.06
96	0.99	2.13	2.55
97	0.81	2.36	3.07
98	0.81	2.91	3.81
99	0.95	2.50	3.21
100	0.95	3.05	3.95
101	0.79	1.90	2.43
102	0.77	2.39	3.05
103	0.99	2.11	2.64
104	0.97	2.59	3.25
105	1.15	1.85	2.20
106	0.91	2.05	2.47
107	1.14	1.83	2.18
108	1.08	2.22	2.64

Table C.6 (cont'd) Drift Ratios Obtained by ASCE/SEI 41 Update (2009)

Specimen No	ASCE/SEI 41 Update Immediate Occupancy	ASCE/SEI 41 Update Life Safety	ASCE/SEI 41 Update Collapse Prevention
	Drift Ratio (%)	Drift Ratio (%)	Drift Ratio (%)
109	0.77	2.31	3.03
110	0.77	2.87	3.77
111	0.89	2.43	3.15
112	0.89	2.99	3.89
113	0.73	1.84	2.37
114	0.72	2.34	3.00
115	0.90	2.02	2.55
116	0.87	2.49	3.15
117	0.76	1.46	1.81
118	0.72	1.86	2.28
119	0.87	1.57	1.92
120	0.87	2.01	2.43
121	0.76	2.31	3.02
122	0.76	2.86	3.76
123	0.88	2.43	3.14
124	0.88	2.98	3.88
125	0.73	1.84	2.37
126	0.71	2.33	2.99
127	0.90	2.02	2.55
128	0.87	2.49	3.15
129	0.80	1.50	1.85
130	0.75	1.89	2.31
131	0.89	1.59	1.94
132	0.91	2.05	2.47
133	0.76	2.31	3.02
134	0.76	2.86	3.76
135	0.87	2.41	3.13
136	0.87	2.97	3.87
137	0.72	1.84	2.37
138	0.68	2.30	2.96
139	0.87	1.98	2.51
140	0.87	2.49	3.15
141	0.91	1.61	1.96
142	0.80	1.94	2.36
143	0.95	1.65	2.00
144	0.93	2.07	2.49